A Slow End: Tracking Glacier Loss on Mount Rainier, Washington

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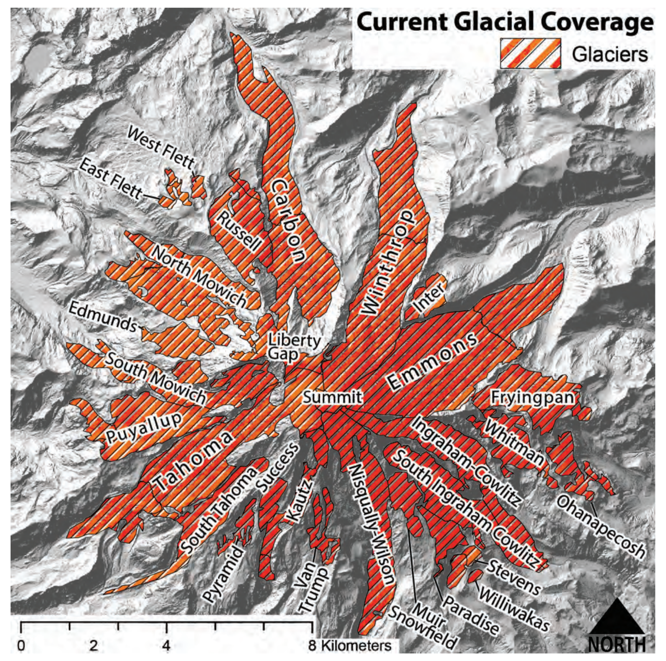
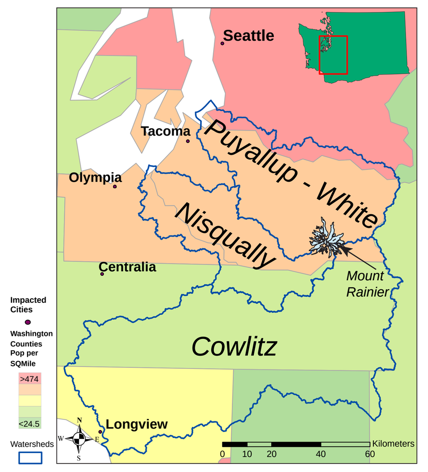
Jonathan Skloven-Gill and Marilyn Daum

