Status of Glaciers in the Western United States based on Sentinel-2A Images and Machine Learning Algorithm

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Key Points:

- This research evaluates the present condition of glaciers in the western United States.
- Over the study period, 930 glaciers have vanished entirely.
- There is a 35.43% reduction in glacier area in the western U.S.
- The volume of glaciers has decreased by 4.9 km^3, roughly equivalent to 4.7 gigatons of water.

Abstract

In this study, we employed random forest machine learning classification to assess the current state of glaciers in the western United States using Sentinel-2A satellite imagery. By analyzing Sentinel-2A imagery from September 2020 and comparing it to the RGI inventory, the study determined the current conditions of the glaciers. Our findings unveiled a significant reduction in both glacier area and volume in the western United States since the mid-20th century. Currently, the region hosts 4091 glaciers spanning seven states, covering a total area of 432.01 km^2 with a corresponding volume of 9.02 km^3. During the study period, a loss of 237.07 km^2 in glacier area was observed, representing a 35.43% decrease when contrasted with the RGI boundaries. The volume lost during this period amounted to 4.9 km^3, roughly equivalent to 4.7 gigatons of water. Among the states, Washington experienced the most significant glacier area reduction, with a loss of 130.06 km^2. Notably, glaciers in the North Cascade Range of Washington, such as those in Mt. Baker and Mt. Shuksan, now cover, on average, only 85% of their original glacier boundaries with ice and snow at the conclusion of the 2020 hydrological year. Major glaciers, including the White River glacier, West Nooksack glacier, and White Chuck glacier, have lost more than 50 percent of their original area.

Plain Language Summary

We used advanced computer programs to study glaciers in the western United States. We analyzed Sentinel-2A satellite images collected in September 2020. By comparing these images with a database of glaciers, we found present conditions of glaciers. Our research found that the glaciers in the western United States have been shrinking since the middle of the 1900s. Currently, there are 4091 glaciers in seven states, covering a total area of 432.01 square kilometers and holding 9.02 cubic kilometers of ice. During our study time, we saw that the glaciers lost 237.07 square kilometers of ice, which is a 35.43% decrease compared to before. The amount of ice that melted during this time is about 4.9 cubic kilometers, roughly the same as 4.7 gigatons of water. Among the states, Washington saw the biggest reduction in glacier size, losing 130.06 square kilometers. Specifically, glaciers in the North Cascade Range of Washington, like those in Mt. Baker and Mt. Shuksan, now only cover 85% of their original boundaries with ice and snow by the end of the 2020 hydrological year. Some major glaciers, including the White River glacier, West Nooksack glacier, and White Chuck glacier, have lost more than 50% of their original size.

1 Introduction

Glaciers in the Western United States have shrunk and lost mass in the last century (McCabe & Fountain, 2013; Inamdar and Ambinakudige 2016; Riedel et al. 2015). An inventory of the current status of glaciers in the US is essential to monitor rapid changes in glacier area and volume due to climate change. The GLIMS (Global Land Ice Measurements from Space) and RGI (Randolph Glacier Inventory) database provides the boundaries of glaciers in the world including the U.S. The boundaries of the U.S. glaciers in GLIMS and RGI database were developed based on old Landsat satellite images and topographic maps. In this study, we present the status of glaciers in the western United States (excluding Alaska) as of 2020. This study assesses glacier parameters (area and volume) and their changes within the study period using Sentinel-SA images and a Random Forest algorithm.

The cryosphere is composed of snow and ice in the form of snow cover, sea ice, freshwater ice, permafrost, and continental ice masses such as glaciers and ice sheets (Ambinakudige & Joshi, 2012). Changes in global climate have had a significant impact on the world's glaciers, causing them to shrink rapidly in size and mass, subsequently raising global sea levels, altering hydrology, and increasing natural hazards (Ambinakudige & Intsiful, 2022; Berthier et al., 2010; Dixon & Ambinakudige, 2015; Hugonnet et al., 2021; Huss & Hock, 2018; Maloof et al., 2014; Rounce et al., 2023; Wouters et al., 2019; Zemp et al., 2019; Fountain et al., 2017; Inamdar & Ambinakudige, 2016; Singh et al., 2018). Glacier retreat and volume loss are directly linked to a warming climate (Intsiful & Ambinakudige, 2021). According to the IPCC (2023), global surface temperatures have increased by 1.09°C due to anthropogenic activities. The IPCC (2023) report also predicts that many low-elevation and small glaciers would lose most of their mass or disappear within decades to centuries. Between 1901 and 2018, the global mean sea level increased by 0.20 m (IPCC, 2023). Glacier mass loss of all glaciers outside Antarctica and Greenland glacier accelerated significantly between 2000 and 2019 with an average loss of 267 ± 16 gigatons per year, equivalent to 21 ± 3% of the observed sea-level rise (Hugonnet et al., 2021). In the mid-19th century, glaciers have retreated substantially due to increased temperature (Moore et al., 2009) and this has resulted in major variations in streamflow throughout the globe. Continuous warming is causing glaciers to melt rapidly, resulting in the loss of small glaciers, and faster shrinking of large glaciers (Moore et al., 2009). These changes in cryosphere subsequently led to raising global sea levels, altering hydrology, and increasing natural hazards (Berthier et al., 2010; Maloof et al., 2014; Rounce et al., 2023).

All parts of the world have witnessed significant decrease in glacier area and volume (Hugonnet et al., 2021; Huss & Hock, 2018; Rounce et al., 2023; Wouters et al., 2019; Zemp et al., 2015, 2019). Hugonnet et al., (2021) assessed the global mass loss of glaciers during the early 21st century using satellite images and airborne elevation datasets as from the year 2000 to 2019 of all glaciers outside Antarctica and Greenland and reported an estimated glacier mass loss has accelerated significantly during this period with average loss of 267 ± 16 gigatons per year, equivalent to 21 ± 3% of the observed sea-level rise.

In the western United States, glaciers continue to lose ice, which is consistent with broader trends of glacier retreat and shrinkage worldwide. Using historic photographs and maps, McCabe & Fountain, (2013) provided an assessment of glaciers in the conterminous United States during the twentieth century. According to this study, 24% of the glacier area has been lost in Mt. Rainer located in Washington State. In addition, McCabe & Fountain (2013) also reported an extensive recession of 66% in the Lewis Range in Montana (located in the Glacier National Park) and the Sierra Nevada in California. Riedel et al., (2015) investigated the status of glaciers in the Olympic Mountains and their contribution to streamflow in the Hoh River basin using a hydrological model and they reported that all glaciers in this area have experienced significant ice loss from 1986 to 2011, with the Anderson and Blue glaciers losing more than 50% of their ice volume. The study also indicated that glacier shrinkage in the past 30 years within the Olympics is greater than in the Cascades and southern Coast Mountains.

In another study, Fountain et al., (2022) examined how glaciers in the Olympic Mountains have changed in area and volume from early 1980 to 2015. They discovered that glaciers decreased at a rate of 0.59 km2 per year, resulting in the disappearance of 35 glaciers and 16 perpetual snowfields. They also noted that warming winter temperatures are particularly contributing to glacier shrinkage. In the Sierra Nevada in California, Basagic & Fountain, (2011) conducted a comprehensive study of glaciers using a combination of historical aerial photographs, satellite imagery, and field measurements to assess glacier area and volume changes over time. This study revealed that the glaciers in the Sierra Nevada have decreased in area by about 39.86 ± 9.59 km2 (56%) in 2004 (a loss since 1903). Declining snowfall and rising temperatures are the main causes of glacier retreat in the Sierra Nevada (Basagic & Fountain, 2011).

