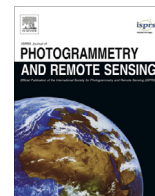




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Automated mapping of persistent ice and snow cover across the western U.S. with Landsat

David J. Selkowitz^{a,b,*}, Richard R. Forster^b^a US Geological Survey, Alaska Science Center, 4210 University Drive, Anchorage, AK 99508, USA^b Department of Geography, University of Utah, 260 S. Central Campus Dr., Rm. 270, Salt Lake City, UT 84112, USA

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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.

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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.

* Corresponding author at: US Geological Survey, Alaska Science Center, 4210 University Drive, Anchorage, AK 99508, USA.

E-mail addresses: dselkowitz@usgs.gov (D.J. Selkowitz), rick.forster@geog.utah.edu (R.R. Forster).

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 (Malooof et al., 2014). In the nearby Teton Range, ice cover declined by

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

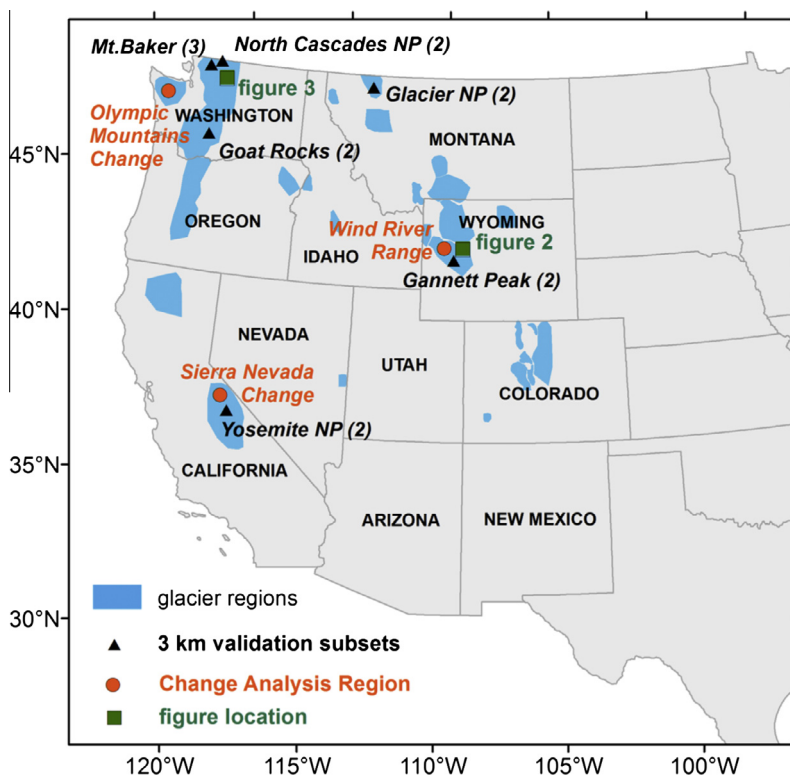


Fig. 1. Overview map of the western United States, including glacier regions defined by the USGS DRG dataset, very high resolution imagery (VHRI) validation subsets, change analysis regions, and locations for other figures.

ranges and the Rocky Mountains, but are not included in this analysis as they are generally smaller than the minimum mapping unit of 2 ha used in this analysis. While the Cascades and Sierra Nevada typically exhibit maritime snow climates with heavy precipitation and temperatures near 0 °C throughout much of the winter, the Rocky Mountains typically exhibit more continental conditions, with lower precipitation totals and winter temperatures well below 0 °C at higher elevations.

The USGS DRG dataset indicates the Cascades contained approximately 413 km² of PISC, with about 90% of the total PISC area mapped in the Cascades located in Washington state, 9% located in Oregon, and 1% located in northern California. With the exception of the northernmost portion of the range, PISC in the Cascades is generally confined to isolated volcanic peaks. The USGS DRG dataset indicates Washington's Olympic Mountains contain an additional 41.9 km² of PISC concentrated within a relatively small area of 9000 km². Both the Cascade and Olympic ranges include several medium-sized glaciers covering >3 km² that account for a substantial portion of the total area of PISC in each range. To the south of the Cascades, 11.4 km² of PISC, composed entirely of small glaciers and perennial snow cover patches, has been mapped in the Sierra Nevada of California. In the Rocky Mountains of Wyoming and Montana, the USGS DRG dataset maps 108 km² of PISC, with several glaciers in the Lewis and Clark and Wind River Ranges >1 km². Finally, the USGS DRG dataset maps about 2 km² of PISC scattered across the Rocky Mountains of Colorado.

2.2. Data

2.2.1. The USGS DRG dataset: digital glacier outlines from USGS topographic maps

The USGS DRG dataset, which has sometimes also been referred to as the US Glacier Database, is a vector dataset of glacier and perennial snow cover patch outlines developed from 1:100,000

Digital Raster Graphics (DRG) maps produced by the USGS (Fountain et al., 2007). The database includes all glaciers and perennial snow cover features mapped in the 1:100,000 series of topographic maps. Maps were produced primarily from aerial photography acquired during the 1960s through the 1980s, although a small number of maps may have used aerial photography from as early as the 1940s. The metadata for this dataset clearly states that not all features included in the database meet the qualifications to be considered active glaciers. In addition to the set of polygons indicating the extent of individual glaciers or perennial snow patches, the database also provides a set of polygons identifying 27 mountain regions where PISC has been mapped.

2.2.2. Landsat data

We obtained 30 m resolution Landsat Climate Data Record (CDR) top-of-atmosphere (TOA) and surface reflectance products (Masek et al., 2006) for Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper (ETM+) scenes located within glacier regions identified by the USGS DRG dataset. We used the USGS LRS Science Research and Development (LSRD) bulk order tool to order, subset, and reproject all Landsat TM and ETM+ scenes acquired between August 20 and September 30 for the 2010–2014 period. The August 20–September 30 period was selected because scenes acquired earlier in the season often contained substantial seasonal snow cover remaining from the previous winter, while scenes acquired after September 30 often included recently accumulated early season snow cover as well as substantial areas in deep shadow in the most northern portion of the region. Using the bulk ordering tool, we subset each scene to the extent of glaciated regions (as defined by the USGS DRG dataset) within the Landsat path/row and reprojected the data to the Albers Equal Area Conic projection used by the National Land Cover Database (NLCD) and other national-scale products. The final PISC classification was developed using data from 754 Landsat scenes from 30 different

Worldwide Reference System 2 (WRS-2) path/rows across the western U.S. The mean number of scenes acquired was 25 per path/row and ranged from 24 to 27.

2.2.3. Land cover and elevation data

We acquired the NLCD 2011 (Jin et al., 2013) land cover classification for the conterminous U.S. in order to assess the extent of PISC mapped by the NLCD as well as for identification of water features that are occasionally mapped as PISC by the automated Landsat approach. While the NLCD 2011 land cover dataset included 25 land cover classes for the conterminous U.S., our analysis focused exclusively on class 11 (open water) and class 12 (perennial ice/snow). We also acquired a seamless 30 m digital elevation model (DEM) covering the conterminous western U.S. from the National Elevation Dataset (NED) (Gesch et al., 2002).

2.2.4. Very high resolution imagery used for validation

We acquired 0.5 m resolution pan-sharpened natural color imagery from the Digital Globe Enhanced View archive for August or September covering 13 separate 3×3 km subsets that each included one or more glacier (Fig. 1). Imagery for each high resolution subset was acquired by the WorldView 2 or WorldView 3 satellites (mention of a specific product does not constitute endorsement by the U.S. government). The selection of very high resolution imagery (VHRI) validation subsets was constrained to 3×3 km blocks containing at least one previously identified glacier where cloud-free August or September imagery from 2010 to 2014 was available and seasonal snow cover was absent or minimal. Allowing for these constraints, we selected subsets intended to represent a range of glacier sizes, topography, and climate conditions.

