70 years of high-resolution glacier surface elevation records derived from historical aerial photography across Western North America

Friedrich Knuth[1], David Shean[1], Eli Schwat[1], and Shashank Bhushan[2]

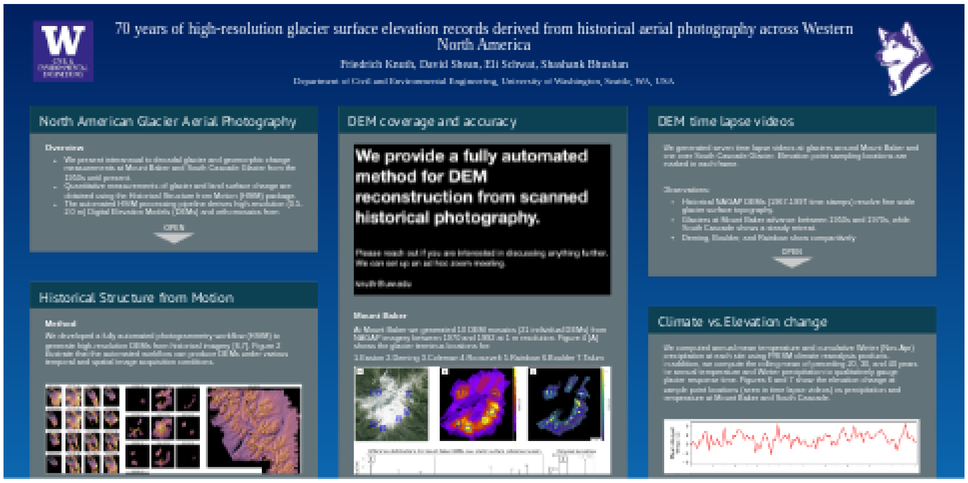
[1]University of Washington
[2]University of Washington,University of Washington

November 23, 2022

Abstract

We present interannual to decadal glacier and geomorphic change measurements at multiple sites across Western North America from the 1950s until present. Glacierized study sites differ in terms of glacial geometry and climatology, from continental mountains (e.g., Glacier National Park) to maritime stratovolcanoes (e.g., Mt. Rainier). Quantitative measurements of glacier and land surface change are obtained using the Historical Structure from Motion (HSfM) package. The automated HSfM processing pipeline can derive high-resolution (0.5-2.0 m) Digital Elevation Models (DEMs) and orthomosaics from historical aerial photography, without manual ground control point selection. All DEMs are co-registered to modern airborne lidar and commercial satellite stereo reference DEMs to accurately measure geodetic surface elevation change and uncertainty. We use scanned historical images from the USGS North American Glacier Aerial Photography (NAGAP) archive and other aerial photography campaigns from the USGS EROS Aerial Photo Single Frames archive. We examine the impact of regional climate forcing on glacier volume change and dynamics using downscaled climate reanalysis products. By augmenting the record of quantitative glacier change measurements and better understanding the relationship between climate forcing and heterogeneous glacier response patterns, we aim to improve our understanding of regional glacier mass change, as well as inform management decisions impacting downstream water resources, ecosystem management, and geohazard risks.

70 years of high-resolution glacier surface elevation records derived from historical aerial photography across Western North America



Friedrich Knuth, David Shean, Eli Schwat, Shashank Bhushan

Department of Civil and Environmental Engineering, University of Washington, Seattle, WA, USA

PRESENTED AT:

NORTH AMERICAN GLACIER AERIAL PHOTOGRAPHY

Overview

- We present interannual to decadal glacier and geomorphic change measurements at Mount Baker and South Cascade Glacier from the 1950s until present.
- Quantitative measurements of glacier and land surface change are obtained using the Historical Structure from Motion (HSfM) package.
- The automated HSfM processing pipeline derives high-resolution (0.5-2.0 m) Digital Elevation Models (DEMs) and orthomosaics from scanned historical aerial images, without manual ground control point selection.
- All DEMs are co-registered to modern airborne lidar and commercial satellite stereo reference DEMs to accurately measure geodetic surface elevation change and uncertainty.
- We use scanned historical images from the USGS North American Glacier Aerial Photography (NAGAP) archive and other aerial photography campaigns from the USGS Earth Resources Observation and Science (EROS) Aerial Photo Single Frames archive.
- We examine the impact of regional climate forcing on glacier elevation change and dynamics using downscaled climate reanalysis products.