Melting of glaciers consistent with the global warming trend observed in the area. O'Neel et al., (2019) conducted a study on the United States Geological Survey Benchmark Glaciers (Gulkana, Wolverine, Lemon Creek, South Cascade and Sperry glaciers) to understand the long-term insight into climate forcing of glacier mass balance from 1953 to 2015. To do this, they reanalyzed all available data from the United States Geological Survey Benchmark Glaciers by combining all available data from each glacier into a single dataset. The results of the reanalysis showed that all five glaciers have experienced negative mass balances since the mid-20th century, with average rates ranging from −0.58 to −0.30 m w.e. a−1.

Glacier inventories have been very valuable in assessing glacier changes and their contribution to the rise of sea level (Gardner et al., 2013; Pfeffer et al., 2014). The first complete inventory of glaciers to assess the status, magnitude, and rate of change of glaciers area in the western United States in the mid-20th century was assembled by (Fountain et al., 2007; Fountain et al., 2017) which is part of the GLIMS and RGI inventory of the United States. They utilized 1:100,000 (100K) and 1:24,000 (24K)-scale topographic maps published by the U.S. Geological Survey (USGS) and U.S. Forest Service (USFS) based on aerial photos to provide the most comprehensive glacier inventory in the western United States. Since the completion of the first glacier inventory of the United States, no comprehensive assessment of the glaciers in the Western United States, particularly the Lower 48 conterminous States, has been carried out. However, there have been studies that have provided information on the status of individual glaciers as well as the status of glaciers on a regional or state level (Basagic & Fountain, 2011; Granshaw & Fountain, 2006; Martin-Mikle & Fagre, 2019). Here, we present the current status of glaciers in the western United States (excluding Alaska) spanning the mid-20th century and 2020. This study assesses glacier parameters (area and volume) and their changes within the study period using Sentinel-SA images and a Random Forest algorithm.

2 Study Area

The Randolf Glacier Inventory (RGI, 2017) identifies 5021 glaciers in the western conterminous United States which are found in California, Washington, Montana, Idaho, Wyoming, Nevada, and Oregon (Figure.1). It includes significant mountain ranges such as the Rocky Mountains spanning Wyoming, Montana, and Idaho; the Cascade Range extending through Washington, Oregon, and California; the Sierra Nevada located in California; and the Olympic Mountains situated in Washington. Most of these glaciers are found in Washington state, specifically in the north Cascade Range. The RGI inventory indicates that the Cascades region hosted ~454 km^2 of glaciers. Among these, around 408km^2 of the total glacier area within the Cascades was observed in Washington state. Roughly 41km^2 of these glaciers were located in cascade of Oregon, while the remaining 5 km^2 was distributed in the northern part of California. Majority of large glaciers (>2 km^2) are located in the Cascade and the Olympic Mountains which make up a significant portion of total area of glaciers in the western U.S. The Sierra Nevada of California and the South of the Cascade Range is composed of small glaciers and snow patches with a total area of ~42 km^2. In the Rocky Mountains of Wyoming and Montana, the RGI inventory maps 139 km^2 of glaciers. Most of the glaciers are found in the Wind River Range, the Lewis Range and the Beartooth Mountains. Several of the glaciers are >1 km^2, including Gannett Glacier, Grasshopper Glacier and the Sacagawea Glacier, the largest glaciers in the continental U.S. outside of Washington.

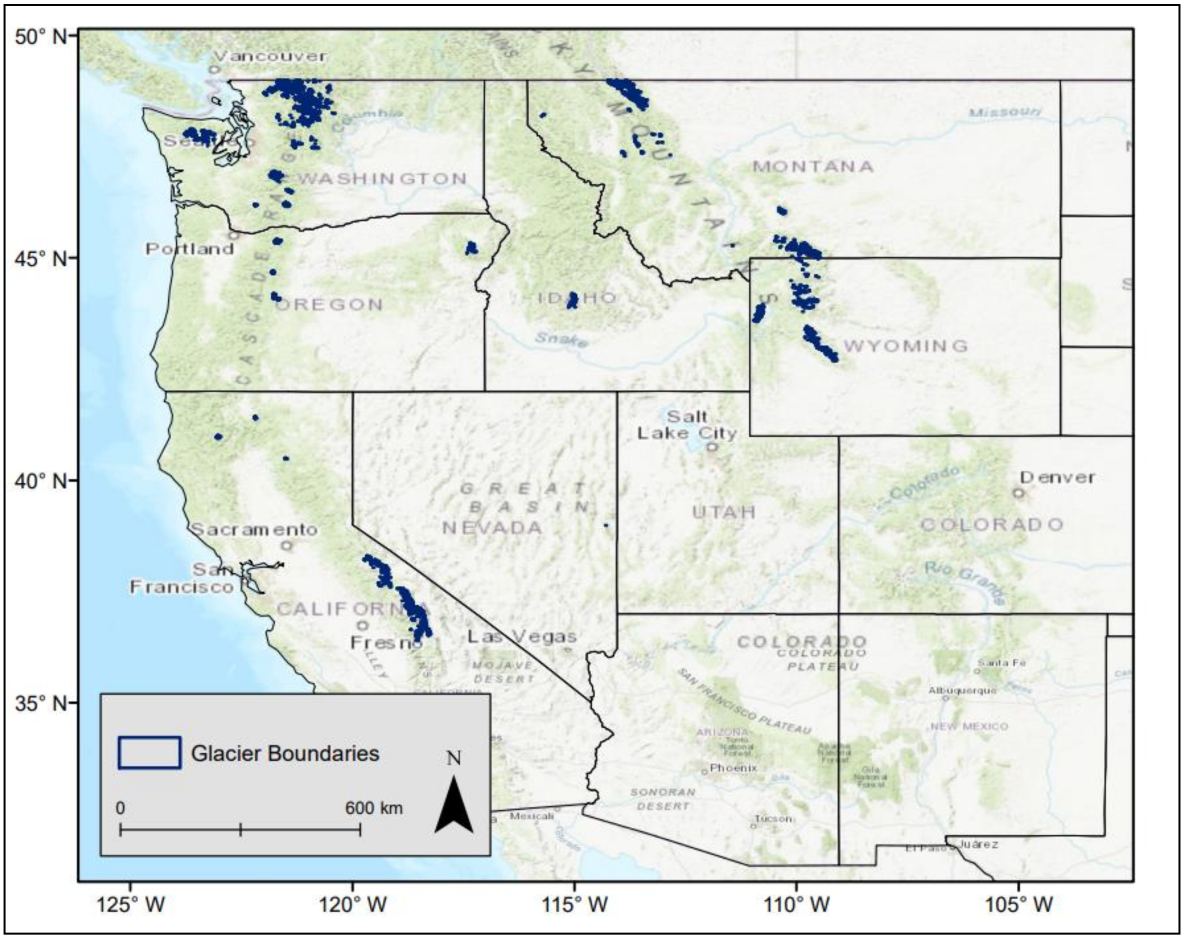


Figure. 1. Distribution of Glaciers in the western United States defined by RGI inventory (Base map Source: ESRI Topographic map)

Typically, the Cascades and Sierra Nevada areas exhibit maritime snow climates, which involve considerable precipitation and temperature around 0°C for a significant portion of the winter. However, the Rocky Mountains tend to showcase more continental conditions. This is evident through comparatively reduced precipitation levels and winter temperatures considerably below 0°C at elevated altitudes (Selkowitz & Forster, 2016).