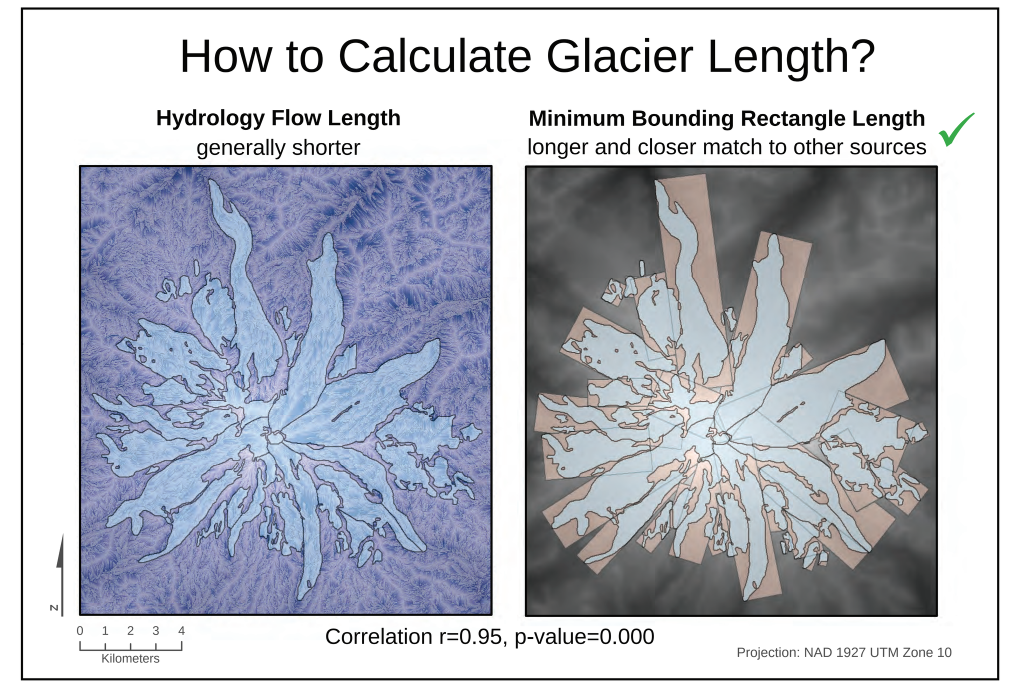


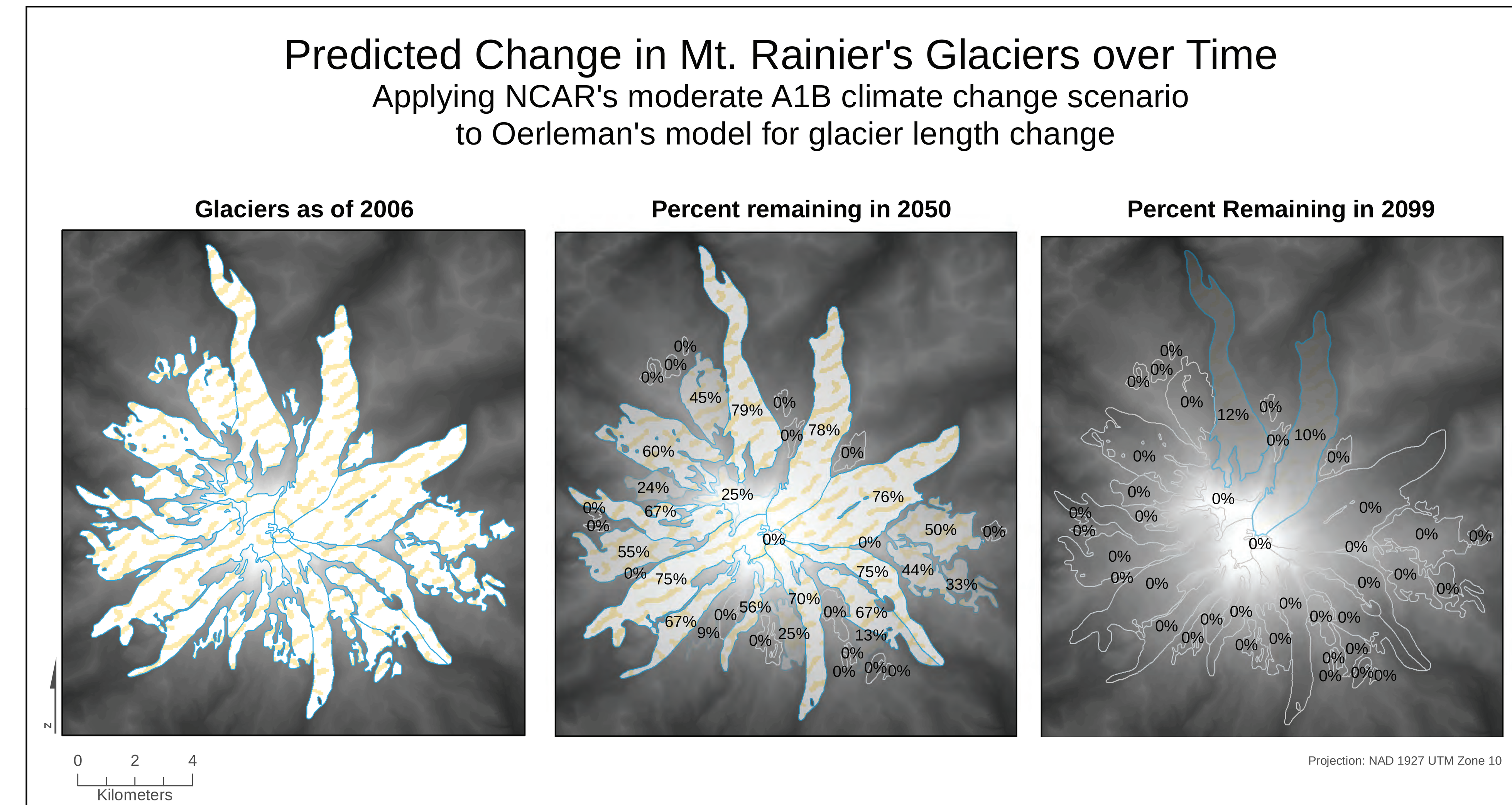
Glacial ice is the largest reservoir of freshwater on earth, and Mount Rainier is the most heavily glaciated peak in the lower 48 states[1]. We have heard that climate change is shrinking glaciers, but what does this mean for Mt. Rainier's glaciers during the next 50 or 100 years? Specifically, what is the risk of losing the freshwater supply from Mt. Rainier's glaciers?

