SUBMISSION

Quantifying Glacier Retreat on Baranof Island

Tracking Glacial Movement through Remotely Sensed Data

BEN HUGHEY AND ALEXANDRA GIESE

As mountain glaciers melt in response to anthropogenic climate change, they are making a significant contribution to global sea level rise. This paper investigates the history of growth and recession of the Jobildunk Glacier on Baranof Island, in Southeast Alaska. A series of 16 Landsat images and one aerial photo supply a temporal span from 1974 to 2010. Using a modified version of the box method for calculating glacial retreat, we were able to quantify the size of Jobildunk Glacier for 17 individual years over the 36-year time frame. The analysis reveals that the glacier has retreated approximately 860 m since 1974, at a rate of 14 m/year during 1974 – 2001 and an accelerated rate of 48 m/year during 2001 – 2010. Potential reasons for this acceleration include a warming climate, the formation of a proglacial lake and the development of a calving ice cliff terminus.

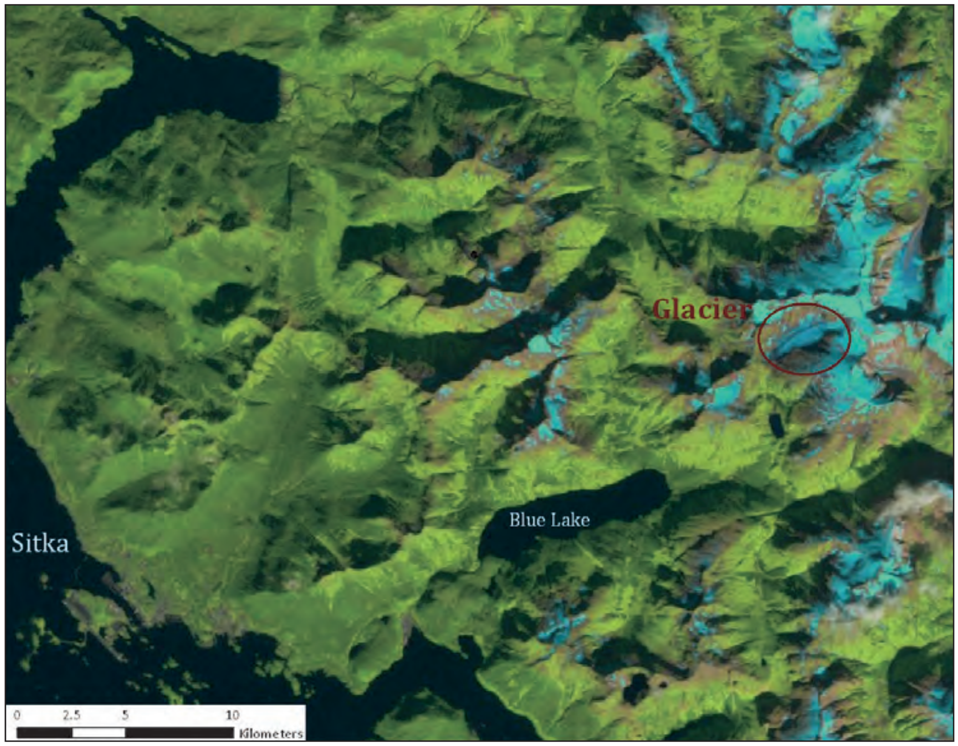

Figure 2: The Jobildunk Glacier in the Blue Lake watershed outside of Sitka. Landsat ETM image from 9 September 2001.

Introduction

Mountain glaciers in Southeast Alaska are of global importance due to their quick response to fluctuations in climate and their significant contribution to global sea level rise. Since glaciers are sensitive to changes in temperature and precipitation, they serve as powerful indicators of climate change (1-3). For a number of years, glacier melt has been accelerating worldwide, leading to global sea level rise (SLR). Between the years of 1951 and 2003, meltwater from mountain glaciers and ice caps contributed 0.51 mm/year to SLR (4). However, that rate of contribution has increased; between 1994 and 2003, the contribution to SLR was estimated to be 0.93 mm/year (4). Recent modeling efforts estimate that from 2001 to 2100, wastage of glaciers and ice caps will amount to an estimated 0.12 +/- 0.04 m contribution to SLR, with the majority coming from glaciers in Arctic Canada, Alaska, and coastal Antarctica (5). It is also projected that the total glaciated area will shrink by 21 +/- 6%, with some areas expected to lose as much as 75% of their current volume (5).

