



Ice Thickness Measurements on the Harding Icefield, Kenai Peninsula, Alaska

Natural Resource Data Series NPS/KEFJ/NRDS—2014/655





ON THIS PAGE

The radar team is descending the Exit Glacier after a successful day of surveying
Photograph by: M. Truffer

ON THE COVER

Ground-based radar survey of the upper Exit Glacier
Photograph by: M. Truffer

Ice Thickness Measurements on the Harding Icefield, Kenai Peninsula, Alaska

Natural Resource Data Series NPS/KEFJ/NRDS—2014/655

Martin Truffer

University of Alaska Fairbanks
Geophysical Institute
903 Koyukuk Dr
Fairbanks, AK 99775

April 2014

U.S. Department of the Interior
National Park Service
Natural Resource Stewardship and Science
Fort Collins, Colorado

The National Park Service, Natural Resource Stewardship and Science office in Fort Collins, Colorado, publishes a range of reports that address natural resource topics. These reports are of interest and applicability to a broad audience in the National Park Service and others in natural resource management, including scientists, conservation and environmental constituencies, and the public.

The Natural Resource Data Series is intended for the timely release of basic data sets and data summaries. Care has been taken to assure accuracy of raw data values, but a thorough analysis and interpretation of the data has not been completed. Consequently, the initial analyses of data in this report are provisional and subject to change.

All manuscripts in the series receive the appropriate level of peer review to ensure that the information is scientifically credible, technically accurate, appropriately written for the intended audience, and designed and published in a professional manner.

This report received informal peer review by NPS managers and subject-matter experts who were not directly involved in the collection, analysis, or reporting of the data.

Views, statements, findings, conclusions, recommendations, and data in this report do not necessarily reflect views and policies of the National Park Service, U.S. Department of the Interior. Mention of trade names or commercial products does not constitute endorsement or recommendation for use by the U.S. Government.

This report is available in digital format from the Natural Resource Publications Management website (<http://www.nature.nps.gov/publications/nrpm/>). To receive this report in a format optimized for screen readers, please email irma@nps.gov.

Please cite this publication as:

Truffer, M. 2014. Ice thickness measurements on the Harding Icefield, Kenai Peninsula, Alaska. Natural Resource Data Series NPS/KEFJ/NRDS—2014/655. National Park Service, Fort Collins, Colorado.

Contents

	Page
Figures.....	iii
Abstract.....	v
Acknowledgments.....	vii
Introduction.....	1
Methods.....	3
Radio echo sounding	3
Results.....	7
Ground-based surveys	7
Discussion and Conclusions	9
Literature Cited	13

Figures

	Page
Figure 1. Ground-based radio echo sounding survey	3
Figure 2. Radar echo showing the electromagnetic wave amplitude versus time in microseconds.....	4
Figure 3. Radargram showing wave intensity versus depth for a series of 1900 traces on the upper Exit Glacier	5
Figure 4. Ice depths derived from a ground-based radar survey of the upper Exit Glacier	7
Figure 5. Ice depths derived from an airborne radar survey of the Harding Icefield.....	8
Figure 6. Comparison of ground based and airborne data	9
Figure 7. Transect across Bear Glacier	10

Abstract

Ongoing changes in glacier ice volume and extent have impacts on the local and global level. An accurate assessment of these impacts requires knowledge of the current ice thickness distribution. Radio echo sounding is a proven method to obtain ice thickness reliably in temperate ice. Here, a radar system was developed that could be deployed by a small team on skis for ground-based surveys or scaled up for airborne surveys. The ground-based survey proved more reliable for surveys in narrow valleys, while the airborne survey allowed for large data coverage that worked particularly well over an open ice field. The system was deployed in both configurations over the Harding Icefield. Maximum ice thickness exceeds 650 m on the Bear Glacier, indicating that it is grounded well below sea level. The ice thickness on the ice field proper reached values up to 450 m.

Acknowledgments

Several people were helping with field work on Exit Glacier: M. Habermann, F. Klasner, C. Lindsay, and M. Tetreau. The airborne radar work was carried out with the help of pilot P. Claus and Steve Davidson. The work was financed by a grant from the National Park Service.