2.3. Methods

Our approach to mapping PISC uses all available Landsat Thematic Mapper TM and ETM+ scenes acquired between August 20 and September 30 during the 2010–2014 period. Cloud-covered and shadowed pixels for each date are identified first and excluded from further analysis. Cloud-free, shadow-free pixels are classified as snow/ice or snow/ice-free for each available cloud-free, shadow-free view. Pixels classified as snow/ice-covered in >80% of available views are initially classified as PISC. We then apply several post-processing routines designed to reduce the occurrence of errors of commission (false positives for PISC), including removing patches of PISC of <25 contiguous pixels, eliminating PISC mapped below a minimum elevation threshold that varies by region, eliminating PISC mapped where the NLCD classification indicates water, and applying a stricter standard to mapping PISC pixels in areas not previously mapped as PISC by the USGS DRG dataset. Fig. 2 provides a visual representation of the approach we used to classify PISC across the study region.

2.3.1. Cloud and shadow masking

Automated approaches to mapping PISC require a fully automated cloud-masking approach that performs well in mountainous environments with mixtures of ice, snow, rock, and other land cover. The CFmask cloud classification (Zhu and Woodcock, 2012) provided with the USGS CDR Landsat surface reflectance products employs a series of rules based on the physical properties of clouds to develop an initial cloud cover classification using Landsat bands 1–5 and 7 as well as brightness temperature from band 6. The initial cloud cover classification is then segmented into cloud objects used to produce the final cloud mask, as well as a cloud shadow mask based on the cloud objects and solar illumination geometry at the time of scene acquisition. While the CFMask represents a substantial improvement over previous cloud classification

approaches and accuracy for the CFmask has been reported as 96.4% (Zhu and Woodcock, 2012), previous work has demonstrated that it is prone to mapping false cloud cover in mountainous areas dominated by rock, snow and ice (Selkowitz and Forster, 2015). Examination of several scenes from mountainous areas of the western U.S. indicated that CFmask cloud masks provided with the surface reflectance CDR product frequently identify cloud cover in cloud-free regions where rock, snow, and ice are the dominant land cover types (an example is shown in Fig. 3). Although occasional errors of commission in cloud cover masks are to be expected and would most likely not pose a substantial problem for an automated PISC mapping approach, the errors of commission in the CFmask cloud cover masks present a more serious problem because they tend to occur consistently at certain locations. This can result in clusters of pixels where very few cloud-free, shadow-free views are available (as shown in Fig. 3) and ultimately result in patches of incorrectly mapped PISC.

In order to address this problem and fully exploit all available cloud-free, shadow-free views acquired between August 20 and September 30 each year, we employed a cloud masking approach developed by Selkowitz and Forster (2015) that accepts pixels mapped as cloud-free by the CFmask approach but re-examines any pixels mapped as cloud-covered. Under this approach, pixels identified as cloud-covered by the CFmask are evaluated by a series of classification trees that provide a final, revised cloud mask value. While the classification tree approach relies on much of the same input data as the original CFmask algorithm (with the exception of band 6 brightness temperature, which is not used), the classification trees were developed using a training dataset that included thousands of pixels from mountainous regions dominated by rock, ice and snow cover that were incorrectly classified by the CFmask approach. Selkowitz and Forster (2015) demonstrate that this approach results in a substantial reduction in errors of commission and an increase in accuracy in mountainous regions from 66% to 88% (see Fig. 4).

Both cloud shadows and terrain shadows can also impact surface reflectance values, and in some cases, the impact can be severe enough that band ratios like the NDSI can no longer reliably discriminate between snow or ice and snow or ice free land. Therefore, it is necessary to identify deeply shadowed pixels and exclude them from further analysis in the same manner as cloud-covered pixels. In our approach, we identified and excluded from further analysis all instances where pixels exhibited an apparent surface reflectance of <7% in both bands 2 and 4. With the exception of some water bodies, surface reflectance for all land surface types in the region would be expected to exceed 7% in one or both of these bands. Although our shadow masking approach did not distinguish between cloud shadows and terrain shadows, it was well-suited for our approach because it did not require accurate cloud heights for identification of cloud shadows or a DEM for identification of terrain shadows. It is important to note that there was an additional advantage in using a reflectance threshold rather than a DEM to identify unusable terrain-shadowed pixels. Many pixels a terrain-based shadow masking approach would have identified as unusable due to the absence of modeled direct solar radiation were actually sufficiently illuminated by diffuse solar radiation or radiation reflected from nearby terrain surfaces and were retained for analysis. In total, the combined cloud masking and shadow masking efforts resulted in no cloud-free, shadow-free views of the land surface in about 2.2% of total pixels. These pixels were typically concentrated in small consistently shadowed patches associated with terrain features such as cirque basins.

Missing data, including pixels outside of each Landsat scene as well as pixels not imaged due to the Landsat 7 scan line corrector failure, were also identified and excluded from further analysis.

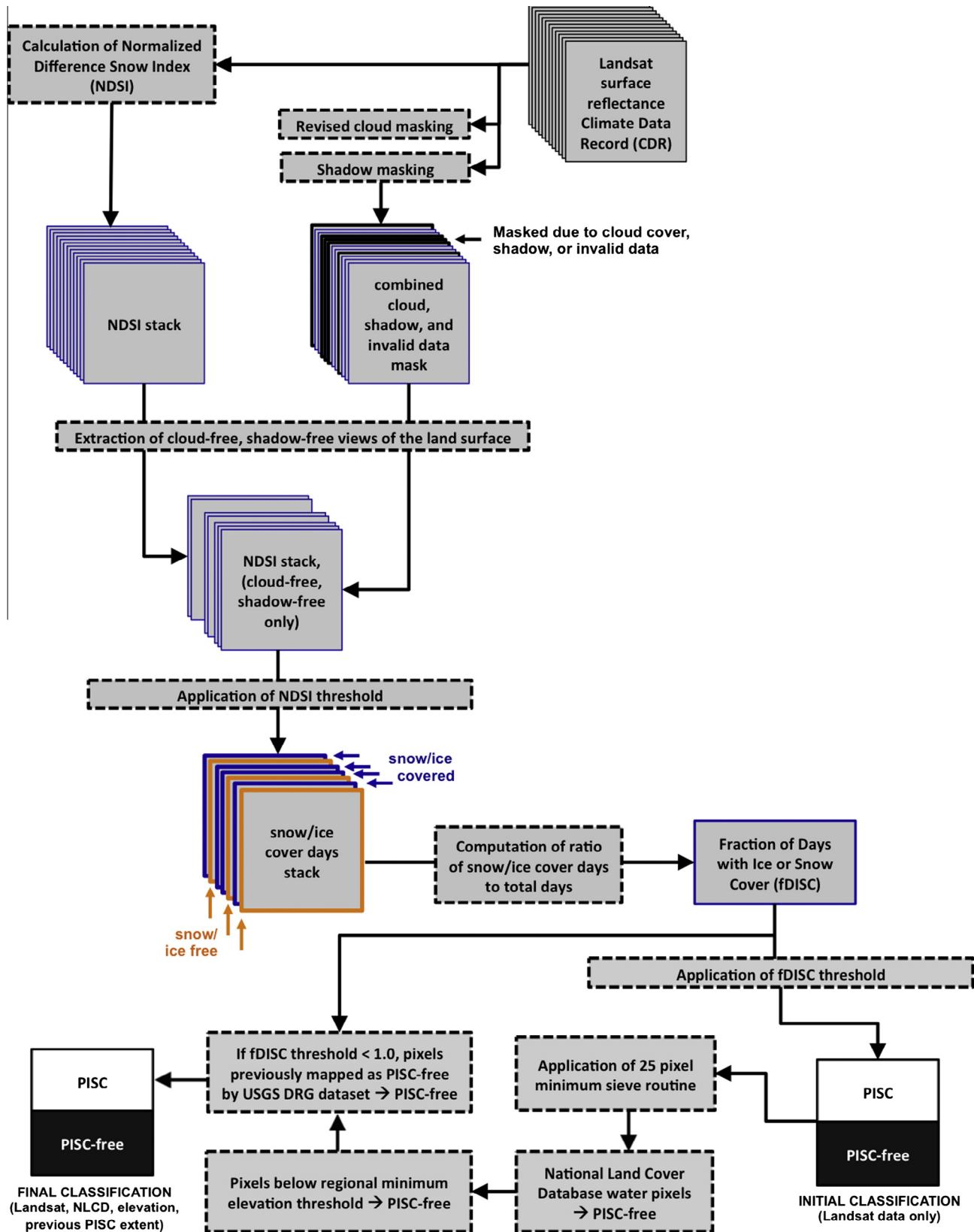


Fig. 2. Diagram of processing flow for classification of Persistent Ice and Snow Cover (PISC).