Figure 1: Sitka on Baranof Island in Southeast Alaska (24).

Alaska is a particularly critical region when considering the future of glacier melt and SLR. The state contains approximately 75110 km^2 glaciers; these glaciers, though representing only 13% of global glaciated area, contribute 50% of the SLR from mountain glaciers (6).

Temperate glaciers are comprised of ice near its melting point. Glaciers in coastal areas like in Southeast Alaska, which are typically characterized by high rates of precipitation and very moderate temperatures, are especially responsive to changes in climate (7). Despite their extreme climatic sensitivity, none of the glaciers on the islands of the Alexander Archipelago have been studied in detail (8). In order to gain a better understanding of the causes of glacier retreat in Southeast Alaska glaciers, we chose to explore the history of the Jobildunk Glacier on Baranof Island (9). This glacier was selected in part for its proximity to the city of Sitka (Fig. 2), which would permit easy access for follow-up field measurements . Additionally, some preliminary data had been collected on Jobildunk Glacier by Jonathan Kriess-

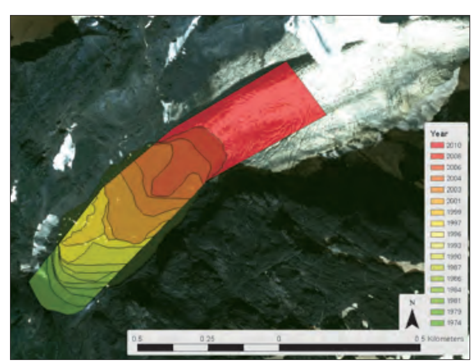

Figure 3: Glacier terminus positions by year (24).

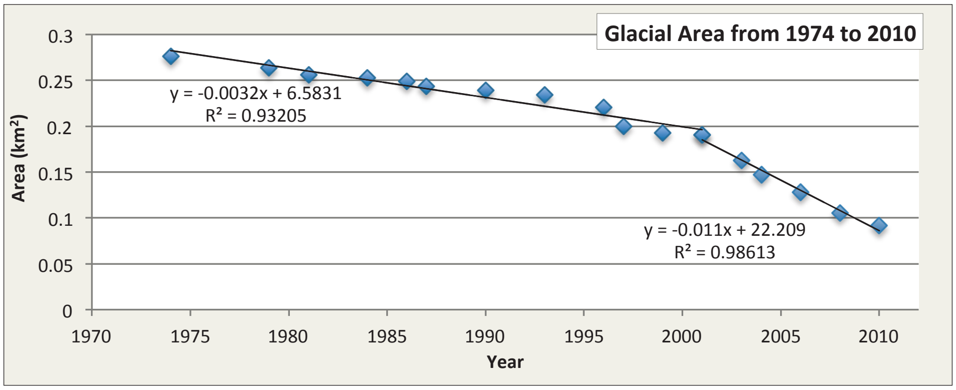

Figure 4: Glacier area (km^2) over time. A marked increase in the rate of retreat is apparent around the year 2001.

Tomkins with support from the Sitka Conservation Society. The Jobildunk Glacier is located approximately 16 km from the open ocean on either side of Baranof Island and is part of the Blue Lake watershed. Blue Lake is a major source of drinking water and hydroelectric power for the city of Sitka. As a result, the health of the glaciers in its catchment basin is of concern to the Sitka residents who depend on Blue Lake as a consistent water source. In 2010, the Jobildunk Glacier measured approximately 945 m at the centerline. It is located at a latitude of 57° 6' N with an elevation ranging from approximately 700 m at its terminus to 800 m at its headwall. In this study, we will be investigating a history of the Jobildunk Glacier's growth and recession in recent decades to understand and quantify its retreat.