Data

The primary dataset used for this study are images collected by the USGS North American Glacier Aerial Photography (NAGAP) program [1]. The program collected around 100,000 aerial photographs of glaciers in Western North America and Alaska between the 1950s and 1990s. Figure 1 shows the coverage map for a subset of the NAGAP photographs (~20,000) acquired between 1964 and 1997, which have digitally scanned and are publicly available through the NSF Arctic Data Center (arcticdata.io)

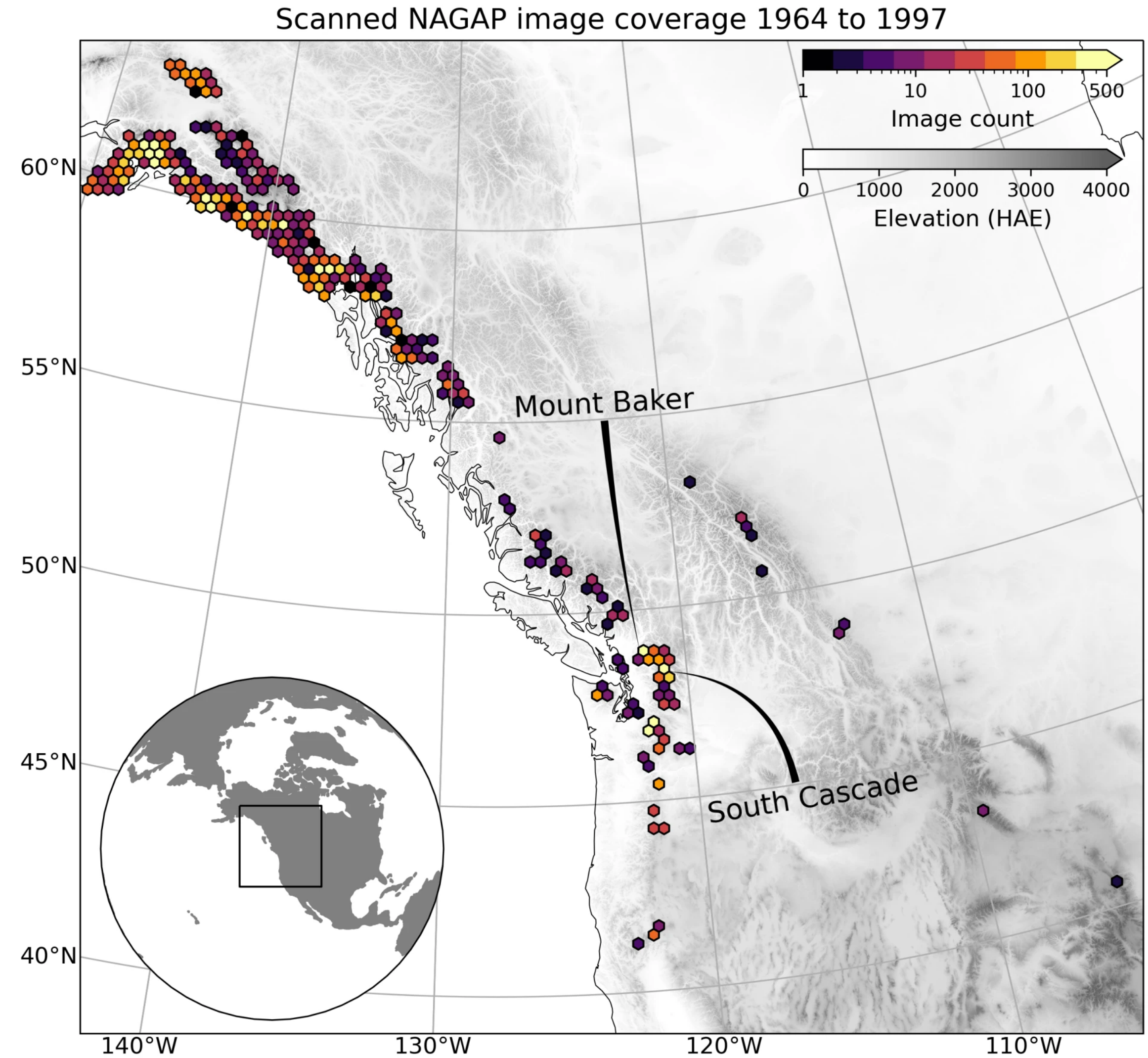


Figure 1. Coverage map for scanned NAGAP imagery acquired between 1964 and 1997 across Western North America available from the NSF Arctic Data Center. Color shows the total number of frames within each ~25 km hexagon (~1,600 km2 area). Annotations point to cells containing the Mt. Baker and South Cascade Glacier sites. Basemap shows surface elevation (height above WGS84 ellipsoid) from the 3-arcsecond Copernicus DEM, resampled to a 1 km grid.

Additional data products

- At Mount Baker we generated a 1 m reference Digital Surface Model (DSM) from LiDAR measurements collected for the USGS 3DEP program by Quantum Spatial on August 27, 2015 [2]. Additionally, we created a preliminary 1950s DEM using imagery acquired on 1950-09-02 by the USGS [3].
- At South Cascade we generated a composite 2-m reference DSM using five summer Maxar WorldView stereo images acquired between 2013 and 2015.
- At both South Cascade and Mount Baker we use modern (2008-2020) 2m EarthDEM products to complete the time series [4].
- We use PRISM interpolated precipitation and temperature reanalysis products at both sites [5].