Introduction

The Harding Icefield is one of several low elevation ice fields in Alaska. It is located entirely within the Kenai Fjords National Park and the Kenai National Wildlife Refuge. With an area of about 1,800 km², it is the largest ice field contained in its entirety within the United States (Adalgeirsdottir et al., 1998). The icefield consists of a central plateau, primarily between 1,200 and 1,400 m above sea level, with outlet glaciers descending downwards, several all the way to sea level.

Between the mid-1950s and mid-1990s the ice field has lost an average of 0.47 m/yr of elevation (Adalgeirsdottir et al., 1998), a rate that has increased by a factor of about 1.5 in the years between 1995 and 1999 (VanLooy et al., 2006). Both studies show little or no elevation changes at higher elevation, but this result is confounded by known map inaccuracies in the accumulation area. Concomitant with the thinning is a general retreat of the tidewater glaciers, although at greatly different rates. While Northwestern Glacier has lost over 5 km since the mid-1950s, others have remained nearly stationary (McNabb, 2013). Land terminating glaciers are also retreating, as evidenced at the well-visited Exit Glacier.

Estimates of the equilibrium line altitude (ELA) vary greatly. This altitude separates the lower areas of annual mass loss from the upper areas of net annual mass gain. It has been estimated as low as 600-700 m above sea level (a.s.l.) on the Holgate and Aialik Glaciers and between 900-1200 m a.s.l. on the Northwestern Glacier (Viens, 1995). If further warming were to result in a rise of the ELA to the elevation of the ice field's plateau, a well-known instability would be triggered, where continued thinning of the ice field exposes it to ever lower elevations and therefore higher temperatures and melt (Bodvardsson, 1955).

While glaciers in the non-polar regions make up a relatively small amount of the planet's ice mass, they currently change so rapidly that they rival the ice sheets as contributors to global sea level. This is particularly true for Alaska, which is one of the hot spots of current ice volume loss (e.g. Arendt et al., 2002; Larsen et al., 2007; Berthier et al., 2010). But in addition to global significance, glacier change has profound regional effects that range from changes in hydrology, sediment transport, ecology of freshly exposed land and ocean, and coast line changes resulting from isostatic adjustment of the land, as it is relieved of the weight of the ice.

Assessments of future changes to landscapes under different climate change scenarios are invariably hampered by the lack of knowledge of subglacial topography. The shape of the bedrock underlying the glaciers determines whether glacier advance or retreat occurs in a stable or unstable fashion. Glaciers with beds that deepen in the upglacier direction are prone to unstable retreats, where an initially small perturbation can lead to large changes. In extreme cases this can lead to the disappearance of entire ice fields; this happened at Glacier Bay (Larsen et al., 2005). On the other hand, rising subglacial terrain at elevations well above sea level generally leads to stabilizing feedbacks. The subglacial topography also determines whether glacial retreat will lead to longer fjords, the formation of lakes, or the exposure of new land. Finally, ice thickness data lead to better estimates of the total volume of ice stored in a glacier. While some progress has been made in deriving ice thickness from surface measurements (Farinotti et al., 2009; McNabb et al., 2012; Huss and Farinotti, 2012), they still need to be constrained by actual measurements of ice thickness.

Here we report on a series of ice thickness measurements carried out by radio echo soundings. A first field effort was ground-based and concentrated on the Exit Glacier. This was followed by an airborne radar survey with the intent of mapping ice thickness more broadly.

Methods

Radio echo sounding

Radio echo sounding is the most commonly used technique to find the ice thickness on glaciers and ice sheets. The physical principle is based on sending an electromagnetic wave through the ice and measure the return time of the wave that is reflected at the boundary to the underlying material. A good dielectric contrast between ice and most substrates often results in clearly identifiable returns. Radio echo sounding poses a special challenge on temperate glaciers, however. These are glaciers with temperatures at their pressure melting point, and they contain pockets of water throughout. The water content leads to increases in scattering and absorption and a decrease in returned signal strength. This can be offset by higher transmitting power and also by using longer wavelength radio waves. The drawbacks of longer wavelengths are decreased resolution and the requirement of longer antennas.



Figure 1. Ground-based radio echo sounding survey. The transmitter and receiver are towed on sleds that are separated by resistively loaded antennas.

