Evolution of Debris Cover on Emmons Glacier, Mount Rainier, Washington

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Abstract

Mount Rainier in Washington State is home to 29 glaciers, 19 of which have significant debris cover. The majority of these glaciers have experienced thinning at the terminus due to increased melting; however, thick debris cover on Emmons Glacier led to thickening at the terminus from 1970 to 2008 as the debris insulated the underlying ice. To better understand how Emmons Glacier is changing, the areal extent of the debris cover and the areal extent of the glacier ice were manually mapped on National Agriculture Imagery Program satellite imagery from 2006 to 2019. Debris cover extent averaged 2.90 km^2, and covered approximately a quarter of the total area of Emmons Glacier. Between 2006 and 2019 the debris covered area increased by 0.13 ±0.1 km^2, although the total area of Emmons Glacier decreased, and the debris covered area decreased at the terminus due to glacier retreat. Increasing debris covered area during a period of decreasing glacier area and terminus retreat indicates that debris cover is expanding up-glacier. This additional debris results from melt out as ice is lost, and may also result from redistribution of the existing debris cover as the surface evolves. In addition, the amount of annual snow cover and ice melt play a role in determining the extent of debris cover. It is expected that debris covered area will continue to increase and expand up-glacier in the future, especially if the amount and seasonal duration of snow cover continues to decrease and the amount of surface melting continues to increase.

Research Question

How has debris cover on Emmons Glacier changed from 2006 to 2019?

Introduction

Mount Rainier is a stratovolcano located within the Cascade Range. Its glaciers and snow fields account for approximately 8.5% of the 956 km^2 of Mount Rainier National Park (Figure 1; Beason, 2017). Debris cover affects how glaciers respond to climate change. Debris cover has been shown to reduce retreat compared to glaciers without debris (Mölg et al., 2019; Tielidze et al., 2020). While the majority of Mount Rainier's glaciers have experienced thinning at the terminus, Emmons Glacier was one of two glaciers that thickened at their termini from 1970 to 2008 (Figure 2). Emmons Glacier's thick debris cover might be why its terminus thickened (Sisson et al., 2011).

Study Area

Emmons Glacier is located on the northeast aspect of Mount Rainier. It is the largest of Mount Rainier's glaciers, and has an extensive debris cover at its terminus (Figure 3; Beason, 2017).

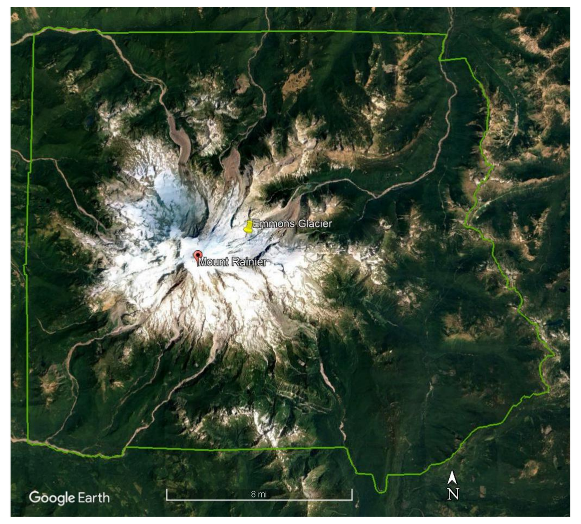

Figure 1. 2018 satellite image of Mount Rainier National Park with Emmons Glacier marked

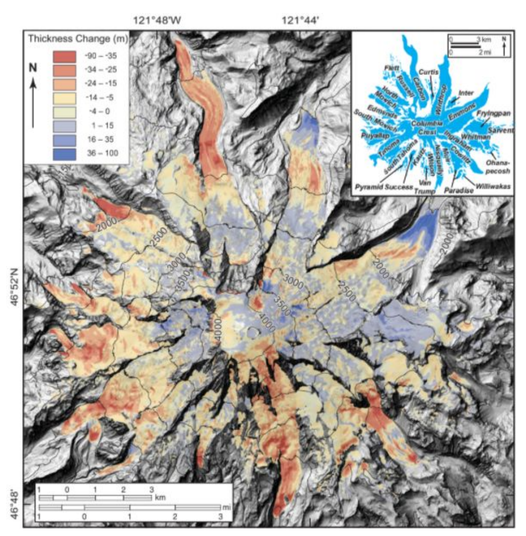

Figure 2. Change in ice thickness from 1970 to 2007/2008 (Sisson et al. 2011)