HISTORICAL STRUCTURE FROM MOTION

Method

We developed a fully automated photogrammetry workflow (HSfM) to generate high-resolution DEMs from historical imagery [6,7]. Figure 2 illustrate that the automated workflow can produce DEMs under various temporal and spatial image acquisition conditions.

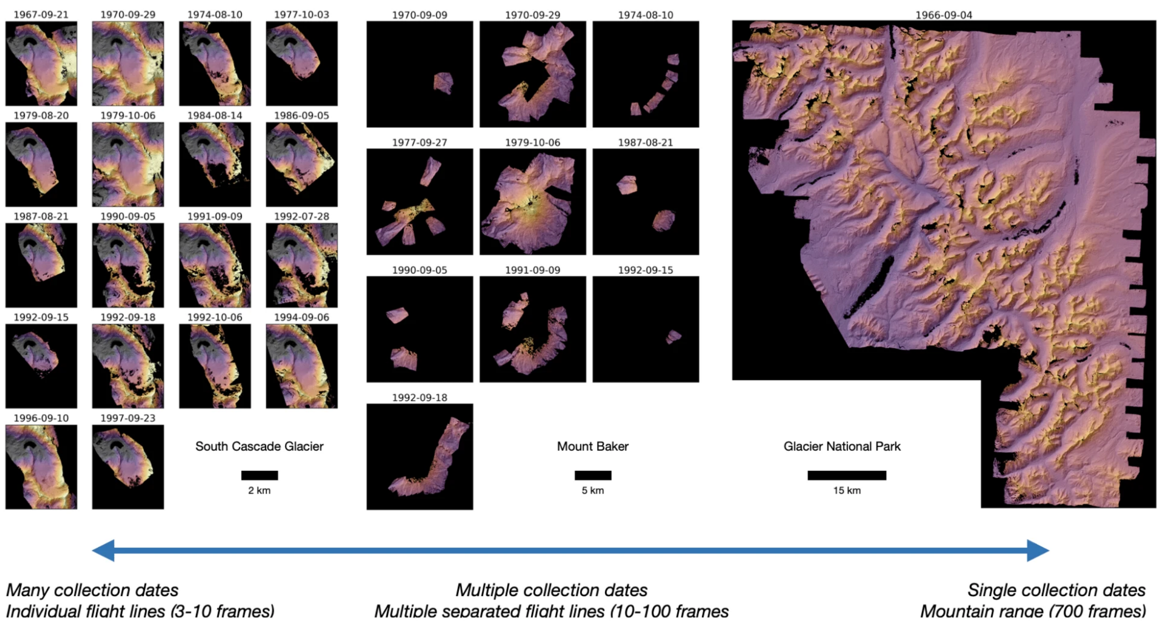


Figure 2. The HSfM processing pipeline derives accurate DEMs under a variety of image aquisition conditions. Image overlap is automatically detected, prior to DEM reconstruction and co-registration.

By "automated" we mean that there are no manual steps involved, such as:

- picking fiducial markers during image pre-processing
- selecting natural Ground Control Points (GCPs)
- pre-selecting overlapping images to be processed together.

The workflow is illustrated end-to-end in Figure 3. We us a multi-temporal bundle adjustment process to correct the relative positions and intrinsic camera model parameters for images collected on various acquisition dates. We use ICP algorithms to align the historical DEM to modern stable-ground reference terrain and correct the absolute camera positions with respect to the reference terrain.