3 Data and Methods

3.1 Satellite Data

Sentinel-2A satellite images for the September month of 2020 were used to identify the current conditions of all the glaciers covering the glacierized areas of the western United States. Images were obtained from the Sentinel Open Hub (https://scihub.copernicus.eu/). Sentinel-2A Multispectral Instrument (MSI), launched in 2015, is a multispectral sensor with 13 bands covering the visible, near infrared (VNIR) and short-wave infrared (SWIR) wavelength regions. These bands comprise spatial resolutions of 10m, 20m, and 60m. The 10m resolution contains four bands: blue, green, red, and near-infrared-1. The 20m resolution contains six bands: red edge 1-3, near-infrared-2, short-wave infrared 1 and 2. The 60m resolution contains: Band 1, Band 9, and Band 10 that are 60m resolution. The three 60m resolution bands specifically dedicated for atmospheric correction and cloud screening (Drusch et al., 2012). Table 1 summarizes Sentinel-2A satellite data by band characteristics, wavelength, and spatial resolution.

Table 1: Sentinel-2A Bands

Sentinel Bands	Characteristic	Central Wavelength(μm)	Resolution (m)
Band 1	Coastal Aerosol	0.443	60
Band 2	Blue	0.490	10
Band 3	Green	0.560	10
Band 4	Red	0.665	10
Band 5	Near Infrared	0.705	20
Band 6	Near Infrared	0.740	20
Band 7	Near Infrared	0.783	20
Band 8	Near Infrared	0.842	10
Band 8A	Near Infrared	0.865	20
Band 9	Water Vapor	0.945	60
Band 10	Cirrus	1.375	60
Band 11	Shortwave Infrared	1.610	20
Band 12	Shortwave Infrared	2.190	20

3.2 Reference Data

The RGI 6.0 glacier outline was used as reference data. Google Earth images and topographic maps downloaded from the National Geologic Map Database developed by the USGS were used as secondary reference data to aid in manual digitization of glacier boundaries and verification of the glacier names.

3.3 Methods

Normalized Difference Vegetation Index (NDVI), Normalized Difference Glacier Index (NDGI), and Normalized Difference Snow/Ice Index (NDSII) were calculated from Sentinel bands (Table 2). NDVI is a normalized ratio of the near-infrared and red bands used to quantify vegetation cover and vegetation health (Huete et al., 2002). NDSI takes advantage of the reflectance of the visible and short-wave infrared regions of the electromagnetic spectrum. NDGI uses the ratio between the red and green regions of the EMS to detect and monitor glaciers. NDSII detects snow and ice by band ratioing the green band and the near infrared. The fact that ice reflectance declines towards the near infrared (NIR) indicates that this spectral region has potential for distinguishing between snow and ice (Keshri et al., 2009). All these band ratios also reduce noise such as illumination differences, cloud shadows, and atmospheric attenuation. Composite bands for all the images in the study area were created using all 13 bands and the four spectral indices to help in classification of the land cover classes.

Table 2: Spectral indices used in the study.

Index	Name	Formula
NDSI	Normalized difference snow index	$\frac{B11 - B3}{B11 + B3}$
NDVI	Normalized Difference Vegetation Index	$\frac{B8A - B4}{B8A + B4}$
NDGI	Normalized Difference Glacier Index	$\frac{B3 - B4}{B3 + B4}$
NDSII	Normalized difference snow/Ice index	$\frac{B3 - B8A}{B3 + B8A}$

A flowchart of the classification process is provided in Figure.2. All bands were resampled to 10 meters using the nearest neighbor method. A machine learning supervised image classification called Random Forest (RF) algorithm is used to classify the Sentinel-2A satellite images. Random forest is a type of non-parametric ensemble model where multiple decision trees are constructed and the final output is determined based on the combined results of these trees (Horning, 2010). Random forest aggregates multiple decision trees' predictions to obtain a more accurate and stable result. The trees produce a class prediction for a pixel, and the model predicts the pixel as the class with the most votes. In this study, classification of the images was done based on RF machine learning classification (Ambinakudige & Intsiful, 2022). During the classification, over 26,500 pixels were selected in each image as training site pixels and each pixel was classified as water, barren, snow, ice, vegetation, shadow, or debris. Shadowed areas were manually classified separately for ice or snow after the main classification, so it was imperative to separate the glacierized areas (Including shadowed areas with ice and snow) from the non-glacierized areas. While 70 percent of the pixels were used for the training, 30 percent of pixels were used for testing. The glacial boundary shapefiles from the RGI 6.0 were used as references. RGI glacier boundaries were overlaid on different color composite bands, to ensure accurate identification of the new glacier boundaries. Classified images, topographic maps and Google Earth images also served as references for detailed manual digitization. Digitization of the new glacier boundaries was done in ArcGIS 10.8.2. As part of the digitization process, a separate polygon feature class was generated for glaciers in the study area, and these polygons served as the new boundaries of the glaciers. The difference between the areas of the RGI boundaries and the newly created boundary for each glacier is computed to assess how much area has been lost or gained within the study period.