Methods

This study employed Landsat imagery due to its uniformity and historic availability. Sixteen images, shot by the Multispectral Scanner (MSS), Thematic Mapper (TM) and Enhanced Thematic Mapper (ETM), provided a temporal span from 1974 to 2010. Additionally, we analyzed a high-resolution U.S. Forest Service aerial photo from 1997 (10). Lastly, a multispectral Worldview scene from 2010 was used as a visual reference to study glacier characteristics (11).

Given that snow cover is present for most of the year at Jobildunk Glacier's elevation, all images were sourced from the end of the ablation season (August, September, or October, depending on availability), allowing us to minimize the potential error from misinterpreting snow as glacial ice.

After examining several images, it became clear that the traditional 'centerline' method would not be the most appropriate approach for this study (12). The Jobildunk Glacier's terminus geometry throughout the past several decades was too dynamic to be captured accurately by a single line. Since the location of the glacier tongue varied laterally from year to year, we decided to employ a modified version of the 'box' method. Similar to the approach of Moon and Joughin, which involved digitizing ice front positions referenced within a three-sided box, we created a reference frame to overlay on each image (14). Our frame, though, is not a box but rather a polygon which better approximates the curve of the glacier; a straight rectangle would miss the southward turn of the flowline and not include the full temporal span of termini positions. The downglacier end of the polygon extends past the earliest and most extensive terminus line (i.e. 1974), while the upglacier end is located behind the most recent and shortest terminus position (i.e. 2010). The reference polygon is narrow enough to avoid the sides of the glacier; accordingly, reported area changes are solely reflective of changes in glacier length. Another advantage of our method relative to the centerline approach is that tracing errors are reduced by averaging over a larger number of pixels. With the centerline method, glacier length changes cannot be detected in finer increments than pixel size (14).

Results

We found that the Jobildunk Glacier retreated dramatically between the years 1974 and 2010 (Fig. 3). Since surface area measurements are recorded within a reference area superimposed on the glacier, reported values represent surface area change only within that reference area rather than over the entire surface, meaning these values represent relative rather than absolute loss. Over the 36-year time-frame, the glacier lost 5,140 m^2/year, corresponding to a retreat of approximately 23 m/year in glacier terminus position. This rate was not constant, however; near the turn of the century, retreat accelerated (See Figure 4). Between 1974 and 2001, glacier area declined at an average rate of 3,200 m^2/year (R2 = 0.932), while after 2001 the rate was 11,000 m^2/year (R2 = 0.986). These correspond to length changes of 14 m/year and 48 m/year, respectively.

Discussion: Process

Delineation of the glacier terminus introduced an inherent error into our analysis due to the 79×79 m and 30×30 m resolution of the Landsat MMS and TM/ETM images, respectively. Terminus tracing was necessarily subjective, but the authors reduced uncertainty through discussion of glacier geometries for the majority of images. The short time intervals between the images (a maximum of 5 yr. and a minimum of 1 yr., with mean = 2.25 yr.) also assisted in terminus recognition (i.e. some consistency in location and geometry was expected year-to-year). The U.S. Forest Service aerial mosaic in the middle of the data series was a particularly useful reference and provided a check for identified terminus locations pre- and post-1997. In addition to the resolution, the presence of a medial moraine presented difficulty in distinguishing the terminus (15). In the area of the moraine, we simply interpolated the well-defined terminus on either side, keeping the approximate geometry dictated by the debris-free ice regions.

Due to the inherent subjectivity and uncertainty associated with terminus delineation in the 17 images, we elected to group authors' measurements by time such that any systematic biases in interpretation would be present only between the groupings. Giese delineated the termini between 1974 and 1999, while Hughey conducted the remainder of the tracings through 2010. Thus, any systematic difference in tracing technique would affect only the change observed in glacier length between the 1999 and 2001 images. We conducted a quantitative assessment of this error through repeated tracing of the 1987 Landsat TM image, which had a resolution, quality, and contrast largely representative of the dataset as a whole. Hughey and Giese traced the terminus 14 times each, with time between interpretations. The standard deviations for Hughey's and Giese's error measurements were 2,073 m² and 2,550 m².