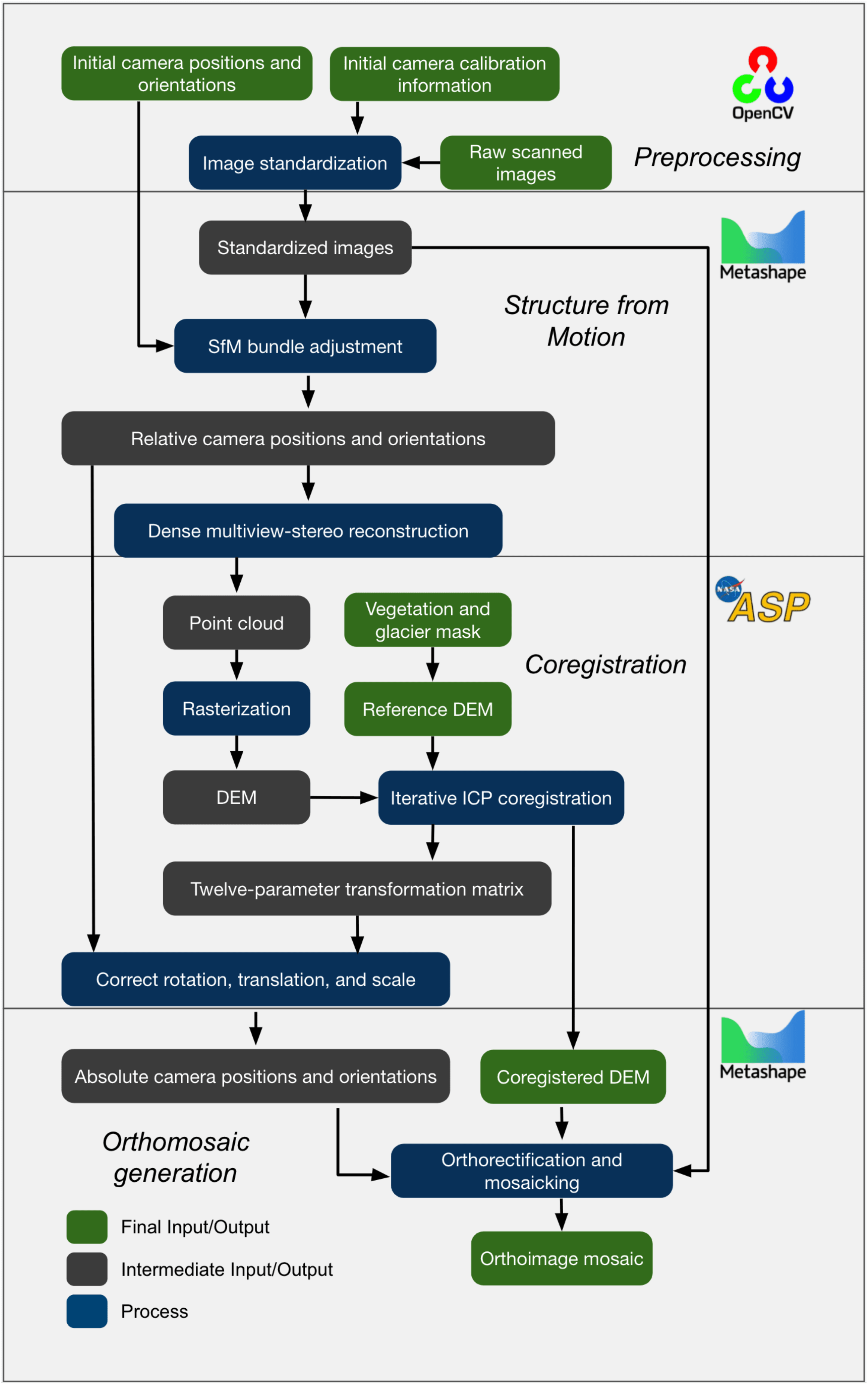


Figure 3. Historical Structure from Motion (HSfM) workflow.

DEM COVERAGE AND ACCURACY

We provide a fully automated method for DEM reconstruction from scanned historical photography.

Please reach out if you are interested in discussing anything further.
We can set up an ad hoc zoom meeting.

knuth@uw.edu

Mount Baker

At Mount Baker we generated 10 DEM mosaics (21 individual DEMs) from NAGAP imagery between 1970 and 1992 at 1 m resolution. Figure 4 [A] shows the glacier terminus locations for:

1.Easton 2.Deming 3.Coleman 4.Roosevelt 5.Rainbow 6.Boulder 7.Talum

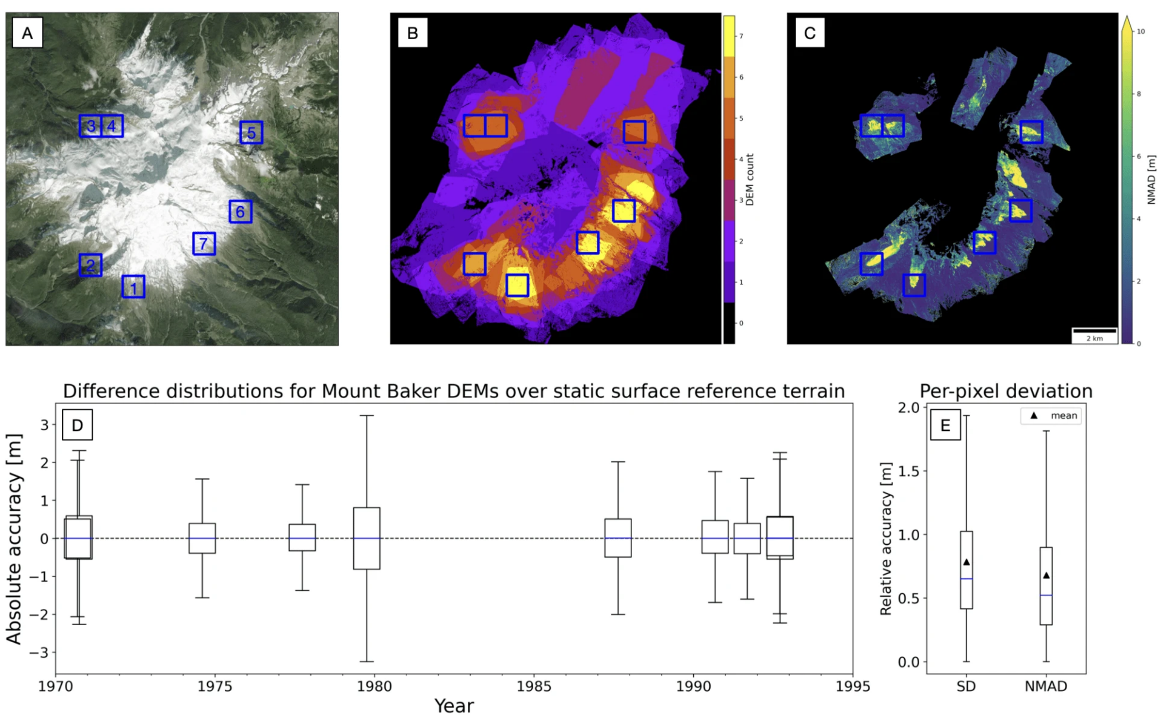


Figure 4. [A] Terminus locations over 2019 Maxar basemap [8]. [B] DEM count at each terminus location. [C] Normalized Median Absolute Deviation (NMAD) of elevation values across all DEMs. [D] NMAD of elevation values for all DEMs over stable ground terrain, with respect to the 2015 LiDAR 1 m reference DEM, as a measure of absolute accuracy. [E] Standard Deviation (SD) and NMAD over stable ground terrain for all historical DEMs, as a measure of relative accuracy.

South Cascade

At South Cascade we generated 18 DEMs from NAGAP imagery between 1967 and 1997 at 1 m resolution (Figure 5).

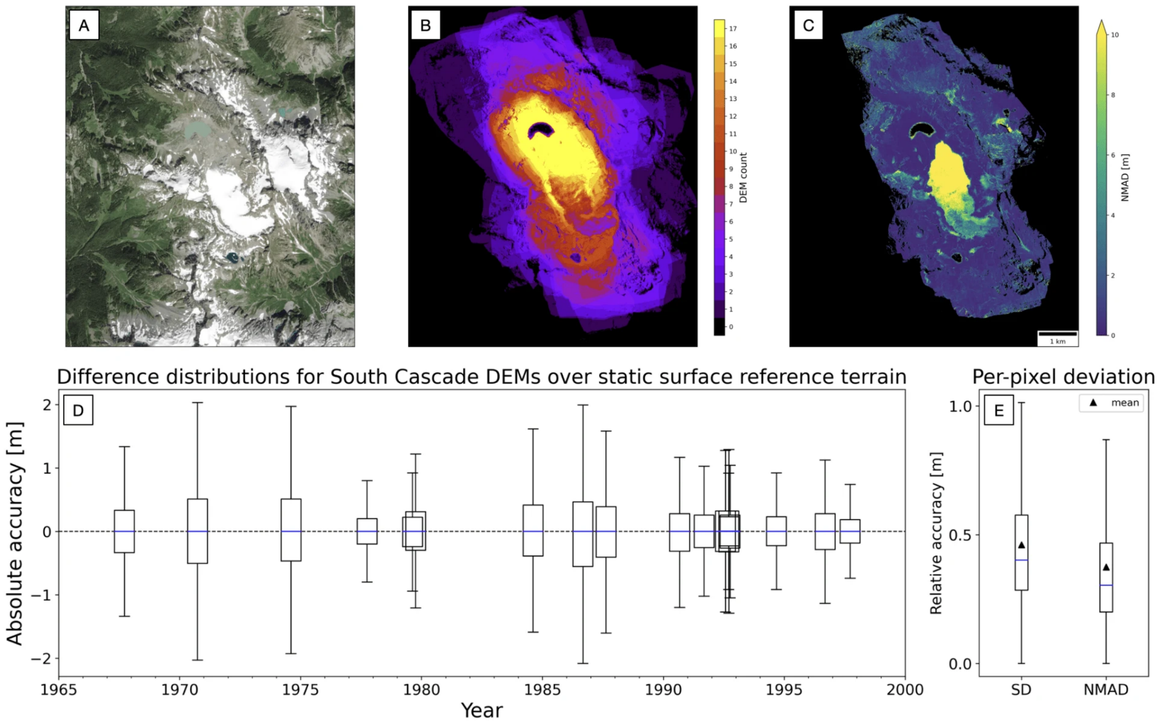


Figure 5. [A] South Cascade Glacier seen in 2020 Maxar basemap [9]. [B] DEM count. [C] Normalized Median Absolute Deviation (NMAD) of elevation values across all DEMs. [D] NMAD of elevation values for all DEMs over stable ground terrain, with respect to the 2013-2015 composite WV 2 m reference DEM, as a measure of absolute accuracy. [E] Standard Deviation (SD) and NMAD over stable ground terrain for all historical DEMs, as a measure of relative accuracy.