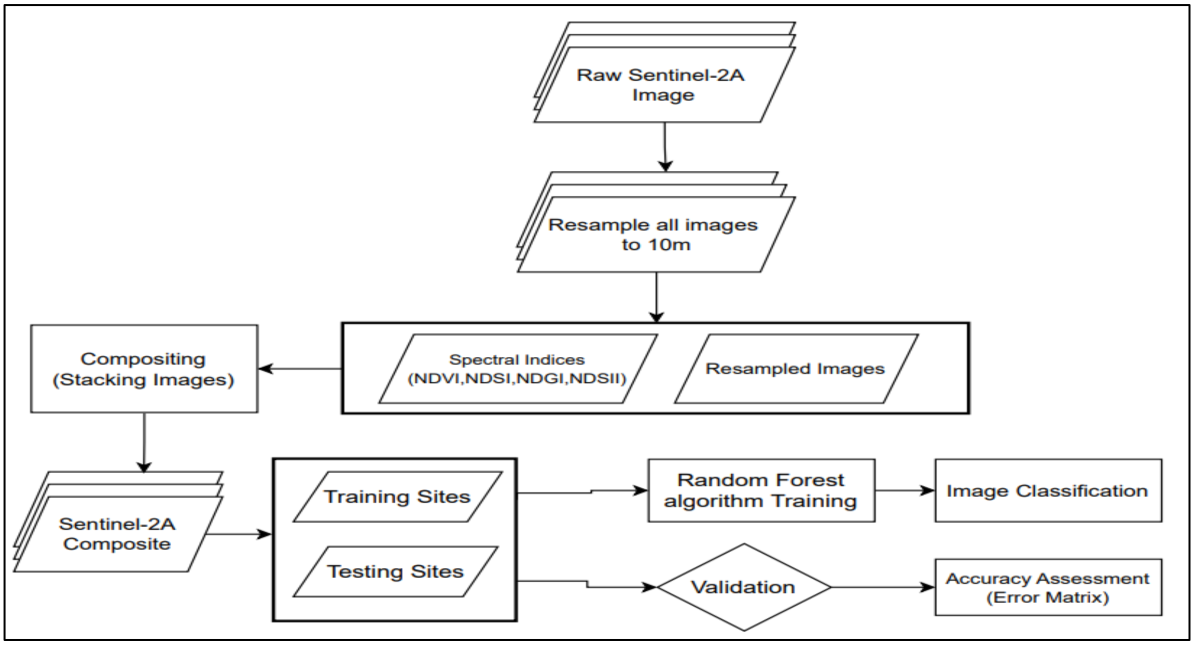


Figure. 2. Schematic diagram of the classification process

Glacier volume change is an important glacier parameter because it can be applied to estimate glacier mass change and to estimate meltwater runoff (Granshaw & Fountain, 2006). Area measurements were used to estimate glacier volume using a simple area-volume scaling relationship (Ambinakudige & Intsiful, 2022; Chen & Ohmura, 1990). The volume of an alpine glacier is related to its surface area as follows:

$$\mathbf{V = c}\boldsymbol{A^e} \quad (1)$$

where *V* is the glacier volume (km^3), A is glacier area (km^2) and *c* and *e* are coefficients and can be empirically or theoretically derived (Basagic & Fountain, 2011; Martin-Mikle & Fagre, 2019). There are several coefficients available for different study areas. Chen & Ohmura, (1990) derived nine coefficients for different study areas with four applicable to alpine glaciers in the western United States. They include “Cascade, small glaciers” (c =0.021346, e = 1.145), “Cascade & other areas” (c =0.03834, e = 1.405), “Alps, Cascade and other areas” (c =0.027551, e = 1.358), and “Alps, Cascade and Svalbard etc.” (c =0.028524, e = 1.357). Fountain et al., (2017) reported that the volume of glaciers in the western United States is better estimated using the empirical “Cascade, small glaciers” approach where c = 0.021346 and e = 1.145. Total volume change is then estimated by calculating the difference between the total volume of the RGI boundary and the total volume of the new glacier boundaries.

3.4 Accuracy Assessment

Assessment of the classifier's accuracy of Random Forest classification was done using the overall accuracy, and Kappa coefficient from the confusion matrix (error matrix). The confusion matrix summarizes the classifier's performance by comparing the classified data with reference data (Banko, 1998).

Overall accuracy is the proportion of correctly classified pixels to the total pixels. It is computed as:

$$\boldsymbol{Overall\ Accuracy} = \frac{\boldsymbol{Number\ correctly\ classified\ pixels}}{\boldsymbol{Total\ Number\ of\ pixels}} \qquad \mathbf{2}$$

Kappa Coefficient provides a measure of the classifier's performance that is less affected by chance agreement (Banko, 1998). It is computed as:

$$\mathbf{K} = \frac{\mathbf{N}\sum_{\mathbf{i=1}}^{\mathbf{r}} \mathbf{x_{ii}} - \sum_{\mathbf{i=1}}^{\mathbf{r}}(\mathbf{x_{i+}} \cdot \mathbf{x_{+i}})}{\mathbf{N^2} - \sum_{\mathbf{i=1}}^{\mathbf{r}}(\mathbf{x_{i}} \cdot \mathbf{x_{+i}})} \qquad \mathbf{3}$$

Where, r = number of rows and columns in the confusion matrix

x_{ii} = total number of observations in row i column i

x_{i+} = Total number of observations in row i

x_{+i} = Total number of observations in column i

N = Total number of observations in the matrix

3.5 Error Estimation

This study used satellite imagery to extract glacier parameters (area and volume), hence it is subject to uncertainties arising from image quality, sensor characteristics, interpretation of glacial features, and post-processing techniques (Paul et al., 2017). To estimate glacier area uncertainty, we employed the buffer method (Bolch et al., 2010; Granshaw & Fountain, 2006). The buffer method which expands and shrinks the outline of each glacier by an uncertainty value provides minimum and maximum estimates of uncertainty for each glacier that can be converted to a standard deviation (STD) when a normal distribution is assumed for the differences. The standard deviation is then used as a component of the precision of the outline, and it is recommended when there is no reliable reference data available (Paul et al., 2017). A buffer of 10m, equivalent to one pixel size was created around each glacier. This resulted in an average mapping uncertainty for a single glacier of 0.032 km^2 and total uncertainty in area change measurement of ±5.3km^2.

4 Results

The Random Forest algorithm applied to classify Sentinel images produced a high level of accuracy, as evidenced by the performance measures obtained from the analysis. Random forest machine learning image classification method provided over 98 percent classification accuracy with a kappa coefficient of 0.989.

4.1 Glacier Distribution and Characteristics

The RGI inventory had 5021 with a total area of 669.08 km^2 in the study area. The inventory created in this study found only 4091 glaciers covering an area of 432.01 km^2. This study identified 1790 glaciers in Washington, 776 in Wyoming, 733 in Montana, 604 in California, 153 in Oregon, 34 in Idaho, and 1 in Nevada (Table 3). That is 930 less glaciers, and about 18.52% decrease in number of glaciers.

The study region is dominated by small glaciers (size <1km^2). Out of 4091 glaciers, 4005 are smaller than 1 km^2, which is ~98% of the total number of glaciers. These form 49.2% of the total area in this study, covering 212.68 km^2. Conversely, the remaining 86 glaciers which are larger than 1 km^2, make up ~ 51% (219.4 km^2). There is a strong unevenness in the number of glaciers towards smaller glaciers (<0.05 km^2). Glaciers less than 0.05 km^2 account for 77% of the number of glaciers in the study area, but they represent only 11% of the total area in this study.