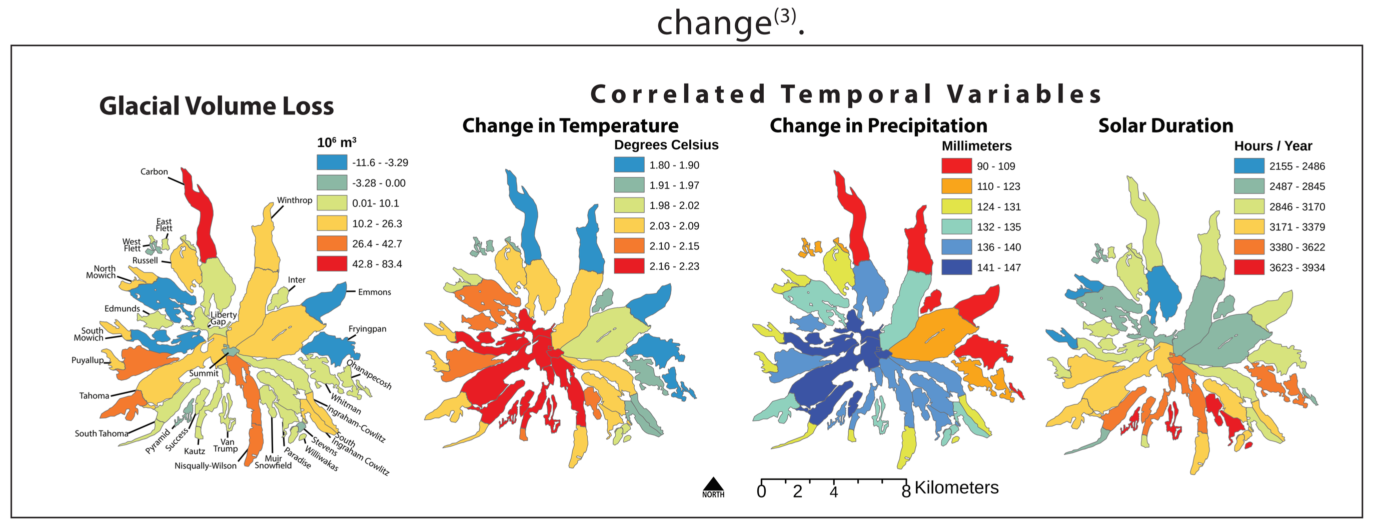
Our investigation includes 3 approaches to analyzing glacial recession. Using one of these, a significant relationship between glacier length and long-term temperature changes, we present a plausible future scenario based on moderate climate change[3].