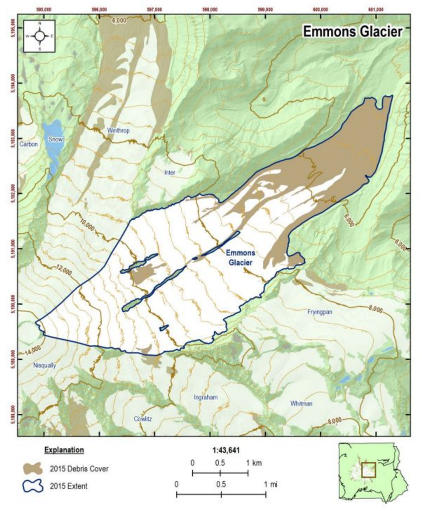

Figure 3. Extent of debris cover on Emmons Glacier in 2015 (Beason, 2017)

Methods

Glacier area and debris cover extent were mapped on satellite imagery from the USDA Forest Service's National Agriculture Imagery Program. Imagery was available for 2006, 2009, 2011, 2013, 2015, 2017, and 2019. Seasonal snow cover, shadows, and dirty ice presented difficulty when mapping (Figure 4; Bhardwaj et al., 2014; Shukla et al., 2010; Paul et al., 2013). Google Earth imagery, Beason's map of debris cover in 2015 (Figure 3), and glacier outlines derived from a 2007/2008 LiDAR of Mount Rainier National Park were used as references when mapping areas with snow and dirty ice (Beason, 2017; Robinson et al., 2010). Straight lines were used across areas completely obscured by shadows.

For each year, debris cover was mapped four times. An exclusive outline and an inclusive outline were each mapped twice, with the first outline used for reference. The exclusive outline only includes areas that could be clearly mapped (Figure 5a). The inclusive outline includes areas of uncertainty due to snow and shadows covering debris (Figure 5b).