Discussion: Results

Results show a significant trend in glacier terminus retreat—and corresponding surface area—between 1974 and 2010, with an increase in rate beginning near the year 2001.

Given that temperate glacier ice is near its melting point and, therefore, particularly sensitive to climate perturbations, we would expect the Jobildunk Glacier to respond quickly to variations in the temperature record. However, the rate of retreat exhibits no significant correlation with the ablation season (16) temperature record, a climatological variable with demonstrated influence in similar cases (17). Furthermore, if the primary mechanism of retreat were climate forcing, we would expect the Jobildunk Glacier to exhibit a closer response to the Pacific Decadal Oscillation (PDO) index. The PDO is an atmospheric and oceanic circulation pattern that, when in a positive (or 'warm') phase, results in higher air and sea surface temperatures in Southeast Alaska (18). The Lemon Creek Glacier (19), an alpine glacier above Juneau, has been shown to have a strong correlation between mass balance and the PDO index (17). During the positive PDO period of 1976 to 1998, the Lemon Creek gained mass only twice; however, from 1999 to 2001, three consecutive years of positive mass balance were recorded, coincident with a swing in the PDO period to cooler temperatures (19). Although temperature anomalies in Sitka are correlated with the PDO index (see Figure 4), the Lemon Creek record contrasts with our observations, which show a dramatic increase in the rate of retreat during a 'cool' PDO phase. Though the PDO index does turn positive in 2002 for a short period of time, the acceleration in retreat both anticipates and outlasts the upswing in temperatures from 2002 to 2006, suggesting that climate forcing is not the primary causal mechanism of inter-annual variation in the rate of retreat.

Even though the temperature record in Sitka does not strongly correlate with glacial retreat, given the evidence of glacier sensitivity to climate elsewhere in Alaska (17, 21), regional climate patterns likely affected the Jobildunk Glacier throughout our study period. It is possible that the turn to a positive PDO phase in 1976 was a significant contributing factor in the initial formation of proglacial lake.

Since the recent changes in the pattern of retreat observed in the Jobildunk glacier do not follow the expected fluctuations of the PDO, it is likely that a different mechanism is responsible. Kirkbride has identified the deepening of proglacial lakes as a critical threshold for retreat rates (22). Landsat imagery from the 1970s, as well as the 1929 and 1948 aerial photographs not used in the retreat analysis, show that the Jobildunk glacier terminated on land. In the early 1980s, however, images begin showing a lake at the terminus of the glacier. Kirkbride suggests that shallow proglacial lakes contribute to a slight increase in the rate of terminal retreat, but rapid retreat does not begin until the lake deepens to allow calving ice cliffs to form (22). Before 2001, when the terminus position of Jobildunk glacier would have constrained the lake to less than half its current size, it is possible the lake was shallow enough, such that the terminus was more stable. Though we do not observe any distinct retreat acceleration coincident with lake formation, this may be a result of having insufficient imagery predating the lake. If our terminus time series could be extended back, it is possible that a change in retreat rate would emerge. It is also possible that the glacier saw little to no retreat acceleration as a result of its transition to a lake-terminating state until the lake was large and deep enough to pass the threshold permitting terminus destabilization and large volumes of calving.