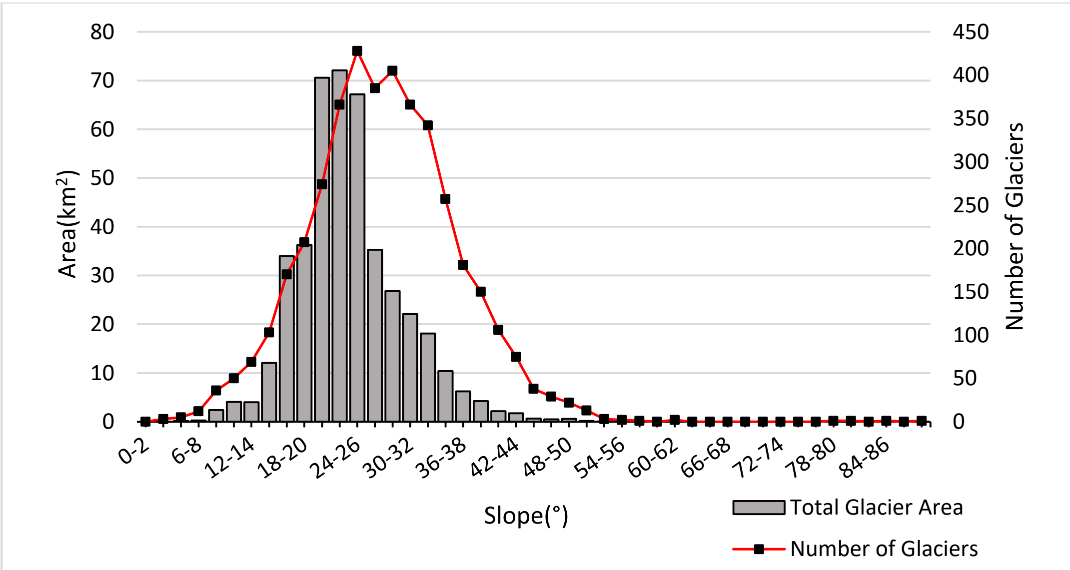


Figure. 3. Slope - Area/Number distribution of all glaciers

Generally, most of the glaciers in this study have a surface slope between 22°-32°. Glaciers with slopes of 20°-26° make up ~49% (209.85 km^2) of the total glacierized area. (Figure.3). Figure 4a shows the elevation-area/number distribution with 1000m elevation intervals in the seven glacierized states. The distribution shows that the majority (352.5 km^2, 81.8%) of the total area in the study region is found between 1000m a.s.l. and 2500m a.s.l. The lowest and highest elevations are 636 and 4340m a.s.l. both in the Cascade Range of Washington while only 0.66% and 17.8% are distributed below and above 1000m a.s.l. and 2500m a.s.l. respectively. The north (n = 1143) and northeast (n = 1236) are the two glacier aspects that occur most frequently (Figure. 4b), as well as having the largest surface areas, 107.7 km^2 and 123.1 km^2 respectively (Figure. 4c). Also, large glaciers tend to have gentle slopes (Figure. 4d).

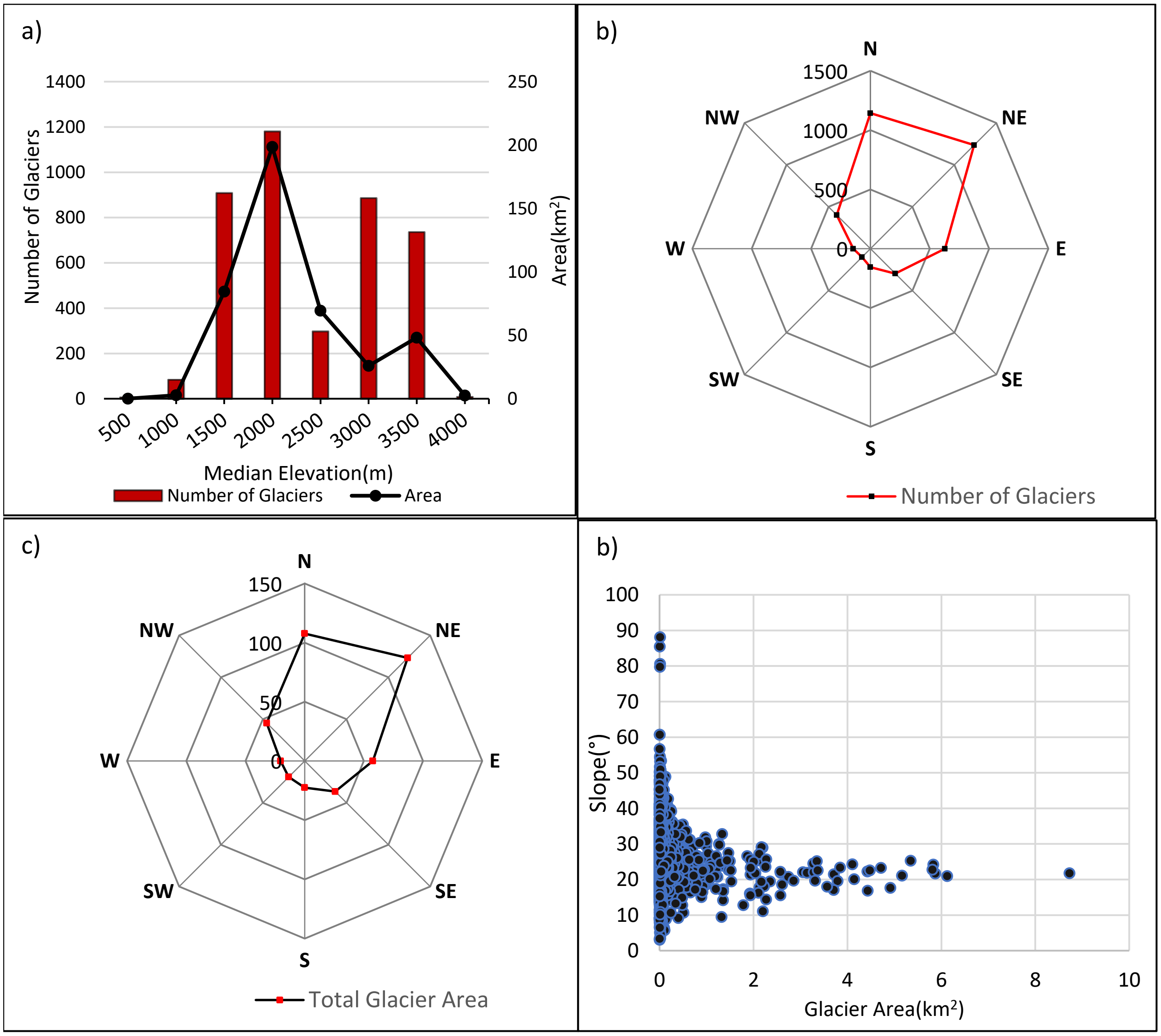
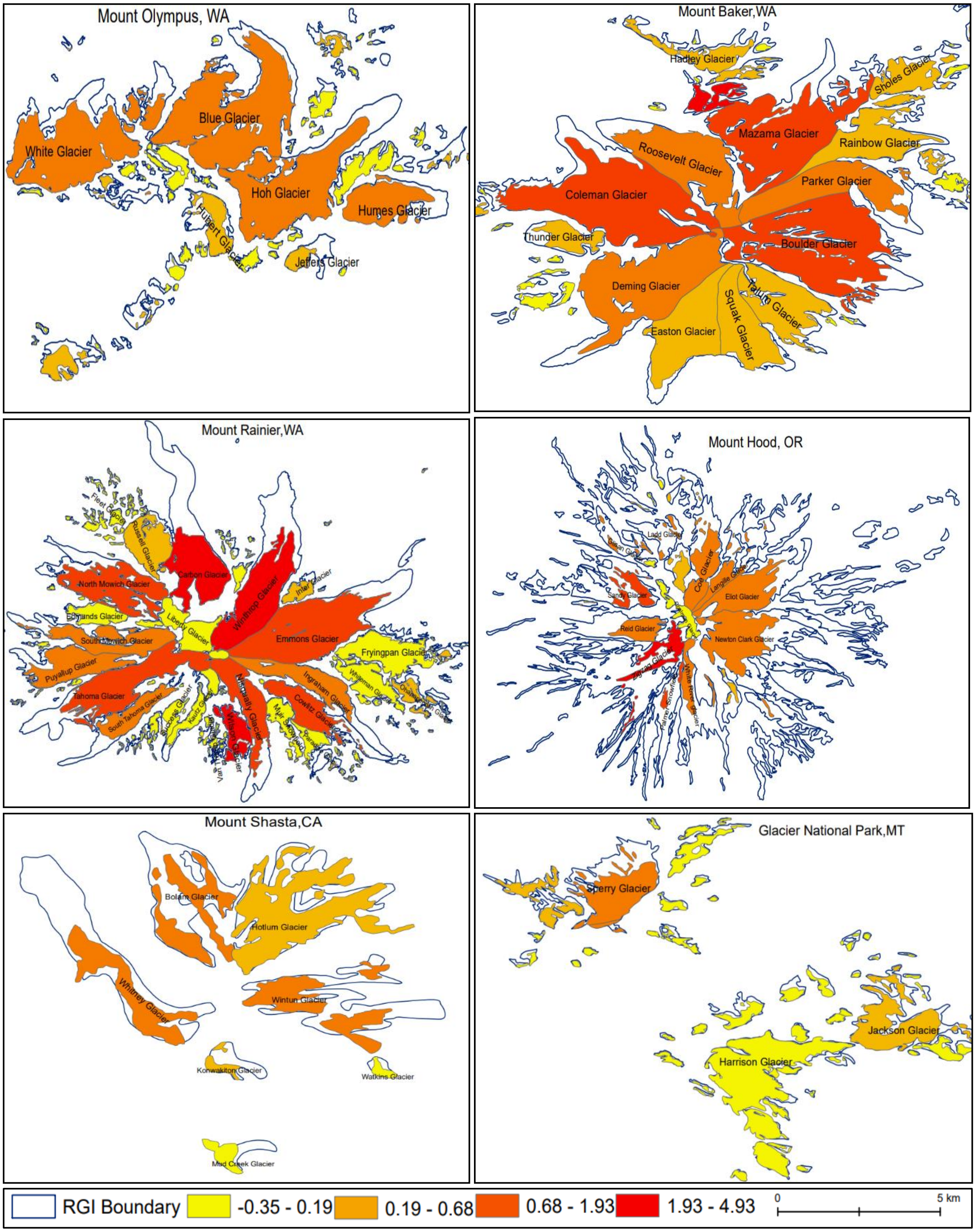