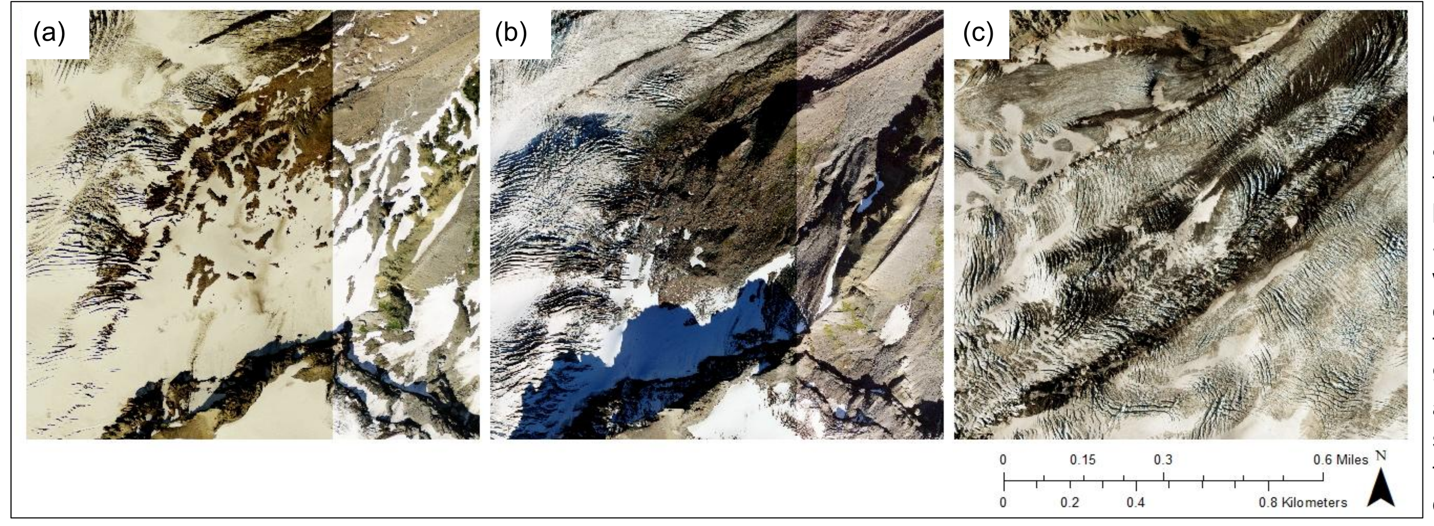

Figure 4. Areas of Difficulty when Mapping. (a) Snow covering debris; 8/16/2011. 4b shows the same area with lighter snow cover. (b) Shadows obscure where debris cover ends and debris next to the glacier begins; 9/28/2017. (c) Dirty ice and debris can have similar color and texture, making them difficult to tell apart; 8/3/2009.

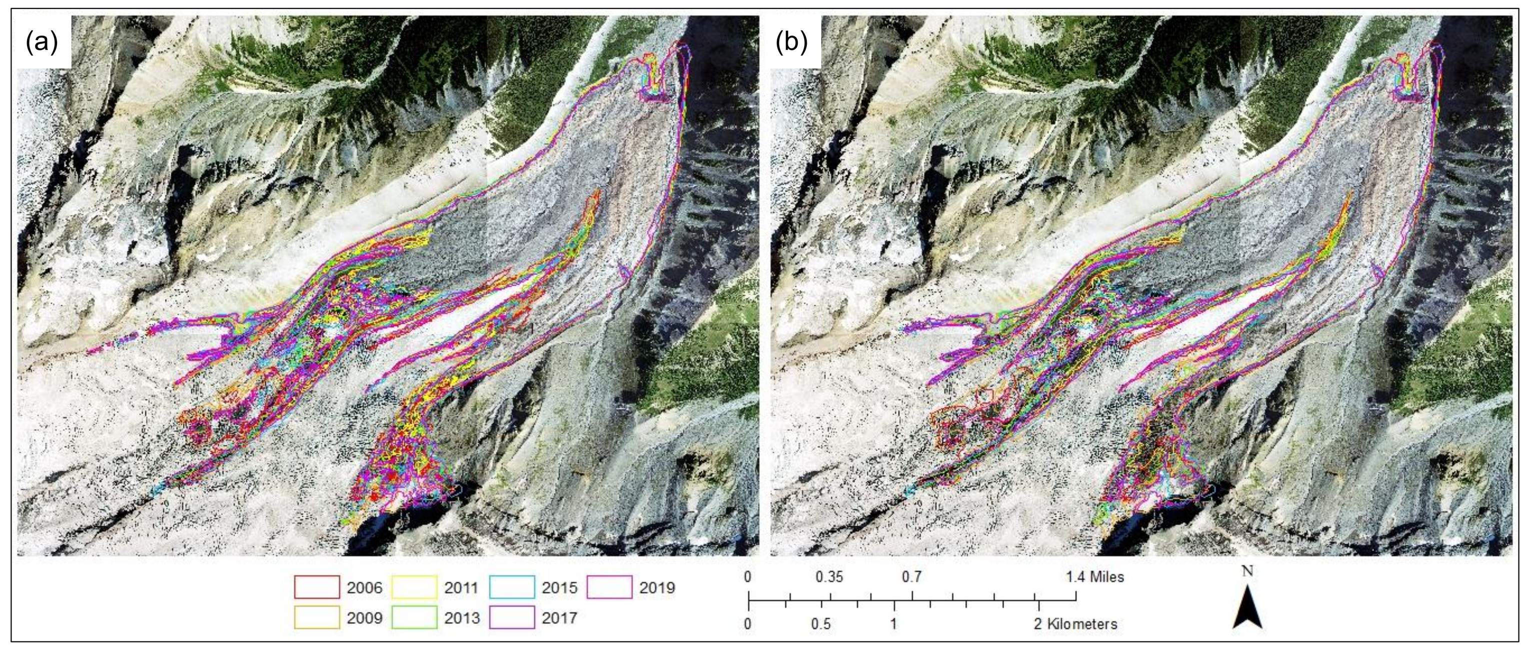

Figure 5. Outlines of debris cover on 8/26/2019 satellite imagery of Emmons Glacier. a. Exclusive outline, which only includes areas of debris that could be clearly mapped. b. Inclusive outline, which includes areas where snow, dirty ice, and shadows created areas of uncertainty.