2.3.2. Ice and snow mapping for individual Landsat scenes

We used the Normalized Difference Snow Index (NDSI) (Dozier, 1989; Riggs et al., 1994) to identify snow or ice cover in each

cloud-free, shadow-free view. For Landsat TM and ETM+, NDSI is defined by the following equation:

$$\text{NDSI} = (\text{TM}_2 - \text{TM}_5) / (\text{TM}_2 + \text{TM}_5) \quad (1)$$

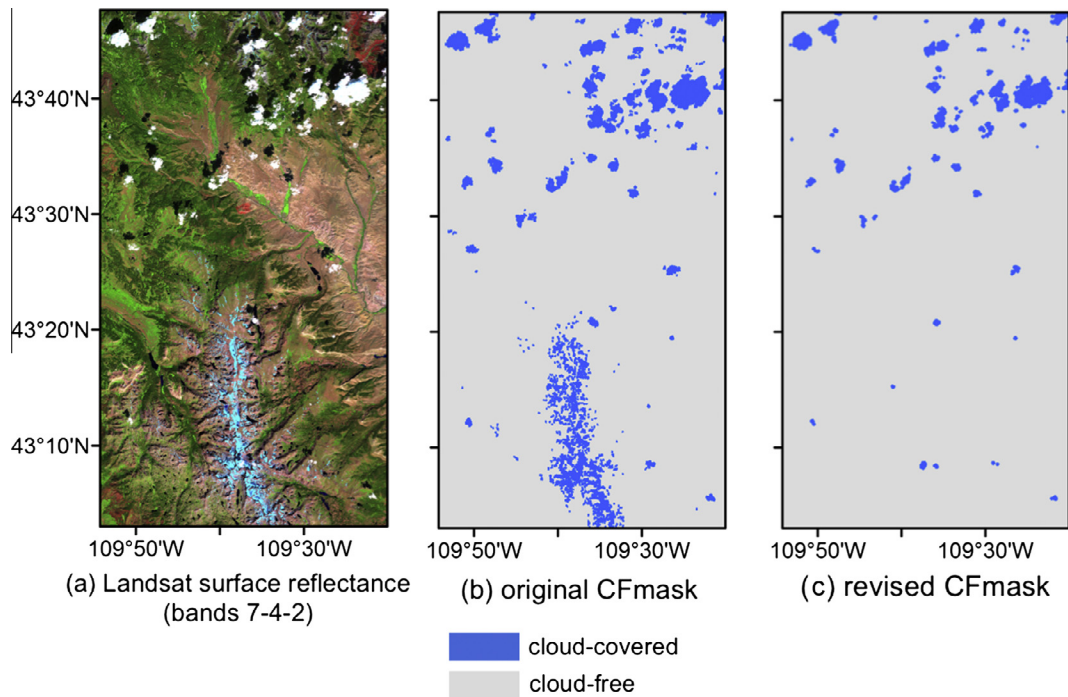


Fig. 3. An example of differences between cloud cover mapped by the CFmask algorithm and the revised cloud masking approach for the Wind River Range of Wyoming. (a) False color Landsat surface reflectance, with clouds appearing white and areas of snow and ice appearing cyan, (b) cloud cover mapped by the original CFmask, and (c) cloud cover mapped by the revised cloud mapping approach. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

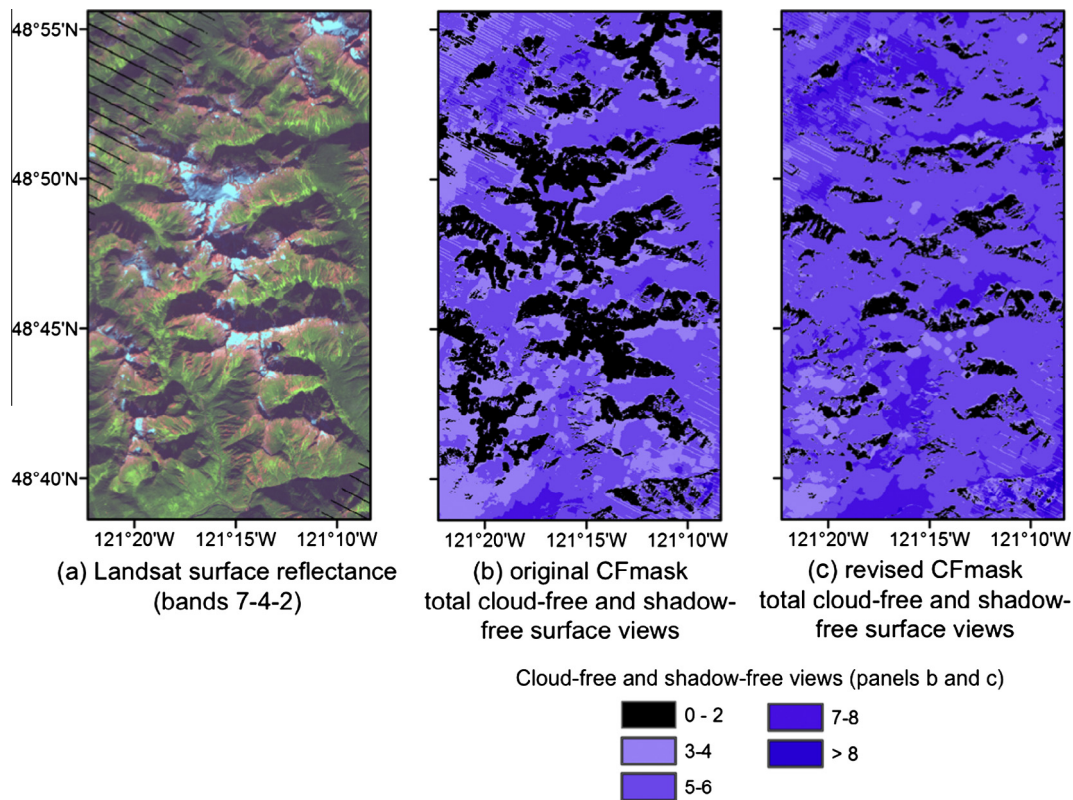


Fig. 4. An example of differences between the number of available cloud-free, shadow-free views resulting from use of the original CFmask algorithm and the revised cloud masking approach for the North Cascades of Washington. (a) Landsat surface reflectance, (b) total cloud-free, shadow-free views available calculated using the original CFmask, and (c) total cloud-free, shadow-free views calculated using the revised cloud mapping approach.

where TM_2 is surface reflectance in Landsat TM or ETM+ band 2 (0.52–0.60 μm), and TM_5 is surface reflectance in Landsat TM or ETM+ band 5 (1.55–1.75 μm). Pixels with NDSI values ≥ 0.4 were classified as snow or ice covered while pixels with NDSI values < 0.4 were classified as free of snow and ice.