Figure. 4. Characteristics of glacier aspect, elevation, and slope. (a) Elevation – Area/Number distribution in 1000m bins. (b) Distribution of number of glaciers at different orientation (c) Total glacierized area at different orientation. (d). Slope-Area distribution of all glaciers.

4.2 Glacier Changes

The area and volume of glaciers and perennial snow fields in this study decreased significantly (Table 3, Figure. 5). The total area of glaciers in the RGI inventory is 669.08 km^2 with an overall volume of 13.92 km^3. In our study, there are only 4091 glaciers that were found with a total area of 432.01 km^2 and volume of 9.02 km^3. Hence, the total area loss during the study period is 237.07 km^2 (Table 3) which represents 35.43% of the area lost compared to the RGI glacier boundaries. The volume lost during this period was 4.9 km^3.

(km^3)



302 Figure. 5. Glacier area changes of major glaciers in the western United States

California	**-0.019**	**604**	**42.04**	**14.891**	**-27.15**	**-64.58**	**0.224**
Cascade Range	-0.037	10	5.04	2.991	-2.05	-40.67	0.060
Sierra Nevada	-0.018	591	35.12	11.86	-23.26	-66.23	0.163
Trinity Alps	-0.050	3	1.88	0.039	-1.84	-97.87	0.001
Idaho	**-0.023**	**34**	**2.02**	**0.195**	**-1.83**	**-90.59**	**0.002**
Sawtooth Range	-0.023	34	2.02	0.195	-1.83	-90.59	0.002
Montana	**-0.026**	**733**	**67.81**	**40.716**	**-27.09**	**-39.95**	**0.678**
Beartooth-Absaroka	-0.034	254	21.85	10.235	-11.62	-53.18	0.155
Cabinet Mountains	-0.150	3	0.71	0.081	-0.63	-88.73	0.001
Crazy Mountains	-0.021	40	1.89	0.839	-1.05	-55.56	0.011
Lewis Range	-0.026	389	39.83	27.54	-12.29	-30.86	0.481
Madison Range	-0.018	1	0.04	0.003	-0.04	-100	0.000
Mission-Swan-Flathead	-0.009	46	3.49	2.018	-1.47	-42.12	0.03
Nevada	**—**	**1**	**0.10**	**0.023**	**-0.08**	**-80**	**0**
Snake Range	—	1	0.10	0.023	-0.08	-80	0
Oregon	**-0.043**	**153**	**41.62**	**13.856**	**-27.76**	**-66.7**	**0.263**
Cascade Range	-0.039	116	40.52	13.146	-27.37	-67.55	0.254
Wallowa Mountains	-0.006	37	1.1	0.71	-0.39	-35.45	0.009
Washington State	**-0.051**	**1790**	**444.79**	**314.734**	**-130.06**	**-29.24**	**6.985**
Cascade Range- North	-0.050	1306	285.41	201.786	-83.62	-29.3	4.291
Cascade Range- South	-0.038	244	122.81	88.682	-34.13	-27.79	2.168
Olympic Mountain	-0.040	240	36.57	24.266	-12.3	-33.63	0.526
Wyoming	**-0.019**	**776**	**70.70**	**47.59**	**-23.12**	**-32.7**	**0.870**
Absaroka Range	-0.011	216	8.38	5.589	-2.79	-33.29	0.077
Teton Range	-0.010	134	6.39	3.854	-2.54	-39.75	0.053
Wind River Range	-0.025	426	55.93	38.147	-17.78	-31.79	0.741
Total	**-0.028**	**4091**	**669.08**	**432.01**	**-237.07**	**-35.43**	**9.023**

Table 3. Glacier Area Changes across western United States including major mountain ranges

Individual glaciers lost area from 0 km^2 to -3.57 km^2. Small glaciers with area <0.5 km^2 lost 109.25 km^2 (41%) while glaciers larger than >0.5 km^2 lost 127.79 km^2 (31%). However, very small glaciers (<0.01 km^2) gained 6.05 km^2 of area (Figure. 6, Table 4).

Table 3. Glacier area changes across different size classes

Size	Count	Area	Area	Change	%

interval(km^2)	(This study)	(This Study) km^2	Count (RGI)	(RGI) km^2	(km^2)	Change
<0.01	1308	7.15	113	1.10	6.05	548.04
0.01-0.05	1832	41.53	3242	73.78	-32.25	-43.45
0.05-0.1	410	28.52	738	51.63	-23.11	-44.62
0.1-0.5	375	79.30	697	139.92	-60.62	-43.02
0.5-1.0	80	56.14	101	71.36	-15.22	-22.23
1.0-5.0	79	176.50	119	253.42	-76.92	-30.35
5.0-10.0	7	42.87	10	67.29	-24.42	-36.29
>10.0	0	0	1	10.58	-10.58	-100
Total	**4091**	**432.01**	**5021**	**669.08**	**-237.07**	**-35.43**