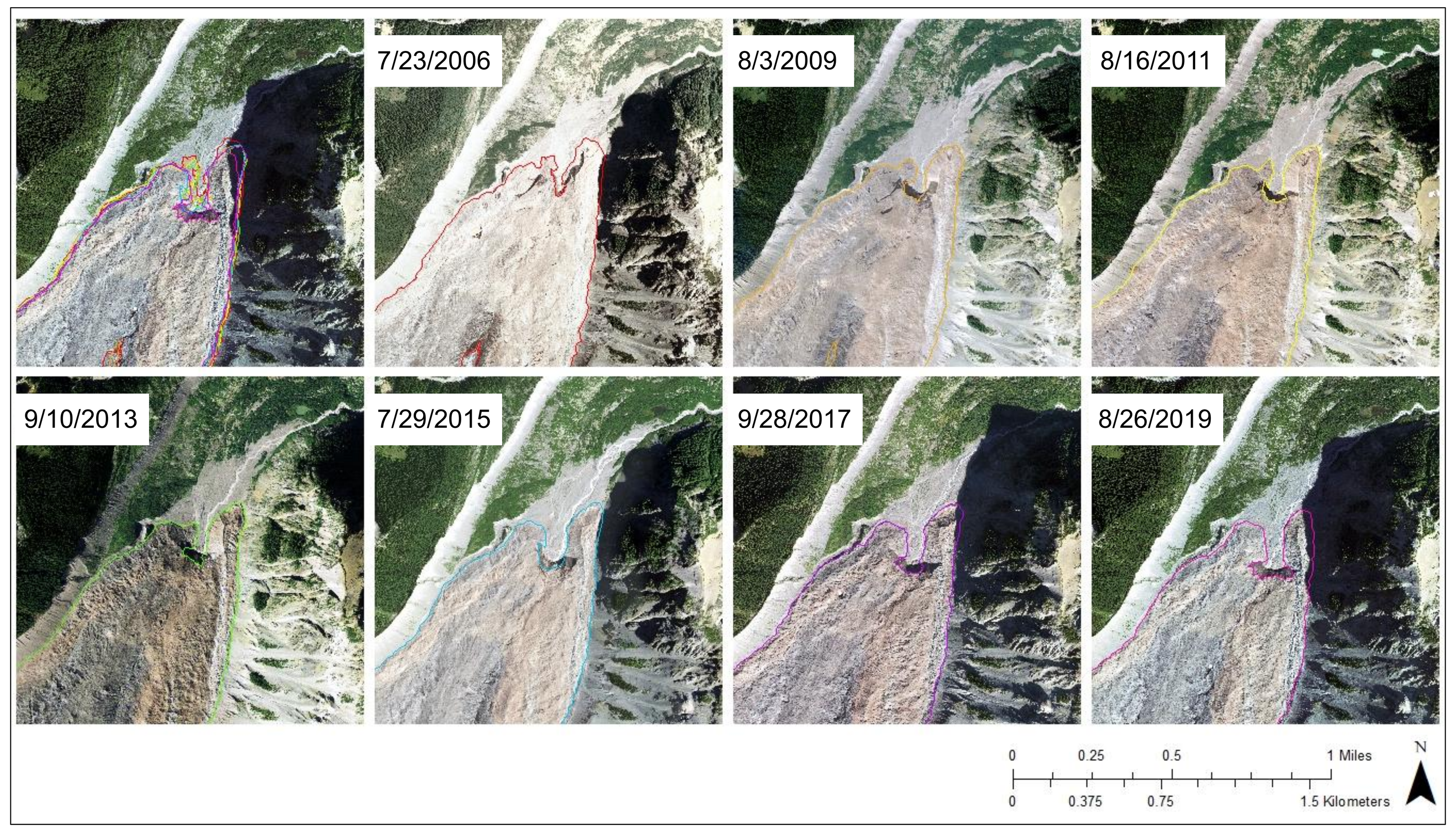

Figure 6. Outline of debris cover at Emmons Glacier terminus. Upper left image is a composite of each year shown individually.