2.3.3. Identification of persistent ice and snow cover pixels

For each pixel, we considered all cloud-free, shadow-free views acquired between August 20 and September 30 for the years 2010–2014 to determine whether the pixel should be classified as PISC. For the initial classification, pixels identified as snow or ice covered in $\geq 80\%$ of the available cloud-free, shadow-free views were identified as PISC. While this approach is less intuitive than classifying only pixels with snow or ice mapped in every available cloud-free, shadow-free view as PISC, Selkowitz and Forster (2015) demonstrated that using a threshold value of 80% resulted in higher accuracy for identifying PISC pixels.

2.3.4. Post processing and incorporation of ancillary data

We implemented several post-processing steps primarily designed to reduce the prevalence of errors of commission for PISC. First, we applied a 5×5 median filter to reduce spatial noise in the resulting classification. Second, we applied a sieve routine (ITT Visual Information Solutions, 2008) to remove patches of PISC of < 25 contiguous pixels. Analysis of our initial PISC maps suggested that, while some small glaciers and true perennial snow cover patches < 25 contiguous pixels did exist, the majority of PISC patches of < 25 contiguous pixels were actually late lying seasonal snow cover that generally disappeared completely by the end of the summer, which we did not wish to include in our PISC inventory. Third, we used a minimum elevation filter to remove PISC mapped below the minimum elevation at which we would expect to find PISC in each region. A separate minimum elevation was calculated for each glacier region identified by the USGS DRG dataset based on the minimum elevation (extracted from the NED DEM) of glacier polygons mapped by the USGS DRG dataset in that region. For each region, we eliminated any PISC pixels where the NED DEM indicated an elevation value > 200 m below the minimum elevation of previously mapped PISC within that region. Fourth, in cases where $< 100\%$ of cloud-free and shadow-free views of the land surface at a pixel location indicated snow or ice cover, as well as in cases where < 3 cloud-free, shadow-free views of the land surface were available at a pixel, we reclassified pixels initially mapped as PISC if they had not previously been mapped as PISC in the USGS DRG dataset. Pixels with > 3 cloud-free, shadow-free views of the land surface mapped as snow or ice cover in all available cloud-free and shadow-free views of the land surface were retained as PISC pixels even if they were not mapped as PISC in the USGS DRG dataset. Finally, pixels mapped as PISC where the NLCD classification indicated water (NLCD class 11) were reclassified as free of PISC.

2.3.5. Accuracy assessment

We conducted two separate accuracy assessments of our Landsat-derived PISC map. First, we compared our results to PISC manually identified in the 13 VHRI subsets (locations shown in Fig. 1). Second, we applied a 500 m buffer to the USGS DRG dataset polygons and then randomly selected 1000 points across the western U.S. from within the buffered area (inclusive of previously mapped PISC) to assess the accuracy of our PISC map. For each validation point, we examined all available high resolution imagery in GoogleEarth acquired in 2000 or later to identify the presence or absence of PISC. Google Earth imagery originated from a variety of aerial and satellite imagery programs but typically consisted of natural color imagery at spatial resolutions between 0.2 and 1 m. Points which appeared to be within 30 m of the edge of a glacier

or perennial snow cover patch were classified in the same manner as other points, but were also flagged as edge points. Points with debris-covered glacier ice were classified as PISC but also flagged as debris-covered. All points had Google Earth imagery available from at least two dates from the mid summer to early fall period, and many points had five or more dates of Google Earth imagery available. At the vast majority of points, we were able to identify the presence or absence of PISC with high confidence due to either the appearance of bare ground or exposed ice on one or more of the image dates. At the remaining points, we used contextual clues such as patch size, patch shape, topographic position, and imagery date to make a final determination of PISC presence or absence.

For both the randomly selected validation points and the VHRI validation subsets, we calculated accuracy assessment metrics for our Landsat-derived PISC maps, the USGS DRG dataset, and the NLCD dataset by considering the manually interpreted PISC classification from Google Earth imagery or WorldView 2 imagery to be “truth”. Comparison between each dataset and the validation datasets resulted in each pixel or point being placed into one of four categories: (1) true positive: PISC mapped in the evaluation dataset and by manual interpretation of high resolution imagery, (2) false positive: PISC mapped in the evaluation dataset, but PISC-free land mapped by manual interpretation of high resolution imagery, (3) true negative: PISC-free land mapped in the evaluation dataset and by manual interpretation of high resolution imagery, and (4) false negative: PISC-free land mapped in the evaluation dataset, but PISC mapped by manual interpretation of high resolution imagery. It is important to note that because the USGS DRG PISC maps and the WorldView 2 PISC maps were based on imagery acquired several decades apart, differences in PISC mapped by the USGS DRG dataset and the WorldView 2 dataset may not reflect mapping errors, but instead indicate potential changes in PISC over time.

Placing each point or pixel into one of these four categories allowed us to calculate several metrics commonly used for assessment of binary snow and ice cover maps (Painter et al., 2012; Rittger et al., 2013): accuracy, precision (the user's accuracy for the PISC class), recall (the producer's accuracy for the PISC class), and F (an accuracy assessment metric designed to balance the importance of precision and recall). The four metrics were calculated using the following equations:

$$\text{Accuracy} = (TP + TN) / (TP + TN + FP + FN) \quad (2)$$

$$\text{Precision} = TP / (TP + FP) \quad (3)$$

$$\text{Recall} = TP / (TP + FN) \quad (4)$$

$$F = 2 TP / (2 TP + FP + FN) \quad (5)$$

where TP is the count of true positive pixels, TN is the count of true negative pixels, FP is the count of false positive pixels, and FN is the count of false negative pixels.

We calculated each of the four metrics for each dataset to be evaluated for each 3×3 km validation subset as well as for all the 3×3 km validation subsets combined. We also calculated the four metrics for each subset of pixels with the same number of cloud-free, shadow-free views of the land surface in order to assess the impact of the number of available views of the land surface on mapping accuracy. Each metric was also calculated for the full set of 1000 randomly selected validation points as well as for a subset of 834 validation points located > 30 m from the edge of a glacier or perennial snow cover patch.

2.3.6. Calculation of glacier area by region

We calculated the total area of PISC mapped by our automated Landsat approach, the USGS DRG dataset, and the NLCD for the entire conterminous western U.S., as well as for 8 regions aggregated from the original 27 regions identified in the USGS DRG dataset.

2.3.7. Comparison to conventional Landsat inventories for selected regions

Our initial comparison between PISC area mapped by the USGS DRG dataset and PISC mapped by our automated Landsat approach showed that in some regions, the automated Landsat approach mapped <50% of PISC mapped by the USGS DRG dataset. In order to determine whether differences in PISC area mapped by the USGS DRG dataset and PISC mapped by our automated Landsat approach were due to changes in PISC area over time or differences between the mapping approaches, we selected three subset areas for additional analysis of changes in PISC between 1987–1988 and 2008–2010. We wanted to ensure that our assessment of change for these regions was conservative and did not overestimate decreases in PISC area due to differences in seasonal snow cover conditions. In order to accomplish this, we compared Landsat scenes from years where data from local SNOTEL sites indicated more seasonal snow accumulation and later snow-free dates for the recent (2008–2010) Landsat scenes relative to the older (1987–1988) Landsat scenes, although we still tried to ensure that scenes used for comparison contained minimal seasonal snow cover. For each region, we selected Landsat TM images from 1987 or 1988 and from 2008, 2009, or 2010 and used a more conventional, semi-automated approach to map the extent of PISC for each period.

Each scene selected for analysis of changes in PISC over time was acquired between September 1 and October 1. PISC for each scene was initially mapped by classifying pixels with NDSI >0.4 as PISC, applying a 5×5 median filter to reduce spatial noise and eliminate areas of patchy seasonal snow cover, and then applying a sieve to eliminate PISC patches of <25 contiguous pixels. We then edited the resulting PISC layer by adding areas of PISC in shadow not initially mapped as PISC and eliminating misclassified patches of PISC. In cases where a patch of ice or perennial snow cover appeared in one date of imagery but did not exceed the 25 contiguous pixel size threshold in the other (usually more recent) date of imagery, we digitized the outline of the remaining snow patch. This was done to ensure that small decreases in the size of a perennial snow or ice patch would not translate into overestimates of change when small patches of ice or perennial snow cover did not actually disappear but were not mapped due to the 25 contiguous pixels requirement.