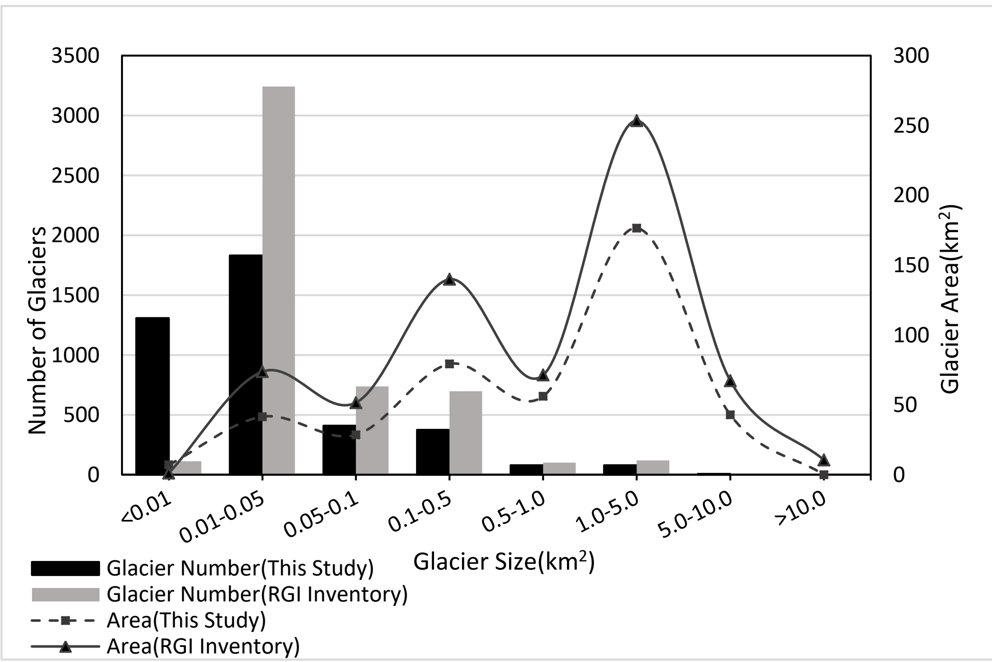


Figure. 6. Glacier distributions and changes according to area-size classes

Among the states that contains glaciers, Washington state is the most glacierized state with an ice coverage of 314.73 km^2, which accounts for ~73% of the total glacierized regions in the western United States. Glacier area reduction is also most prominent in Washington State (Table 3). This study identified 1790 glaciers in Washington, with a mean area of 0.176 km^2. Washington State glacier coverage has decreased by 29.24% of the RGI value, from 444.79 km^2 to 314.73 km^2. This region has the highest mean area of the seven states (Table 3). Approximately 96% of the glaciers in Washington state are less than 1 km^2 with their total area contributing to ~39% (123.3 km^2) of the total area in the region. Only 69(~4%) glaciers had an area between 1-10 km^2; they had a combined area of 191.4 km^2, representing ~61% of the total area in Washington state. The total number of glaciers has declined from 1968 in the RGI inventory to 1790 in this current study. Glacier area reduction from Washington state alone represent ~55% of glaciers lost in the entire western United States during the study period. The area of glaciers <0.5 km^2 in this state decreased in area extent by 35.84% (-44.59 km^2) while the total area of glaciers >0.5 km^2 declined by 26.67% (85.47 km^2). These findings underscore that larger glaciers in Washington state have a more profound impact on local water resources due to their greater contribution to ice loss.

Glaciers across Oregon, California, Idaho, Oregon, Montana, and Wyoming make up only 27% (117.27 km^2) of the total area of glaciers in this study with a combined mean area of 0.051 km^2. The number of glaciers less than 0.5 km^2 accounted for 99% (2266 glaciers) of the glacier population in these states. Glaciers in California and Oregon also experienced substantial ice loss with both states with both states seeing glacier areas decline by over 60%. In contrast, Montana and Wyoming recorded comparatively less shrinkage, with reductions of around 40% (27.09 km^2) and 33% (23.12 k km^2), respectively. The most drastic shrinkage occurred in Idaho which shrunk over 90% of its glacier coverage. This can be attributed to the few numbers of glaciers in Idaho, coupled with their smaller size, rendering them exceptionally vulnerable to accelerated melting.

The study area has experienced changes in the number of glaciers, either through the fragmentation of larger glaciers or the disappearance of smaller glaciers. This study found complete disappearance of 930 glaciers. All states experienced a decrease in glaciers except Nevada with an unchanged number of glaciers. The number of glaciers <0.01 km^2 increased from 113 in the RGI inventory to 1308 in this study, with a corresponding increase in glacier area from 1.1km^2 to 7.2km^2. This is directly related to a 43.15% decrease in the number of glaciers between 0.01-10 km^2 from the RGI inventory. The total number of glaciers that disappeared accounts for 18.5% of the total number of glaciers in the RGI inventory. The highest rate of glacier disappearance occurred in California, which lost 356 glaciers. It could be explained by the fact that this area mainly consists of smaller glaciers, which are more detached than larger glaciers, making them more prone to melting (Intsiful & Ambinakudige, 2021). We discovered 408 glaciers that grew, most of which are small glaciers. The area gain of individual glaciers varied from 0.00 km^2 to 0.163 km^2.

Glacier variability in the western United States shows that glaciers at lower elevations lose more area than those at higher elevations (Figure. 7). The rapid decline in glacier size at lower elevations can be linked to temperature rise. This is because glaciers at lower elevations (ablation zone), are highly sensitive to temperature variations while glaciers at higher elevations (accumulation zone), are more sensitive to trends in precipitation (Tian et al., 2014).

Also, as shown in Figure 7, glaciers in the north, northeast and northwest facing aspects experienced the most shrinkage with a reduction of -72.9km^2 (-40.4%), -68.5km^2 (-35.8%) and -26km^2 (-36.5%) respectively. A factor that may have contributed to the faster shrinkage in the north, northeast and northwest facing aspect glaciers could be the size of the glaciers. Majority of glaciers with these aspects (N, NE, NW) tend to be smaller (<0.1). However, other factors such as elevation, relative humidity, and temperature may also contribute to the shrinkage, but a comprehensive analysis of these factors would require further research and investigation.

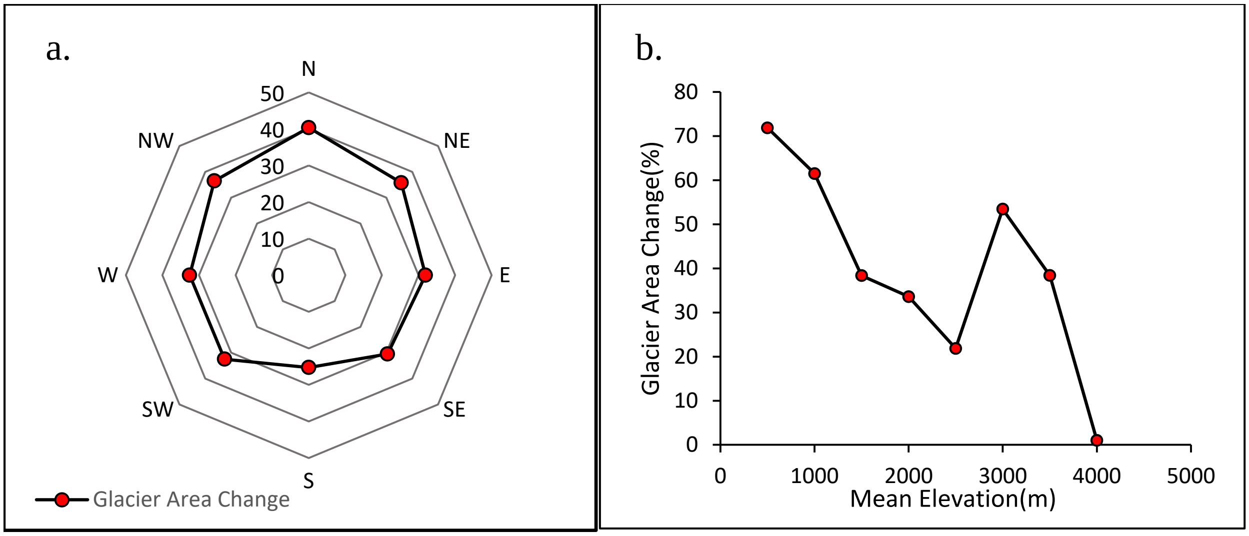


Figure. 7. Glacier Area Changes at different (a.) orientation and (b.) elevation. All percentage changes are negative.