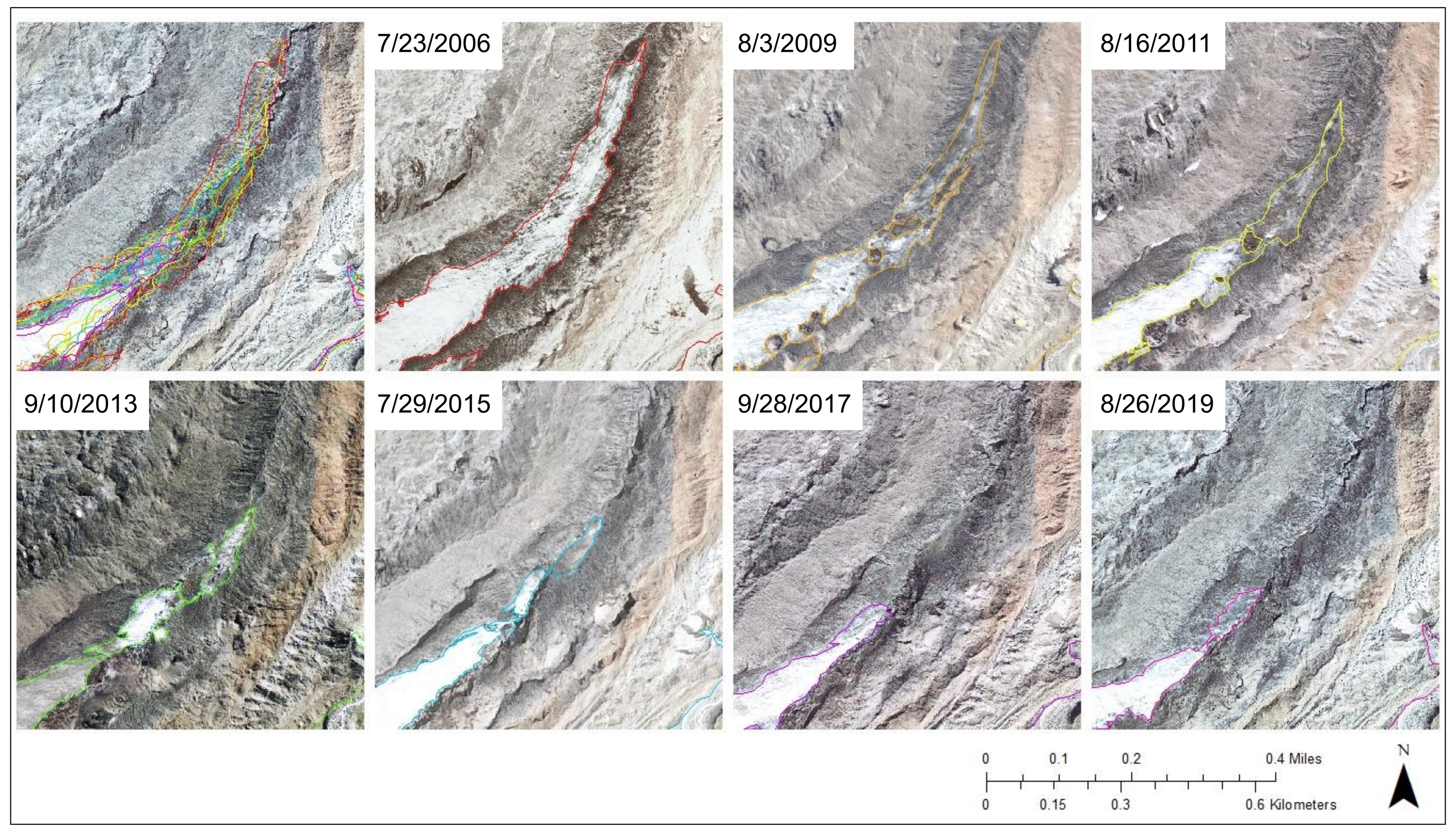

Figure 7. Exclusive outline of the center of the glacier, where the debris cover is extending up glacier and obscuring ice. Upper left image is a composite of each year shown individually.