We calculated total PISC area for 1987–1988 and for 2008–2010 for each of the three change assessment regions and then compared PISC area for both periods to PISC area calculated from the USGS DRG dataset and from the 2010–2014 Landsat-derived dataset.

3. Results

3.1. Accuracy assessment

For all $13 \times 3 \times 3$ km VHRI validation subsets, accuracy and F were higher for the Landsat-derived PISC dataset than for the USGS DRG dataset or the NLCD land cover classification (Table 1). Mean F for the Landsat-derived PISC dataset that incorporated ancillary data was 0.848, a major improvement over both the USGS DRG and the NLCD 2011 datasets, with F scores of 0.676 and 0.758 respectively (see Fig. 6).

PISC maps from the USGS DRG, the NLCD, the automated Landsat, and the revised automated Landsat approach incorporating ancillary data are shown for the Mammoth Glacier subset in Wyoming in Fig. 5.

We observed a weak negative relationship between the fraction of a validation subset containing PISC and overall accuracy as well as a much more pronounced positive relationship between the fraction of a subset containing PISC and F (Fig. 7).

Accuracy assessment metrics for the set of 1000 randomly selected validation points also indicate the automated Landsat approach incorporating ancillary data provides a more accurate depiction of PISC across the western U.S. than the USGS DRG dataset or the NLCD dataset. Accuracy, precision, recall, and F metrics for both the full set of 1000 points and the subset of 834 non-edge points are shown in Fig. 8. The difference in accuracy between the Landsat PISC dataset and the USGS DRG PISC dataset is primarily due to the higher precision (user's accuracy for the PISC class) achieved by the automated Landsat mapping approach. This is not surprising, given that PISC has been demonstrated to have declined in area across much of the western U.S. between the time of acquisition for the aerial photographs used for the original USGS maps and the 2010–2014 period. Pixels covered by PISC at the time of acquisition for the aerial photographs (generally between 1960 and 1987) but free of PISC during the 2010–2014 period will often be labeled as true negatives for the automated Landsat datasets but labeled as false positives for the USGS DRG dataset, even if they were mapped correctly at the time. On the other hand, recall (producer's accuracy for PISC class) metrics are nearly the same for the USGS DRG dataset and the automated Landsat datasets. This is also not surprising, as we would expect little difference in recall metrics between the datasets if both mapping approaches have similar accuracy, assuming that the majority of pixels with PISC cover in 2010–2014 were also covered by PISC several decades earlier when the aerial photographs were acquired (see Table 2).

Table 1

F metric for USGS Topographic Maps glacier layer, NLCD 2011 perennial snow and ice cover, initial Landsat-derived PISC, and revised Landsat-derived PISC. Revised Landsat-derived PISC includes revisions based on ancillary data.

Subset name	USGS topo maps	NLCD 2011	Initial landsat-derived PISC	Revised landsat-derived PISC
Mt. Baker Summit	0.951	0.939	0.957	0.963
Mount Baker SW	0.910	0.837	0.931	0.940
Mount Baker NE	0.894	0.830	0.889	0.909
Redoubt Glacier West	0.840	0.747	0.862	0.880
Redoubt Glacier East	0.783	0.636	0.831	0.824
Goat Rocks West	0.611	0.384	0.770	0.768
Goat Rocks East	0.680	0.515	0.768	0.782
Harrison Glacier	0.813	0.762	0.835	0.857
Blackfoot Pumpelly Glaciers	0.826	0.770	0.891	0.892
Gannett Glacier	0.816	0.675	0.864	0.879
Mammoth Glacier	0.799	0.694	0.868	0.888
Lyell Glacier	0.503	0.491	0.701	0.700
Mount Ritter	0.430	0.502	0.701	0.736
All Subsets	0.758	0.676	0.836	0.848

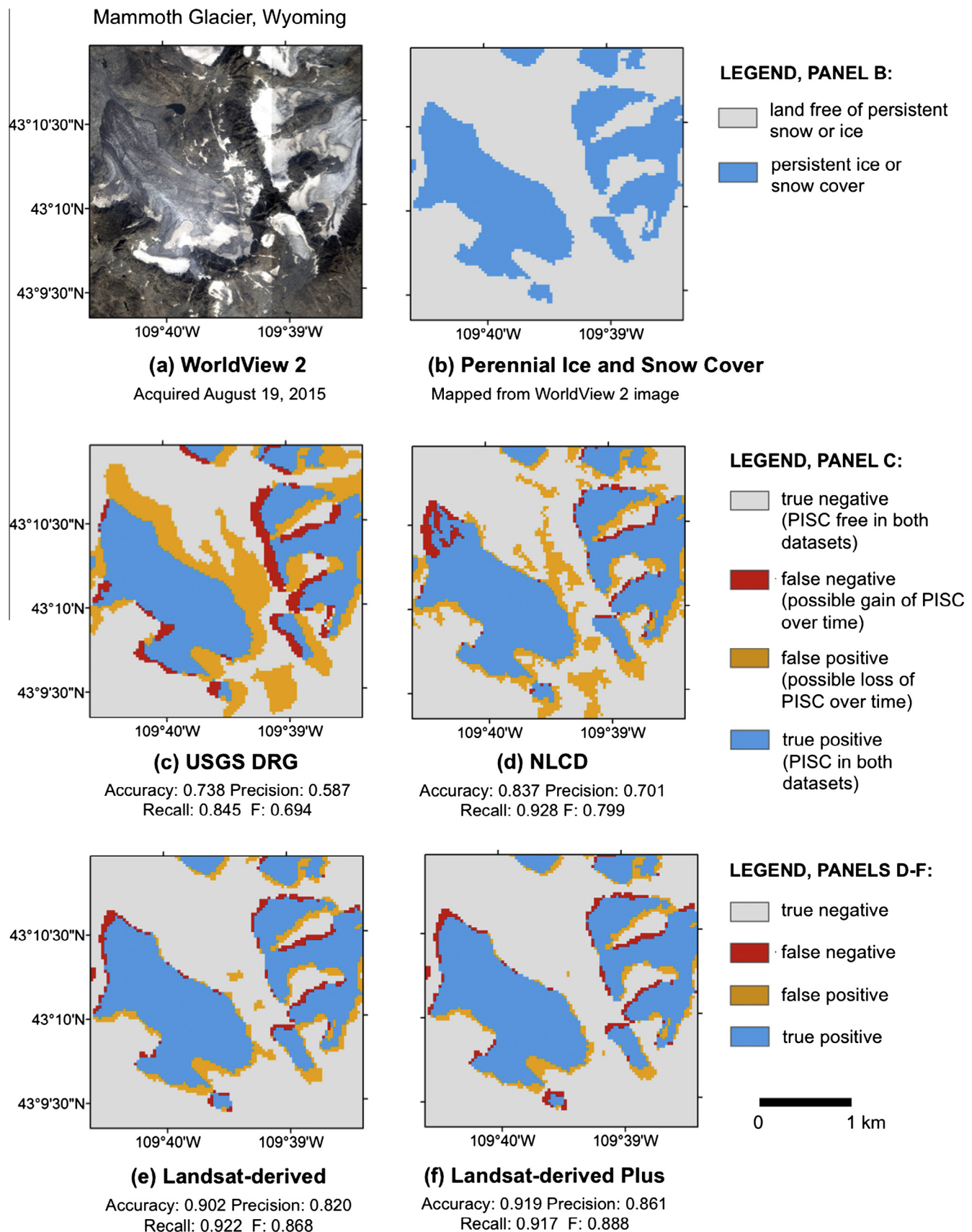


Fig. 5. Agreement between PISC mapped using late summer WorldView 2 imagery and PISC datasets for the Mammoth Glacier (Wyoming) VHRI subset. (a) WorldView 2 imagery, (b) PISC mapped from WorldView 2 imagery, (c) agreement between WorldView 2 PISC and USGS DRG PISC, (d) agreement between NLCD PISC and WorldView 2 PISC, (e) agreement between Landsat-derived PISC and WorldView 2 PISC, and (f) agreement between Landsat-derived plus ancillary data PISC and WorldView 2 PISC.