DEM TIME LAPSE VIDEOS

We generated seven time lapse videos at glaciers around Mount Baker and one over South Cascade Glacier. Elevation point sampling locations are marked in each frame.

Observations:

- Historical NAGAP DEMs (1967-1997 time stamps) resolve fine scale glacier surface topography.
- Glaciers at Mount Baker advance between 1950s and 1970s, while South Cascade shows a steady retreat.
- Deming, Boulder, and Rainbow show comparitively far advances, likely due to differences in hypsometry and local geometry.
- There is a curious mass moving with the ice near the sampling point at the Coleman glacier terminus.

Mount Baker

1. Easton

[VIDEO] https://res.cloudinary.com/amuze-interactive/video/upload/vc_auto/v1638927186/agu-fm2021/3D-5A-78-CD-B3-98-02-9D-7A-B8-E5-A2-EC-CA-93-D7/Video/time_series_Easton_ws892i.mp4

2. Deming

[VIDEO] https://res.cloudinary.com/amuze-interactive/video/upload/vc_auto/v1638927246/agu-fm2021/3D-5A-78-CD-B3-98-02-9D-7A-B8-E5-A2-EC-CA-93-D7/Video/time_series_Deming_gk6spv.mp4

3. Coleman

[VIDEO] https://res.cloudinary.com/amuze-interactive/video/upload/vc_auto/v1638927268/agu-fm2021/3D-5A-78-CD-B3-98-02-9D-7A-B8-E5-A2-EC-CA-93-D7/Video/time_series_Coleman_wireus.mp4

4. Roosevelt

[VIDEO] https://res.cloudinary.com/amuze-interactive/video/upload/vc_auto/v1638927294/agu-fm2021/3D-5A-78-CD-B3-98-02-9D-7A-B8-E5-A2-EC-CA-93-D7/Video/time_series_Roosevelt_s4zhqp.mp4

5. Rainbow

[VIDEO] https://res.cloudinary.com/amuze-interactive/video/upload/vc_auto/v1638927326/agu-fm2021/3D-5A-78-CD-B3-98-02-9D-7A-B8-E5-A2-EC-CA-93-D7/Video/time_series_Rainbow_dbkbwu.mp4

6. Boulder

[VIDEO] https://res.cloudinary.com/amuze-interactive/video/upload/vc_auto/v1638927144/agu-fm2021/3D-5A-78-CD-B3-98-02-9D-7A-B8-E5-A2-EC-CA-93-D7/Video/time_series_Boulder_dbygev.mp4

7. Talum

[VIDEO] https://res.cloudinary.com/amuze-interactive/video/upload/vc_auto/v1638927363/agu-fm2021/3D-5A-78-CD-B3-98-02-9D-7A-B8-E5-A2-EC-CA-93-D7/Video/time_series_Talum_mrawu6.mp4

South Cascade

[VIDEO] https://res.cloudinary.com/amuze-interactive/video/upload/vc_auto/v1638946252/agu-fm2021/3D-5A-78-CD-B3-98-02-9D-7A-B8-E5-A2-EC-CA-93-D7/Video/time_series_SCG_s7rmvl.mp4

CLIMATE VS. ELEVATION CHANGE

We computed annual mean temperature and cumulative Winter (Nov-Apr) precipitation at each site using PRISM climate reanalysis products. In addition, we compute the rolling mean of preceding 20, 30, and 40 years for annual temperature and Winter precipitation to qualitatively gauge glacier response time. Figures 6 and 7 show the elevation change at sample point locations (seen in time lapse videos) vs precipitation and temperature at Mount Baker and South Cascade.