Acknowledgements

PLU Division of Natural Sciences, PLU Department of Geosciences, National Park Service, Matthew Hacker, Carol Holder and John Mallinckrodt's Glacial Geology Research Fund, NASA SSW award 80NSSC20K0747, Baylee Fontana, Calie Rose, Allison Sheflo, Greta Schwartz

Results

Emmons Glacier

From 2006 to 2019, Emmons Glacier decreased in area by approximately 0.16 km^2 due to terminus retreat (Table 1; Figure 6). Maximum terminus retreat occurred where the White River emerges from the glacier, where the glacier retreated 103 m.

Debris Cover

The average debris covered area overall for 2006 to 2019 is 2.90 ±0.9 km^2. From 2006 to 2019, the debris covered area increased by 0.13 ±0.1 km^2 (Table 1). This increase in debris cover area can be observed in the center of the glacier where ice is increasingly obscured by the debris cover which has extended 483 m up glacier. (Figure 7).

	Emmons Glacier Area (km^2)	Exclusive Debris Cover Area (km^2)	Exclusive Debris Cover Area (%)	Inclusive Debris Cover Area (km^2)	Inclusive Debris Cover Area (%)
7/23/2006	11.34	2.71	23.90%	3.07	27.07%
8/3/2009	11.29	3.15	27.90%	3.42	30.29%
8/16/2011	11.30	2.43	21.50%	2.54	22.48%
8/26/2019	11.18	2.93	26.21%	3.10	27.73%
2006-2019 Average	11.26	2.80	24.87%	2.99	26.56%
2006-2019 Change	-0.16	+0.22	+2.31%	+0.03	+0.66%

Table 1. Glacier area, debris cover area, and percent of glacier area covered in debris. 2013, 2015, and 2017 are mapped, but not included in the table.

Discussion

The area of the glacier that is covered by debris is expanding up glacier to higher elevations (Figure 7). Despite terminus retreat reducing the debris-covered area of the lower glacier, there is still an increase in the total debris-covered area because there is more debris across the upper glacier. This can also be seen on glaciers in the Eastern Alps (Fleischer et al., 2021), the Swiss alps (Mölg et al., 2019), and the Caucasus Mountains (Stokes et al., 2007; Tielidze et al., 2020). Debris accumulates as glacial ice melts, which can initially create a thin debris layer that enhances melting at higher elevations on the glacier. Once the debris cover is thick enough, it may not be stable and debris may be redistributed to nearby areas (Moore, 2018).

The amount and seasonal duration of snow cover and the amount of ice melt play a role in determining the extent of debris cover. 2009 and 2011 exemplify this. 2009 had an above average debris covered area, which can be attributed in part to an equilibrium-line altitude 1000 m above the average for 2003-2009 due to below average winter accumulation (Riedel and Larrabee, 2011). 2011 had a below average debris covered area because above average winter accumulation, as well as a cold and wet spring, led to an almost neutral net mass balance (Riedel and Larrabee, 2015).

The debris covered area is expected to continue to increase and expand up-glacier. We presume that as the debris cover expands up-glacier, it does so initially in a thin layer, which increases melting, allowing for more debris to melt out. If increasing temperatures cause the amount and seasonal duration of snow cover to decrease, and the amount of surface melting to increase, debris-covered area will likely continue to increase.

Conclusions

Emmons Glacier's areal extent has decreased while the extent of the debris covered area has increased. The debris covered area is expanding and filling in up-glacier due to melt out and redistribution of the existing debris cover. The debris covered area is expected to continue to increase due to continuation of current processes, especially if increasing temperatures cause a decrease in snow cover and an increase in melting.

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