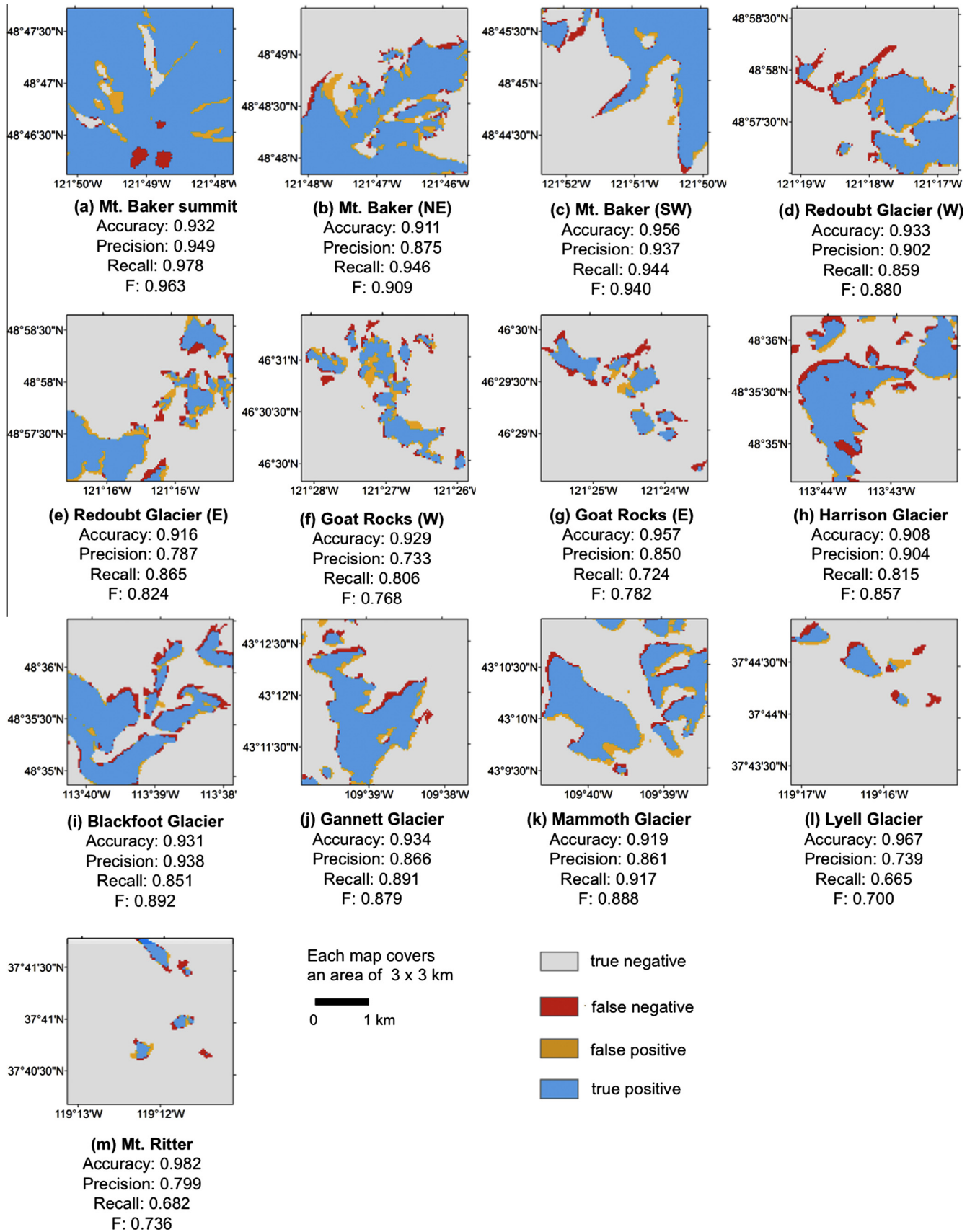


Fig. 6. Agreement between PISC mapped using late summer WorldView 2 imagery and PISC mapped by the automated Landsat approach plus ancillary data for all 13 VHRI subsets. (a) Mt. Baker (summit), (b) Mt. Baker (northeast), (c) Mt. Baker (southwest), (d) Redoubt Glacier (west), (e) Redoubt Glacier (east), (f) Goat Rocks (west), (g) Goat Rocks (east), (h) Harrison Glacier, (i) Blackfoot Glacier, (j) Gannett Glacier, (k) Mammoth Glacier, (l) Lyell Glacier, and (m) Mt. Ritter.

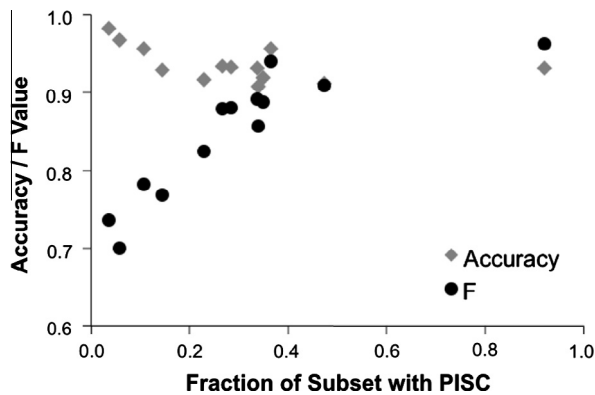


Fig. 7. Relationship between fraction of validation subset with PISC and Accuracy and F metrics.

3.1.1. Effect of number of cloud-free, shadow-free views on mapping accuracy

The relationship between the number of available cloud-free, shadow-free views of the land surface and the F metric is shown in Fig. 9. The data indicate that while accuracy is typically poor when <3 cloud-free, shadow-free views are available, 3 views appears to be sufficient for accurate mapping, as no increase in F is associated with increased cloud-free, shadow-free views beyond this point. The small decrease in F that occurs as the number of cloud-free views exceeds 8 is likely due to the geographic distribution of pixels in the dataset with >8 cloud free views. The vast majority of these pixels are from the two subsets in the Sierra Nevada, where more cloud-free views were available than in other regions, and where the automated Landsat approach performed relatively poorly compared to its performance in other regions.

3.2. Glacier area mapped by different datasets

The USGS DRG dataset maps a total of 575.9 km² of PISC, while the automated Landsat approach maps 28% less PISC for a total of 412.3 km². The NLCD 2011 dataset maps a total of 1243.4 km². Fig. 10 and Table 3 report the total area of PISC mapped by each dataset within each region. In most regions, the automated Landsat approach indicated a much smaller total area of PISC than either the USGS DRG dataset or the NLCD dataset. The largest difference between the DRG dataset and the automated Landsat dataset is in the northern Cascades of Washington, where the automated Landsat approach mapped 51.9 km² less PISC than the USGS DRG dataset, which equates to a 21% difference between the two

datasets. The largest differences by percentage are observed in the Colorado Rocky Mountains, where 82% less PISC was mapped by the automated Landsat approach, and in the Sierra Nevada, where 74% less PISC was mapped by the automated Landsat approach. While the relative differences for these regions are large, the actual difference in PISC area mapped is relatively small, as both the Colorado Rocky Mountains and the Sierra Nevada never had substantial PISC area to begin with. For regions with more substantial PISC, the largest differences by percentage are found in the Southwest Montana/Northwest Wyoming region, where 54% less PISC was mapped by the automated Landsat approach, and in the Northwest Montana region, where 37% less PISC was mapped by the automated Landsat approach.