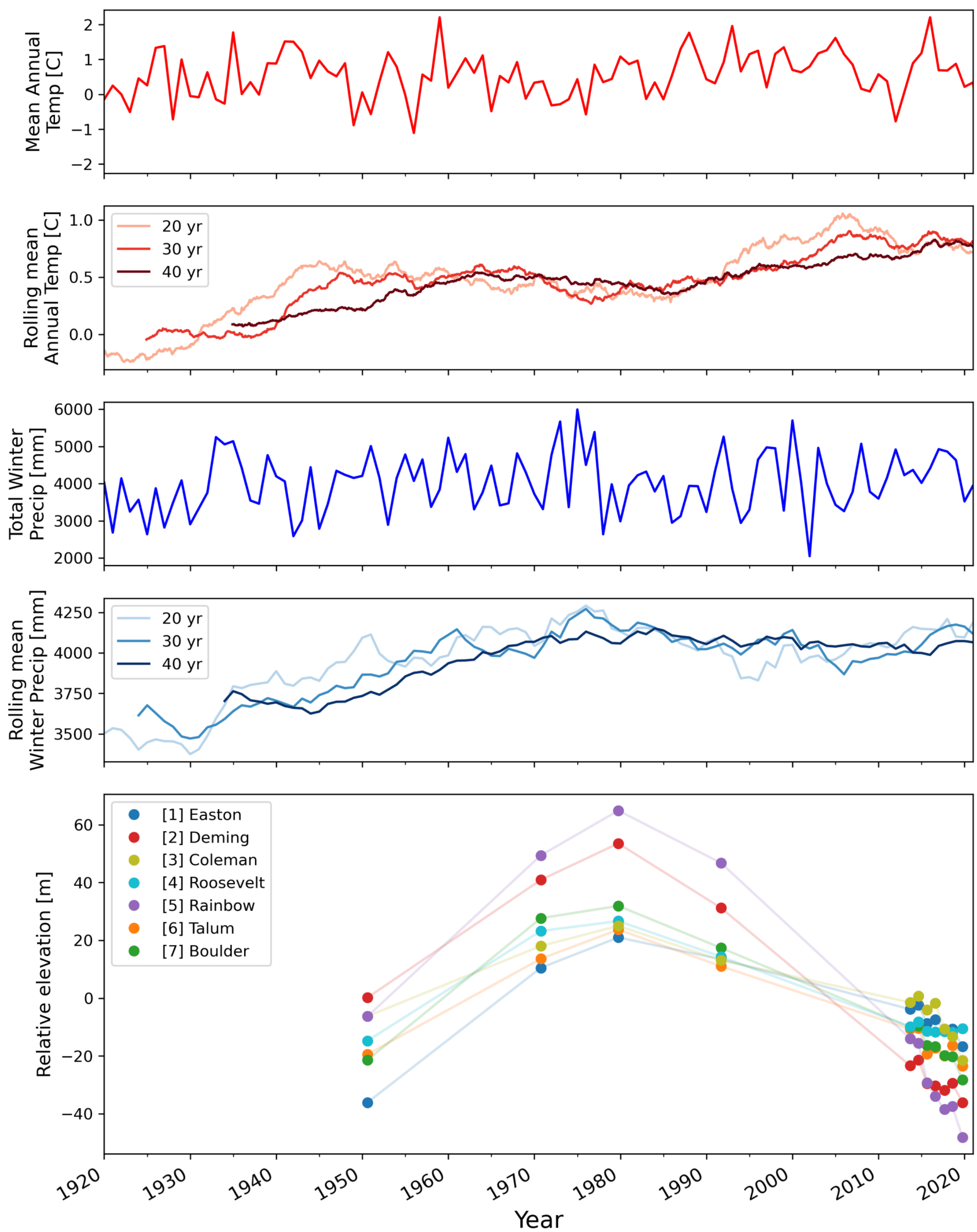


Figure 6. Climate and elevation change time series at Mount Baker. The relative elevation shown in the bottom panel is the elevation - mean elevation at each sample location. There appears to be a relationship between rolling mean winter precipitation values and glacier elevation change. The 40 year rolling mean Winter precipitation may present the strongest correlation, which indicates a ~40 year glacier response time.