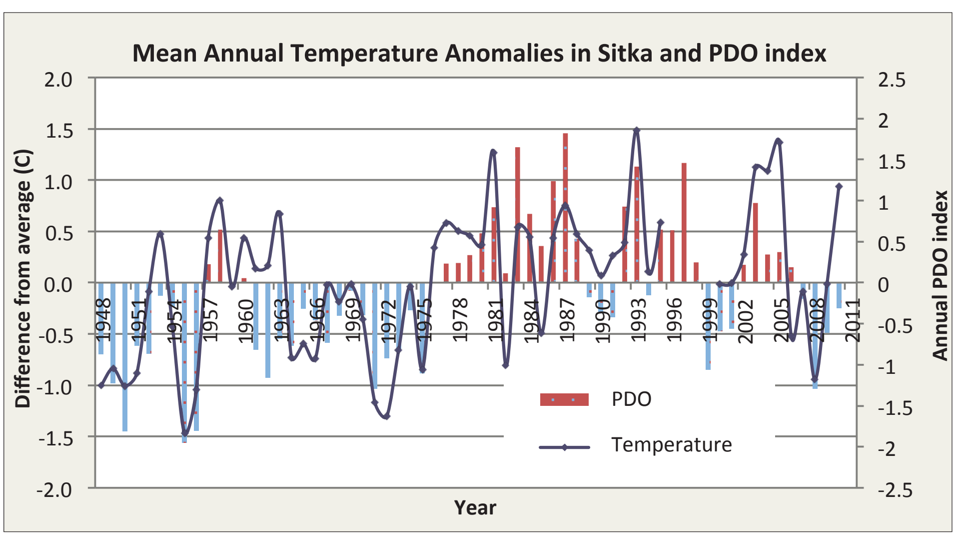

Figure 5: PDO phases color-coded as blue for negative, red for positive (25). Sitka climate data from Japonski airport weather station (26).

Conclusion

Retreat of the glacier in this study since 1974 is incontrovertible; the changes in glacier length far exceed the uncertainties inherent to the interpretation of coarse resolution Landsat imagery. We find that the glacier area shrunk 3,200 m²/year between 1974 and 2001 and 11,000 m²/year between 2001 and 2010, measured within a reference area. This study sought to quantify only the changes in glacier length, and, thus, a more appropriate measure of retreat may be: 14 and 48 m/year. Extrapolating this average retreat rate into the future gives only 26 years before glacier disappearance. It is unlikely the glacier will disappear within this timeframe, given that the glacier may eventually retreat into shallower water and the terminus would stabilize; however, the number serves to provide a sense of the retreat rate. Also illustrative of the magnitude of retreat is a first-order approximation of total surface area change over the entire surface of the glacier, which indicates a 40 percent reduction between 1974 and 2010.

Since our method does not incorporate changes in either the lateral shrinking of the glacier or its thinning, we cannot draw robust, quantitative conclusions about changes in glacier volume or even total surface area. However, terminus retreat is commonly correlated with glacier thinning and volume decline, and this study clearly shows a dramatic retreat in glacier terminus position. Forming a more comprehensive understanding of the glacier's shrinkage over the past several decades requires future investigations of total surface area change as well as ice elevation change. Airborne laser altimetry would be an accurate method of determining thickness of the glacier

(23). Bathymetric measurements of the proglacial lake could aid in substantiating the theory of ice calving as a mechanism for rapid retreat.

Although we did not find a relationship between changes in climate and glacier retreat for the Jobildunk Glacier, it is possible that the effect of the lake masked the influence of temperature fluctuations. The multiple other glaciers on Baranof Island merit studies of their own. Research is needed to show if glaciers on the island not terminating in proglacial lakes exhibit a stronger response to climate forcing.