3.3. Comparison to traditional mapping approaches for selected study areas

Results from the conventional change detection using the semi-automated Landsat mapping approach demonstrate substantial decreases in PISC between 1987–1988 and 2008–2010 (Table 4). The decrease in PISC between 1987–1988 and 2008–2010 for the three test regions correlates closely with the difference between PISC mapped by the USGS DRG dataset and PISC mapped by the automated Landsat approach. This strongly suggests that much of the difference between the PISC area mapped in the USGS DRG dataset and the PISC area mapped by the automated Landsat approach can be attributed to decreases in PISC area over time rather than differences in mapping methods.

4. Discussion

Results from two independent validation approaches indicate that the automated Landsat dataset provides the most accurate representation of contemporary PISC for the entire conterminous Western U.S.

The positive relationship between the fraction of a subset with PISC and F (perhaps the most useful validation metric) indicates that the automated approach presented here should work well for the region's medium and larger glaciers. We anticipate the approach will not be as effective, however, for mapping the region's smallest glaciers and perennial snow cover patches. Many of these cover <25 contiguous Landsat pixels and would be eliminated by the minimum size threshold in our approach. In addition, the smallest glaciers are often remnants of larger glaciers that have retreated into protected north-facing cirques where consistent shadowing may reduce the odds of PISC detection.

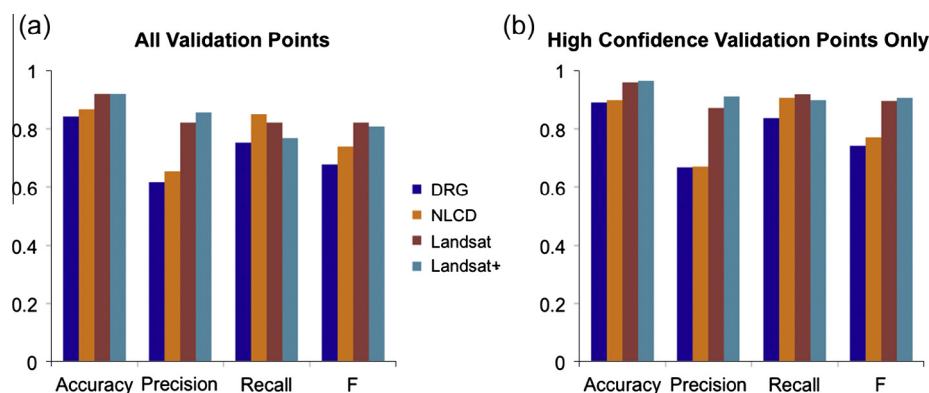
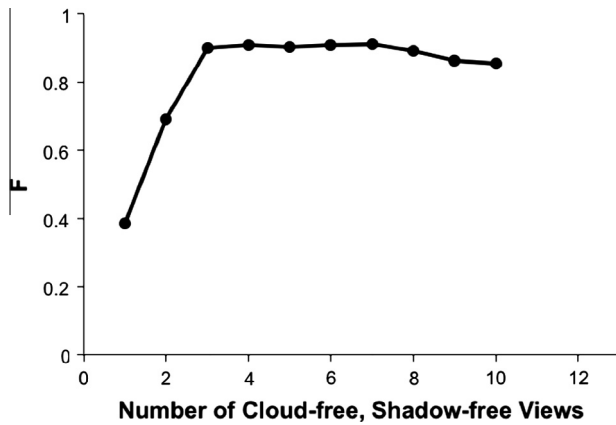


Fig. 8. Accuracy, precision, recall, and F metrics for 1000 points randomly selected from areas on or near (within 500 m) of previously mapped glaciers and perennial snow cover patches. (a) all 1000 points, and (b) High confidence validation points (the subset of 834 points located >30 m from the edge (either on or off) of glacier or perennial snow cover).

Table 2

Accuracy, precision, recall and F metrics for 1000 randomly selected validation points.

Dataset	Full dataset				Non-edge points subset			
	Accuracy	Precision	Recall	F	Accuracy	Precision	Recall	F
USGS DRG	0.843	0.615	0.753	0.677	0.891	0.668	0.836	0.743
NLCD								
Landsat	0.922	0.822	0.822	0.822	0.960	0.874	0.918	0.895
Landsat + ancillary data	0.921	0.857	0.767	0.810	0.964	0.911	0.899	0.905

**Fig. 9.** Relationship between the number of cloud-free, shadow-free views and F metric for all pixels from VHRI validation subsets.

Accurate mapping of PISC extent in consistently terrain-shadowed locations remains a challenge for optical remote sensing efforts. At the latitude of the western conterminous U.S. ($\sim 30^{\circ}$ – 49° N) consistently terrain-shadowed pixels covered only a small fraction of the landscape (2.2% for pixels with no cloud-free, shadow-free views, and an additional 2.5% for pixels with only one cloud-free, shadow-free land surface view). Nevertheless, for these pixels, accuracy can be lower, with both false positive and false negatives relatively common. False positives can sometimes occur in terrain-shadowed areas where seasonal snow cover remains into the late summer. This is because terrain shadowing at these locations does not occur during the earlier part of the August 20–September 30 period (when snow is still present), but does occur (due to increasing solar zenith angles) at the end of the period (e.g. September 15–30), when the seasonal snow has finally melted. As a result, all shadow-free land surface views at these locations indicate snow, with no usable land surface views available during the very brief snow-free period. Conversely, false

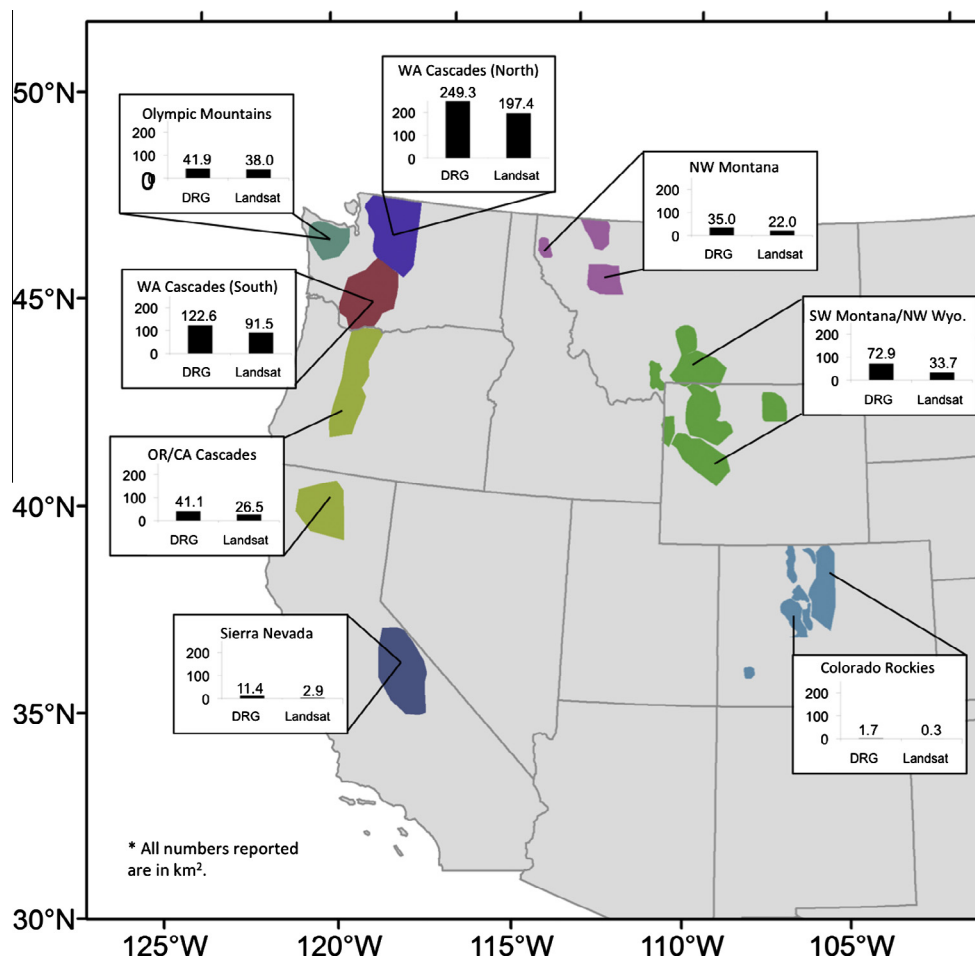
**Fig. 10.** Area of PISC mapped by the USGS DRG dataset and by the automated Landsat-derived dataset for 8 regions in the western U.S.