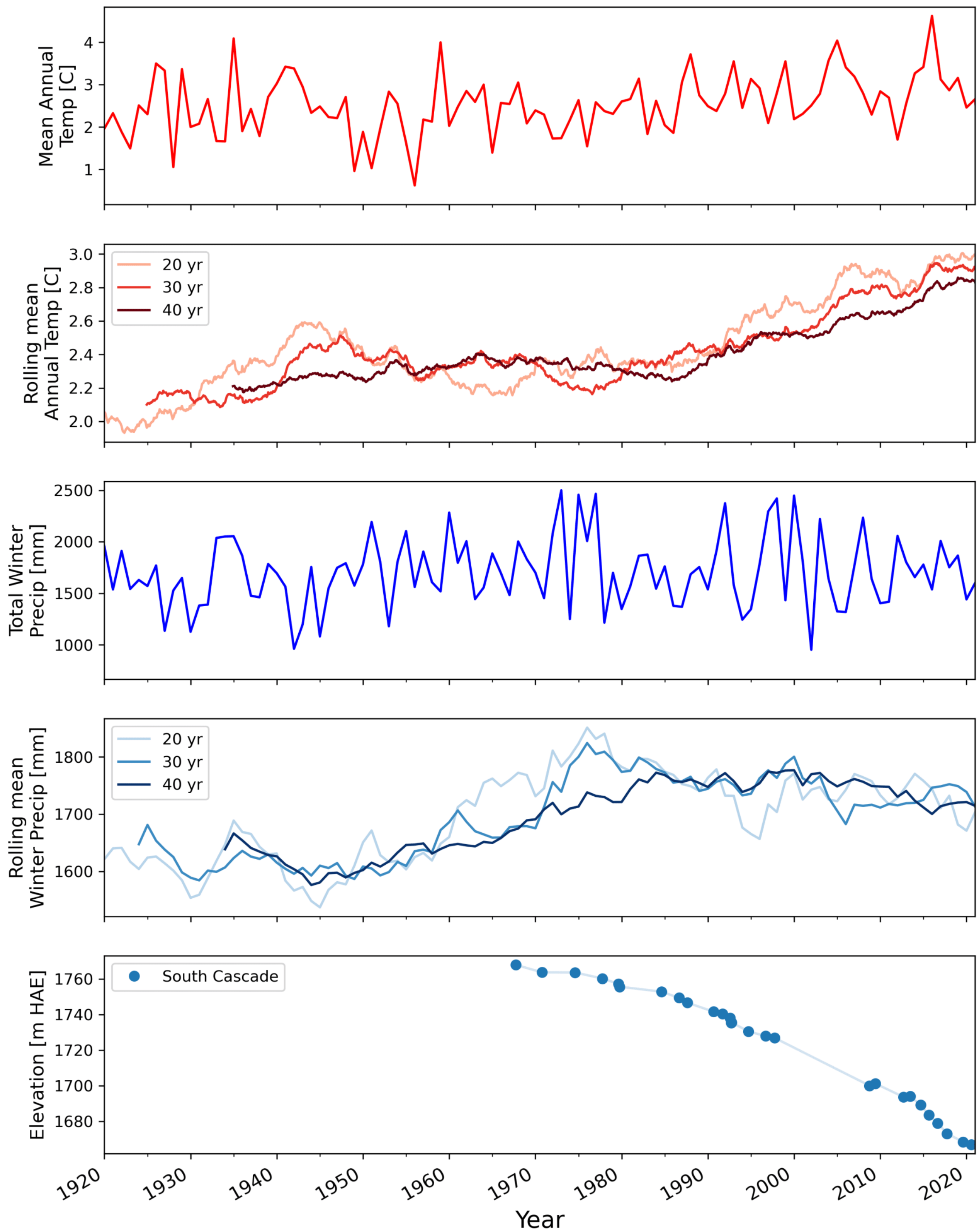


Figure 7. Climate and elevation change time series at South Cascade. Steady retreat since 1967. Unlike in Figure 6, the bottom panel here simply shows elevation over time. Rolling mean temperatures appear to show a stronger correlation with glacier retreat than precipiation. The 20 year rolling mean temperature may present the strongest correlation, which indicates a ~20 year glacier response time.

Next steps

- Programatically evaluate at which rolling mean window size the correlation is strongest to glacier terminus elevation change. This may provide insight to individual glacier response times and help with categorical classification, based one hypsometry and local geometry.
- Use the automated HSfM pipeline to process all available NAGAP and EROS imagery across glacierized sites in Western North America.
- Determine time stamps with full glacier coverage and compute geodetic mass balance.
- Fill voids in DEMs with partial glacier coverage using a combination of spatial and temrporal interpolation techniques.

AUTHOR INFORMATION

Friedrich Knuth
PhD Candidate
Civil and Environmental Engineering
University of Washington
Seattle, WA , USA

Please reach out if you are interested in discussing anything further! We can set up an ad hoc zoom meeting.

knuth@uw.edu

Related AGU presentation:

EP55A-1050 Eli Schwat et al. 2021, Historical aerial images & SfM allow repeat sediment yield measurements in proglacial environments, https://agu2021fallmeeting-agu.ipostersessions.com/?s=D6-04-0C-4D-BE-8F-B2-3C-2A-CE-29-F3-D2-B2-FD-C6 (https://agu2021fallmeeting-agu.ipostersessions.com/?s=D6-04-0C-4D-BE-8F-B2-3C-2A-CE-29-F3-D2-B2-FD-C6)

REFERENCES

[1] Nolan, M., Post, A., Hauer, W., Zinck, A., O'Neel, S., 2017. Photogrammetric scans of aerial photographs of North American glaciers, https://arcticdata.io/

[2] Washington Lidar Portal - Mount Baker DSM - https://lidarportal.dnr.wa.gov/

[3] USGS EROS - Single Frame Aerial Photographs - collected on Sep 10, 1950

[4] Polar Geospatial Center - EarthDEM – https://www.pgc.umn.edu/data/earthdem/

[5] PRISM Climate Group - Oregon State University - https://prism.oregonstate.edu

[6] Friedrich Knuth, Eli Schwat, David Shean, & Shashank Bhushan. (2021). Historical Image Pre-Processing (HIPP) pre-release v0.1 (v0.1). Zenodo. https://doi.org/10.5281/zenodo.5510876

[7] Friedrich Knuth, Eli Schwat, David Shean, & Shashank Bhushan. (2021). Historical Structure from Motion (HSfM) pre-release v0.1 (v0.1). Zenodo. https://doi.org/10.5281/zenodo.5510870

[8] Maxar (Vivid) imagery - Mount Baker basemap - collected on Oct 10, 2019

[9] Maxar (Vivid) imagery - South Cascade basemap - collected on Aug 14, 2020