Shrinkage patterns varied across various mountain ranges (Table 3). There was an indication of a drastic decrease in glacier extent. In particular, the Trinity Alps, Sawtooth Range and Maddison Range lost more area than other mountain ranges. In the north cascades national park complex in the Cascade Range, glaciers and perennial snowfields area have declined by 29.3% (83.62 km^2) of its coverage from the RGI glacier boundaries, with major glaciers such as White River glacier, West Nooksack glacier, and White Chuck glacier losing more than 50 percent of their area. A large area reduction was found in glaciers on Mount Baker (-12.32 km^2, -24.24%), Mount Shuksan (-4.05 km^2, -23.72%), and Mount Challenger (-3.38 km^2, -25.12%) in the North Cascade Range, Washington. The glaciers in the Olympic mountains and Glacier National Park of the Lewis range in the Rocky Mountains only have 66% and 69% of their original glacier boundary covered by snow/ice in 2020. Glaciers such as Blue glacier (-0.747 km^2, 13.19%), White glacier (-0.719 km^2, -16.78%), Hoh glacier (-0.826 km^2, -18.22%) and Sperry glacier (-0.491 km^2, -38.09%) declined at a rate of 2.26%a^{-1}, -2.19%a^{-1}, -2.5%a^{-1} and -0.91%a^{-1} respectively. The Wind River Range and the Teton Range of Wyoming have lost -31.79% (-17.78 km^2) and -39.65% (-2.533 km^2) respectively, with an average rate of a single glacier being -0.076%a^{-1} and -0.027%a^{-1} respectively. The Gannett Glacier in the Wind River Range, which is the largest glacier in the contiguous United States excluding Washington State, currently retains only 85% of its original coverage. It is diminishing at an approximate rate of 1.002% a^{-1}.

5 Discussion and Conclusion

From the Randolph Glacier Inventory (RGI), the Western United States (excluding Alaska) had 5021 glaciers with a combined area of 669.08 km^2 with a corresponding volume of 13.92 km^3. By 2020 the number of glaciers had decreased to 4091, with the total area shrinking to 432.01 km^2 and the volume declining to 9.02 km^2 as well. Over the study period, combined glacier area decreased by 237.07 km^2 (35.43%) and volume loss of 4.9 km^3, indicating a general decrease in glacier extent in the study area during the study period.

Evidence from various studies monitoring changes in glacier area over time in the western U.S., reveals notable reductions in glacier area extent (Fountain et al., 2017; Riedel et al., 2015; Selkowitz & Forster, 2016). Generally, results from this study indicate a substantial decrease in glacier extent in the American West from the mid-20th century to 2020. The total area of glaciers and snowfields reduction by 35.43% (237.07 km^2) in our study is comparable with the findings from Selkowitz & Forster, (2016) who reported a total area change of 163.6 km^2 with a corresponding area change of 28% from 2010 to 2014. Similarly, while the study conducted by (Fountain et al., 2017) reported a 39% decrease in glacier and perennial snowfield coverage, our study reveals a slightly lower ice coverage decrease of 35.43%. However, it is crucial to consider the specific findings and methodologies of both studies when interpreting these results.

Examination of glacier extent changes across distinct regions in the western U.S. reveals consistent patterns of glacier area reduction. For instance, the glacier area within North Cascades National Park has decreased by 29.3% according to the present study. This finding corresponds to prior research by (Granshaw & Fountain, 2006), which reported a 7% reduction in glacier area in the North Cascades region between 1958 and 1998. Additionally, Selkowitz & Forster, (2016) documented a 21% loss of area in the North Cascade Range between 2010 and 2014. In a similar vein, the Wind River range in Wyoming has experienced a 31.79% reduction in glacier area. DeVisser & Fountain, (2015) observed comparable trends, noting a 26.9% and 47% reduction in glacier extent from 1963 to 2006 and 1900 to 2006, respectively. Furthermore, Maloof et al., (2014) reported a 39% reduction in glacier area across 44 studied glaciers in this region. These findings collectively highlight the consistent trajectory of glacier area decline across different regions in the western U.S.

As expected from the area loss, the glaciers also experienced a decrease in volume. Volume estimates based on area-volume scaling indicate a volume loss of about 4.9 km^3. This is equivalent to about 4.7 gigatons of water.

Despite the fact that a number of factors, including wind speed, aspect, elevation, cloud cover, relative humidity, avalanche, glacier size, and glacier type, can affect glacier recession or growth, temperature and precipitation are the primary drivers of glacier variability. Increasing temperatures and snowpack decline are the main factors influencing glacier loss in the United States. Vose et al., (2017) observed a similar trend of increasing temperatures in the United States since the start of the 20th century. Similarly, (Basagic & Fountain, 2011; Mote et al., 2005, 2016, 2018) reported a similar pattern of decreasing snowpack in the western United States. They emphasized that anthropogenic activities and sea surface temperature (SST) are factors that brought about snow drought across the Pacific states, with SST contributing twice the amount of anthropogenic influence. Therefore, if climate models continue to predict higher temperatures and reduced precipitation in the western United States, the ongoing trend of glacier retreat is expected to persist.

A number of issues arise as a result of glacier shrinkage, including glacier hazards such as ice avalanches and glacial lake outburst floods (GLOFs), the rise of sea level and changes in hydrology (Intsiful & Ambinakudige, 2021). From the satellite imagery used in this study as well as images from Google Earth, we noticed that several proglacial lakes have been formed and developed. As glaciers shrink, GLOFs may increase. Therefore, considering all these factors mentioned above, continuous monitoring of glaciers to gather valuable data on their changing conditions holds great significance in understanding the impact of global climate change, the rise in sea levels, and ensuring the sustenance of the communities downstream from the glaciers.

The new glacier inventory created in this study (a complete list of glaciers will be published online) can be used as a baseline for future glacier change assessment study in the western U.S. Its accuracy would equip researchers and policymakers with reliable data, facilitating the monitoring and comprehensive understanding of the dynamic condition of these glaciers over time. However, there are several uncertainties which we have faced in the area change assessment that potentially have an impact on the quality of the inventory. Uncertainties could be caused due to the resolution of the satellite images, amount of seasonal snow remains, the time of satellite image acquisition, image classification and digitization accuracies.

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