Table 3

Area of PISC mapped by the USGS DRG dataset, the automated Landsat dataset, and the NLCD 2011 dataset by region.

Region	USGS DRG PISC area	Automated landsat PISC area	NLCD 2011	Percent difference (DRG vs landsat) (%)
N Washington Cascades	249.3	197.4	243.2	21
Olympic Mountains	41.9	38.0	142.3	9
S Washington Cascades	122.6	91.5	143.8	25
Oregon/California Cascades	41.1	26.5	37.4	36
Sierra Nevada	11.4	2.9	15.2	74
NW Montana	35.0	22.0	47.4	37
SW Montana/NW Wyoming	72.9	33.7	83.0	54
Colorado Rocky Mountains	1.7	0.3	531.1	82
Western US Total	575.9	412.3	1243.4	28

Table 4

PISC area mapped by semi-automated Landsat approach for 1987–1988 and 2008–2010 for three test regions.

Region	USGS DRG 1960s–1980s	Automated landsat 2010–2014	Difference (relative to DRG area) (%)	Semi-automated landsat 1987–1988	Semi-automated landsat 2008–2010	Difference (relative to DRG area) (%)
Olympic Mountains	35.8	33.8	–5.6	34.2	32.0	–6.6
Sierra Nevada	2.2	1.1	–50.0	3.0	1.6	–46.7
Wind River Mountains	44.9	26.8	–40.3	45.7	29.8	–34.8

negatives can occur at locations that are perpetually shadowed from August 20–September 30 at the time of Landsat scene acquisition, as pixels with no cloud-free, shadow-free land surface views are automatically flagged as PISC-free in our approach.

The automated Landsat approach using scenes from the 2010–2014 period maps 28% less PISC area than the USGS DRG dataset, which is based on aerial photography acquired during the 1960s, 1970s, and 1980s. The difference between PISC mapped by the two datasets, however, varies substantially between regions, from as little as 9% difference in the Olympic Mountains to as much as 82% difference in the Colorado Rocky Mountains.

Results from the more conventional change detection approach employed for test areas in the Olympic Mountains, Sierra Nevada, and Wind River Mountains indicate that a substantial fraction of PISC present in the 1987–1988 period had disappeared by the 2008–2010 period in the Wind River Mountains (loss of 15.9 km² or 34.8%) and in the Sierra Nevada (loss of 1.4 km² or 46.7%). In the Olympic Mountains, only 6.6% of total PISC disappeared during this period. Both the absolute and relative amounts of PISC lost at each of these three study areas correlate closely with the differences between the USGS DRG dataset and the automated Landsat dataset. This strongly suggests that a large fraction of the difference in PISC mapped by the USGS DRG dataset and the automated Landsat dataset can be attributed to decreases in PISC over time, rather than differences in methods between the mapping approaches.

Results from several other studies monitoring changes in glacier area over time in the western U.S. also indicate substantial reductions in glacier area, providing further evidence that much of the difference between PISC mapped by the USGS DRG dataset and PISC mapped by the automated Landsat approach can be attributed to changes in PISC area rather than differences between mapping approaches. The 54% difference in PISC area in the Wind River Range is similar to the 39% reduction in ice area observed by Maloof et al. (2014) between 1967 and 2006, and it is not unreasonable to expect that substantial additional ice loss may have occurred after 2006. While the 21% difference in PISC mapped in the North Cascades is substantially more than the 7% reduction observed by Granshaw and Fountain (2006) between 1958 and 1998 in this region, ice loss has continued at a rapid rate since 1998 in the North Cascades (Pelto and Brown, 2012). Finally, the

37% difference in PISC area in Northwest Montana between the two datasets is only slightly greater than the 29% loss of ice between 1966 and 2005 reported by the USGS (2013).

It is important to note that, aside from the inclusion of perennial snow cover and most likely some seasonal snow cover (Fountain et al., 2007), the USGS DRG dataset is essentially a conventional glacier inventory and has been included in the Randolph Glacier Inventory (Pfeffer et al., 2014) and the Global Land Ice Measurements from Space (GLIMS) datasets (Bishop et al., 2004), along with other similar inventories from locations around the world. The automated Landsat-derived dataset, on the other hand, is a binary raster dataset that maps the presence or absence of PISC at 30 m resolution and does not provide any of the attribute information often included in glacier inventories for each individual glacier or perennial snow cover patch, such as size, mean elevation, or aspect. However, an object-based image segmentation approach where snow and ice cover persistence forms the basis for object delineation such as the approach introduced by Thompson and Lees (2014) could facilitate the conversion of a binary raster PISC dataset into a vector dataset of probable glacier outlines. This would allow for the calculation of attribute information for each polygon. It is likely, however, that a substantial amount of editing would be required to bring the resulting vector dataset up to the standards of a conventional glacier inventory.

Despite the limitations described above, the 2010–2014 Landsat-derived PISC dataset for the conterminous western U.S. provides a valuable update to the original USGS DRG dataset and also provides a more accurate representation of PISC than the NLCD 2011 classification. We caution against interpreting differences in area mapped by the Landsat-derived dataset and the USGS DRG dataset as precise estimates of change in PISC area because the original DRG dataset is based on a wide range of years and was created using a different approach. Nevertheless, differences between the USGS DRG dataset and the 2010–2014 Landsat-derived dataset do highlight areas in the region that have experienced the greatest and least amount of changes in PISC over the past 30–50 years. The greatest strength of the dataset and automated mapping approach presented here is that it can be updated with relative ease as new imagery, including imagery from Landsat 8's OLI sensor, becomes available and as additional changes in PISC continue to occur across the region.

5. Conclusions

We implemented a fully automated approach for mapping perennial ice and snow cover across the western conterminous U.S. using Landsat TM and ETM+ imagery acquired between August 20 and September 30 for the years 2010–2014. Accuracy assessment of this dataset using two different validation approaches indicates that the 2010–2014 Landsat-derived dataset is substantially more accurate than both the USGS DRG glacier dataset (based on aerial photography from the 1960s, 1970s, and 1980s) and the National Land Cover Database land cover classification perennial snow and ice class. Analysis of change in PISC area between 1987–1988 and 2008–2010 using a more traditional semi-automated Landsat-derived mapping approach for each period indicates substantial loss of PISC and suggests that differences between PISC mapped by the USGS DRG dataset and PISC mapped by the automated Landsat approach are due primarily to decreases in PISC area, rather than differences between mapping approaches. Our 2010–2014 Landsat-derived PISC dataset indicates that as much as 28% of PISC has been lost across the western U.S. since the original USGS maps were developed. In some regions with substantial PISC, loss of PISC may be as much as 54%, and in regions with smaller total PISC area, loss of PISC may be as high as 82%. While our updated Landsat-derived PISC dataset is not designed to serve as a standard glacier inventory, it identifies areas where major changes in PISC have occurred since the original USGS maps were developed, highlighting the need for a regularly updated PISC inventory across the region.

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