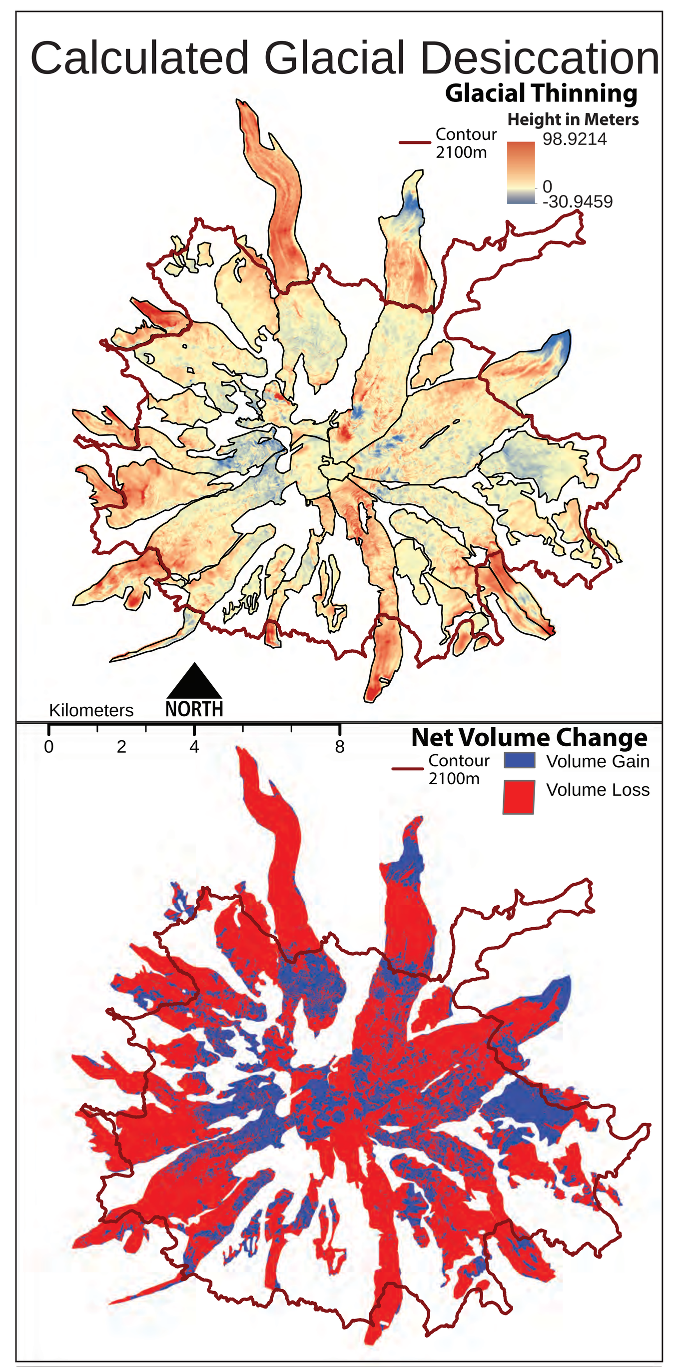


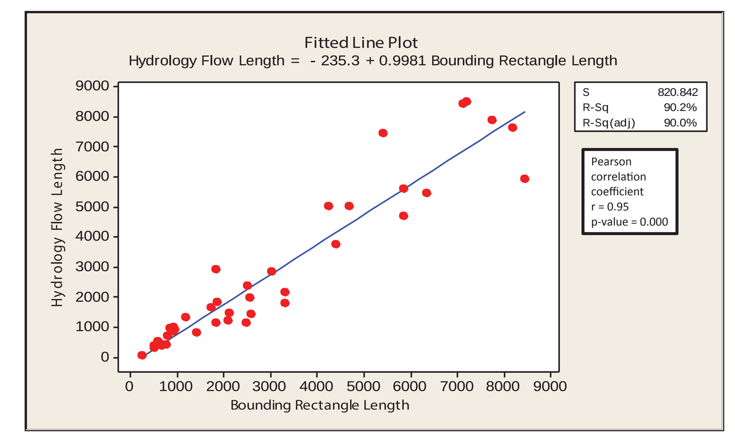
Why Mt. Rainier's Glaciers Matter











Name	Length (Meters)	Aspect
Carbon Glacier	8450.716	North
East Flett Glacier	830.539	North
Edmunds Glacier	2506.334	West
Emmons Glacier	7204.868	NorthEast
Fryingpan Glacier	3319.733	NorthEast
Ingraham-Cowlitz Glacier	7133.678	East
Inter Glacier	1723.257	NorthEast
Kautz Glacier	4401.837	South
Liberty Gap Glacier	2597.644	North
Muir Snowfield	1850.982	South
Nisqually-Wilson Glacier	6350.873	South
North Mowich Glacier	4698.779	NorthWest
Ohanapecosh Glacier	2482.419	East
Paradise Glacier	2083.261	SouthEast
Puyallup Glacier	4240.209	West
Pyramid Glaciers	2123.019	South
Russell Glacier	3301.068	NorthEast
South Ingraham-Cowlitz Glacier	5414.88	East
South Mowich Glacier	5860.147	West
South Tahoma Glacier	5848.794	SouthWest
Stevens Glacier	1170.132	West
Success Glacier	1819.806	South
Summit Glacier	663.349	East
Tahoma Glacier	7755.577	West
Van Trump Glacier	1825.598	South
West Flett Glacier	920.09	North
Whitman Glacier	3032.225	SouthEast
Williwakas Glacier	611.451	SouthEast
Winthrop Glacier	8195.913	NorthEast

Volume/Thickness Analysis

Monitoring and calculating area and volume on alpine glaciers is fraught with limitations and the possibility for errors. 1986 marked the first volume calculations by Driedger and Kennard, estimating 4.42 km³ of snow and ice in 1970 on Mount Rainier using radar and 1970 contour maps[2]. Much like Sisson in 2011, we attempted to redraw the areas bounds using the 1m 16bit LiDAR hillshade alone. Because of the difficulty and limited knowledge of glaciology, we only analyzed the 29 named glaciers of the recognized 49 perennial snow/ice fields that are on Rainier. Straight away, we began to see significant differences from the 2011 study.