CONTACT BEN HUGHEY AT BENJAMIN.W.HUGHEY.12@DARTMOUTH.EDU

References

1. B. Fitzharris *et al.*, "Behaviour of New Zealand glaciers and atmospheric circulation changes over the past 130 years" *The Holocene* **2**, 97-106 (1992).
2. W. Haeberli, M. Hoelzle, "Application of inventory data for estimating characteristics of and regional climate-change effects on mountain glaciers: a pilot study with the European Alps." *Ann. Glaciol.* **206** (1995).
3. J. Oerlemans, B. Reichert, "Relating glacier mass balance to meteorological data by using a seasonal sensitivity characteristic," *J. Glaciol.* **4**, 1-6 (2000).
4. M. B. Dyurgerov, M. F. Meier, "Glaciers and the changing earth system: a 2004 snapshot," *Arctic Alpine Res.* OP-58 (2005)
5. V. Radic, R Hock, "Regionally differentiated contribution of mountain glaciers and ice caps to future sea level rise," *Nat. Geosci.* **4**, 91-94 (2011).
6. M. Meier, M. Dyurgerov, "How Alaska affects the world," *Science* **297**, 350-351 (2002).
7. M. Shulski, G. Wendler, The Climate of Alaska (U. Alaska Press, Fairbanks, AK, 2007).
8. B. Molnia, "Glaciers of North America -- Glaciers of Alaska," in R. Williams, J. Ferrigno, Satellite image atlas of glaciers of the world: USGS 1386-K (2008).
9. Jobildunk Glacier is named after a glacial cirque on New Hampshire's Mount Moosilauke.
10. Image identified and dated with help from Craig Buehler, Sitka Ranger District, USFS.
11. Worldview imagery provided by CRREL. This image was not used to digitize a terminus as it duplicated a Landsat scene that provided sufficient resolution.
12. I. Howat *et al.*, "Rapid retreat and acceleration of Helheim Glacier, east Greenland," *Geophys. Res. Lett.* **32**, L22502 (2005).
13. J. Kargel *et al.*, "Multispectral imaging contributions to global land ice measurements from space," *Remote Sens. Environ.* **99**, 187-219 (2005).
14. T. Moon, I. Joughin, "Changes in ice front position on Greenland's outlet glaciers from 1992 to 2007," *J. Geophys. Res.* **113**, F02022 (2008).
15. E. Gjermundsen *et al.*, "Assessment of multispectral glacier mapping methods and derivation of glacier area changes, 1978-2002, in the central Southern Alps, New Zealand, from ASTER satellite data, field survey and existing inventory data." *J. Glaciol.* **57**, 667-683 (2011).
16. Ablation season approximated by months of April through September, following Criscitiello (17).
17. A. Criscitiello, M. Kelly, B. Tremblay, "The response of Taku and Lemon Creek Glaciers to climate," *Arct. Antarct. Alp. Res.* **42**, 34-44 (2010).
18. C. Bitz, D. Battisti, "Interannual to decadal variability in climate and the glacier mass balance in Washington, Western Canada, and Alaska," *J. Climate* **12**, 3181–3196 (1999).
19. The Lemon Creek Glacier is relatively small, close to the ocean and about 150 km from Sitka, making it an ideal candidate for comparison.
20. M. Miller, M. Pelto, "Mass Balance Measurements On The Lemon Creek Glacier." (2011). Available at http://www.nichols.edu/departments/glacier/Lemon.html (May 20, 2012).
21. S. Hodge *et al.*, "Climate variations and changes in mass of three glaciers in western North America," *J. Climate* **11**, 2161–2179 (1998).
22. M. Kirkbride, "The temporal significance of transitions from melting to calving termini at glaciers in the central Southern Alps of New Zealand," *The Holocene* **3**, 232-240 (1993).
23. A. Arendt *et al.*, "Rapid wastage of Alaska glaciers and their contribution to rising sea level," *Science* **297**, 382–386 (2002).
24. National Climate Data Center (NOAA), Climate Data Online. (2012). Available online at http://www.ncdc.noaa.gov/cdo-web/ (May 20, 2012).
25. N. Mantua, The Pacific Decadal Oscillation (PDO). (2012). Available at http://jisao.washington.edu/pdo/ (May 20, 2012).
26. Background imagery from National Geographic World Basemap, ESRI ArcMap 10.

Acknowledgements

We thank Jonathan Kriess-Tomkins for the impetus to pursue research of this glacier, the Sitka Conservation Society, for their original contribution to the study of the glacier, as well as for facilitating comments, Scott Harris and Matt Goff, for their valuable input, and Jonathan Chipman, for advice in the science of remote sensing.