We measured 84.9 km² of glacier cover, Sisson calculated 93.3 km² of total perennial snow and ice cover. Utilizing the 3D Analysis toolset in ArcGIS, we calculated a 3D surface area of 94.1 km² across the same shapefiles using the 10m 1970 DEM.

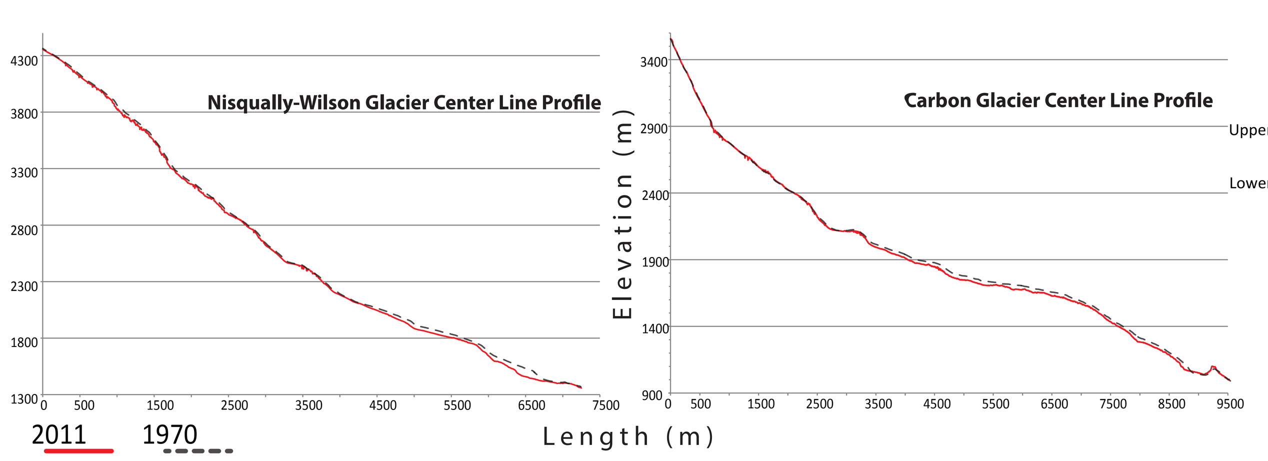
We used both the same differencing method as Sisson and the 3D Analyst tool "Cut-Fill" to calculate the volume change between the 1970 and 2011 DEMs, maintaining a 10m resolution as opposed to resampling to 100m[2]. Both methods resulted in identical output. Ultimately we found a total volume loss of 0.47 km³. Sisson calculated 0.56 km³ across all the same glaciers using the 2008 LiDAR. Despite using the same method, our results are varyingly different across the board. We attribute this random, gross difference to our conservatively digitized shapefiles. We believe it nearly impossible that such volumetric differences could occur over a 3 year span.

In spite of these errors, we were still able to visually produce nearly identical visual outputs as Sisson. Using the same data generation as the recession analysis, we were able to visually see variable correlation. The most dramatic is the nearly uniform equilibrium elevation at 2100m.

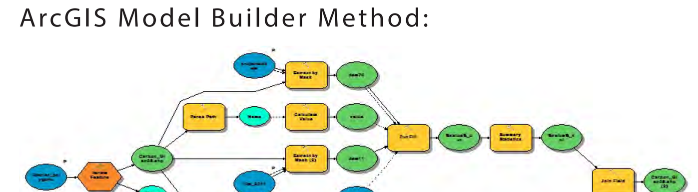
It is our hope that with the increasing use of LiDAR, more precise measurements consisting of shorter time-frames can become regular. Over all we saw the same trends and anomalies as the 2011 research report with respect to volume change on Mount Rainier.

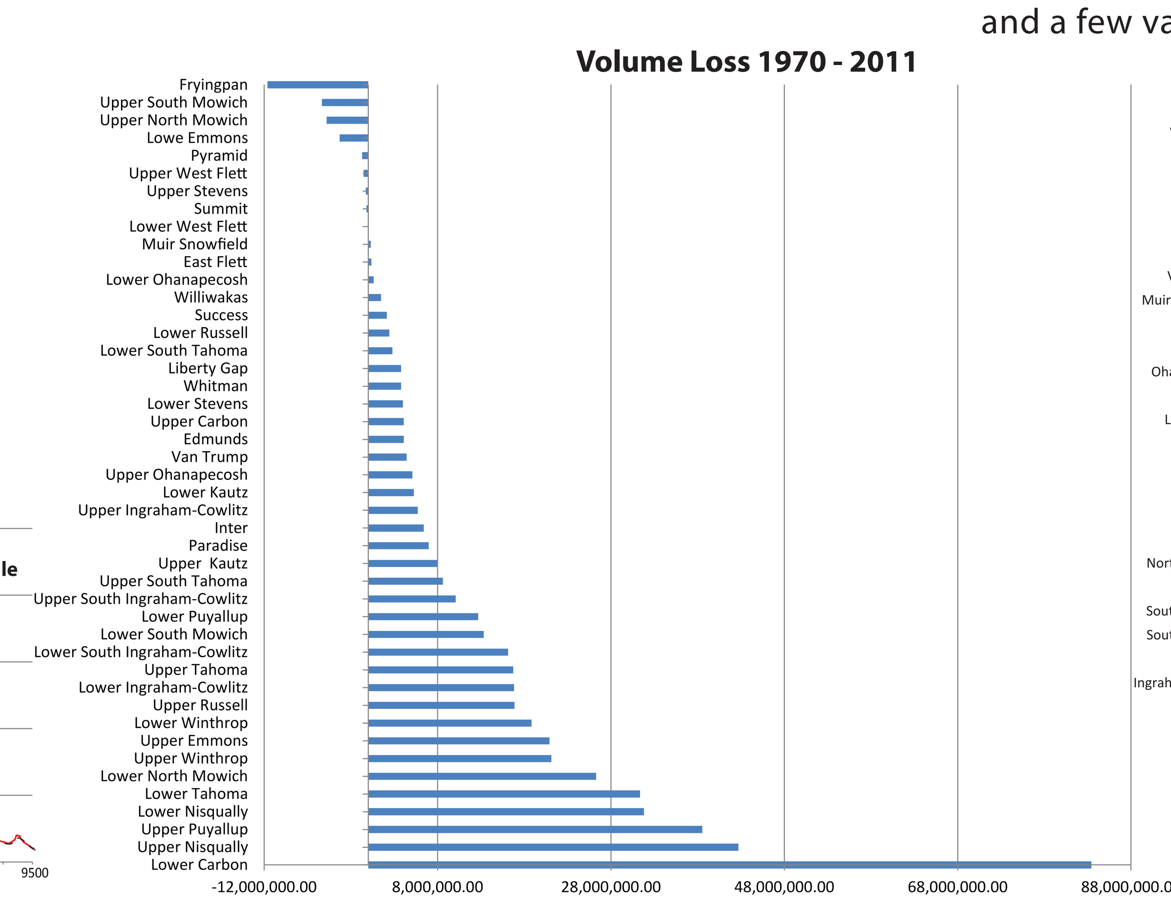
Project			Sisson[2]			
	Volume*	Elevation	Volume*	Elevation	% Volume Diff.	% Elevation Diff.
Carbon Glacier	87.517	-10.7	97.9	-11.1	-10.61	-3.32
Edmunds Glacier	4.0874	-3.2	12.1	-8.8	-66.22	-63.75
Emmons Glacier	17.615	-2.3	-13.8	1.2	-227.64	-288.08
Fryingpan Glacier	-11.621	3.7	-17.2	4.7	-32.44	-22.34
Nisqually-Wilson Glacier	74.515	-17.2	93.5	-20.3	-20.30	-15.38
Russell Glacier	19.308	-6.4	18.7	-5.7	3.25	12.18
South Tahoma Glacier	11.397	-4.3	23.2	-8.1	-50.88	-47.28
Tahoma Glacier	48.087	-5.0	83.3	-10	-42.27	-50.20
Williwakas Glacier	1.472	-14.3	2	-9.4	-26.40	52.55
Winthrop Glacier	39.972	-4.4	24.3	-2.7	64.49	61.96
Over all of Shared Names	471.27		564.8		-16.56	

*Volumes reported in $10^6 m^3$



ArcGIS Model Builder Method:





Recession Analysis

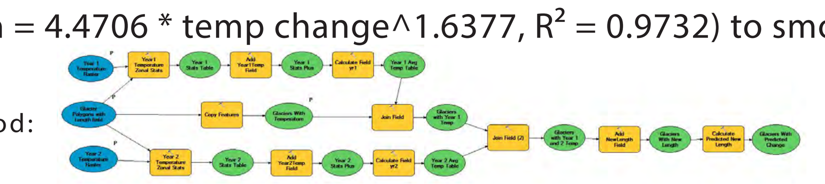
We applied an existing model developed by Johannes Oerlemans[4] to estimate changes in the length of Mt. Rainier's glaciers based on long-term temperature changes. Oerleman's model comes from his analysis of 48 glaciers around the world receding from 1850 onward. He concludes there is an average of 2 km recession per year for a temperature change of 1 degree K, over a period of 94 years. Based on his detailed results, we used a temperature-based recession factor of 21.10501030 meter per year per degree K in our model.

To calculate glacier length, we investigated two alternatives: the length of the minimum bounding rectangle for each glacier polygon and the upstream flow length from a hydrology analysis. Though both yielded similar results (Pearson correlation coefficient = 0.95, p-value = 0.000), the former was chosen as the best fit, as its results were both longer and more consistent with lengths reported in other resources[1,5].

This model was applied to historical Nisqually glacier recession data for the period 1868 to 1960 from Mount Rainier National Park (MORA)[6]. The observed recession was 1.6km, and the model-predicted recession was 1.5km, which is well within the 15% stated error for the model. We chose this model and applied it to all the glaciers on Mt. Rainier for the periods 2006 to 2050 and 2006 to 2099. Average annual temperatures for each year were acquired from NCAR as point shapefiles. Using cokriging, these were combined with the DEM to yield temperature surfaces. Zonal statistics provided the mean temperature for each glacier.

This model was further used to estimate when the glaciers on Mt. Rainier might disappear, based on an exponential regression analysis (recession = 4.4706 * temp change^1.6377, $R^2 = 0.9732$) to smooth the predicted yearly changes in temperature.

ArcGIS Model Builder Method:



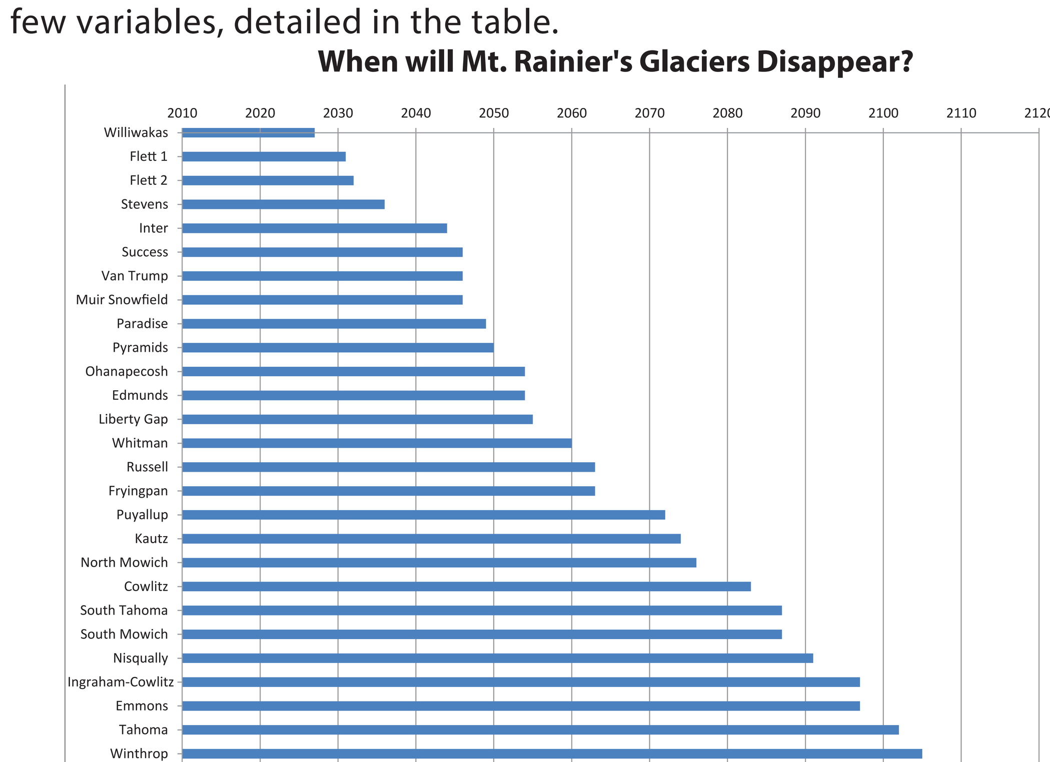
Regression Analysis

We ran ordinary least squares and exploratory regression analysis with calculated yearly length changes for up to 10 of the glaciers on Mt. Rainier, for most of the years between 1919 and 1991. We also ran the same analyses for the volume changes of 29 glaciers over a 44 year span.

The concepts behind this approach came from Nylen's master's thesis and Sisson's 2011 Geology article. Time-based predictor variables included temperatures, precipitation, and carbon dioxide levels. Geomorphological predictor variables included aspect (transformed, then averaged for the glacier), slope (mean), elevation (min, max and mean), length, and area. This analysis did not yield a usable model for predicting length or volume change. However, correlation analysis using this data and the data from the MORA reports[6] indicates there is a significant correlation between glacier change and a few variables, detailed in the table.

Linear Correlations

Variable		Thickness Loss	Recession
Solar Exposure	Pearson Corr.	-0.067	n/a
	Sig.	0.661	
Precipitation	Pearson Corr.	-0.061	n/a
	Sig. (2-tailed)	0.691	
Temperature	Pearson Corr.	-0.04	0.363
	Sig. (2-tailed)	0.793	0.0004
Surface Area	Pearson Corr.	-0.186	n/a
	Sig. (2-tailed)	0.22	
Mean Elevation	Pearson Corr.	-0.506	n/a
	Sig. (2-tailed)	0	
CO_2 (redundant with temperature)	Pearson Corr.	n/a	0.621
	Sig. (2-tailed)		0.000
Winter Snow 5yrs Prior	Pearson Corr.	n/a	0.147
	Sig. (2-tailed)		0.0453
Winter Snow 10yrs Prior	Pearson Corr.	n/a	0.141
	Sig. (2-tailed)		0.0549



Conclusions

Glacier recession can be estimated at a gross level (plus/minus 15%) using changes in temperature and Oerleman's formula, however this is best suited for long periods of time, ideally using smoothed temperature data. As exemplified by volume analysis, accurate estimation on a year-to-year basis depends on too many factors (recent winter snowfall, temperature/CO2, time above freezing, insolation, and geomorphological attributes and anomalies specific to each glacier) to be defined by a simplified equation.

We see that the glaciers on Mt. Rainier and the freshwater they supply may be largely gone by the end of the 21st century based on the A1B moderate-climate-change scenario[3]. Other scenarios offer more or less dramatic increases in temperature, with end-of-century differences around plus or minus 2 degrees C from the A1B. With Oerlaman's model, this might yield differences in glacier recession of plus or minus 4 kilometers.

Data Sources and References: GeoCommunity (geocomm.com) USGS 1970 10m DEM; Puget Sound LiDAR Consortium (pugetsoundlidar.ess.washington.edu) 2011 1m DEM and 16bit Hillshade; National Center for Atmospheric Research (gisclimatechange.ucar.edu/gis-data)(3); Washington State Department of Ecology (ecy.wa.gov/services/gis/data); Department of Commerce, Census Bureau; National Oceanic and Atmospheric Administration (ncdc.noaa.gov/cdo-web and esrl.noaa.gov/gmd/ccgg/trends); Glaciers of the American West (glaciers.us/Downloads)(6); National Snow and Ice Data Center (nsidc.org/data/docs)(5); Nylen, Thomas H., "Spatial and Temporal Variations of Glaciers (1913-1994) on Mt. Rainier and the Relation with Climate Change", Portland State University Master's Thesis, 2001; Oerlemans, Johannes, "Quantifying Global Warming from the Retreat of Glaciers", Science Magazine, 8 April 1994 (sciencemag.org/content/264/5156/243)(4); Sisson, T.W., "Whole-edifice Ice Volume Change A.D. 1970 to 2007/2008 at Mount Rainier, Washington, based on LiDAR surveying", Geology, July 2011, v. 39, no. 7, p. 639-642 (geology.gsapubs.org)(2); National Park Service (nps.gov/mora/naturescience/glaciers.htm)(1).

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