The work reported here was carried out in two stages. First, we conducted a ground-based survey, dragging the transmitter and receiver with their antennas on a ski traverse of Exit Glacier. Then we redesigned and expanded the system with a faster digitizer and flew an airborne survey over most of the Harding Icefield. The advantage of the airborne survey is that a large area can be surveyed in a short time. But the results tend to become difficult to interpret over outlet glaciers, since it is difficult to fly cross profiles, and reflections from the side can lead to clutter and dominate the signal. Ground-based surveys are much slower, of course, but they tend to work better in narrow valleys, as

long as the glacier is not too crevassed to work in. A typical set-up for ground surveys is shown in Figure 1.

We used a Kentech radar pulser to create a high energy radar pulse that was sent out over a resistively loaded antenna to avoid ringing, following the general principle outlined by Watts and England (1976) and Narod and Clarke (1994). An identical receiving antenna is connected to a digitizer and data are recorded on a computer. For the ground-based radar we used a USB oscilloscope as digitizer with a ruggedized field computer. For the airborne system we adapted a Real-Time National Instrument digitizer to allow high rates of data acquisition and enough storage capacity. The setup was similar to that described by Conway et al. (2009).

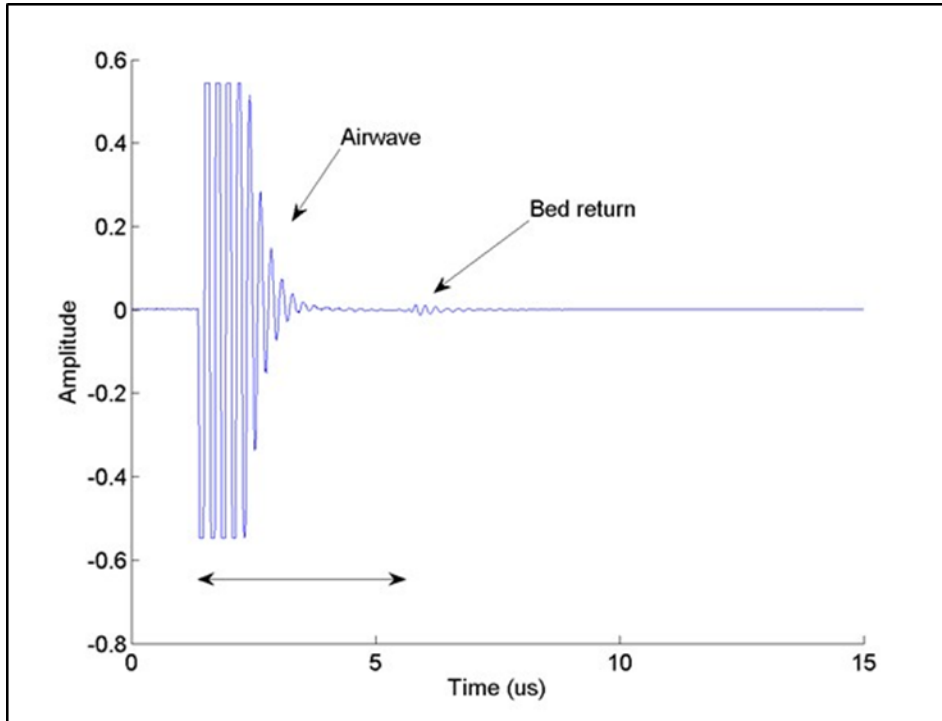


Figure 2. Radar echo showing the electromagnetic wave amplitude versus time in microseconds. Data acquisition is triggered by the air wave and the time difference to the bed return determines the two-way travel time.

Figure 2 shows an example of a recorded wave that shows a clear bedrock return. The data acquisition is triggered by the arrival of the airwave, which travels at the speed of light in air the known distance from the phase center of the transmitter to the receiver. The time delay to the arrival of the bedrock return indicates the two-way travel time, which is then used to determine the depth of the ice. The speed of the radar wave in ice is assumed to be 169 m/ μ s.

A common way of displaying a series of waveforms, such as those in Figure 2, is to show an intensity versus depth plot for each trace in a transect (Fig. 3). This allows for a quick visualization of the topography underlying the glacier. Here we took all acquired radar transects and digitized the bedrock return where it was unambiguously discernible. We estimate that the two-way travel time can be determined to the nearest 0.1 μ s, which leads to an error in ice depth of 8.5 m. An additional

uncertainty stems from the assumed value of the wave velocity in ice. That uncertainty (about 2 m/ μ s) leads to an error in ice thickness that scales with ice thickness. For a typical value of 500 m it leads to 6 m of error. If we assume that the two error sources are independent, we obtain an estimated total error of 10 m.

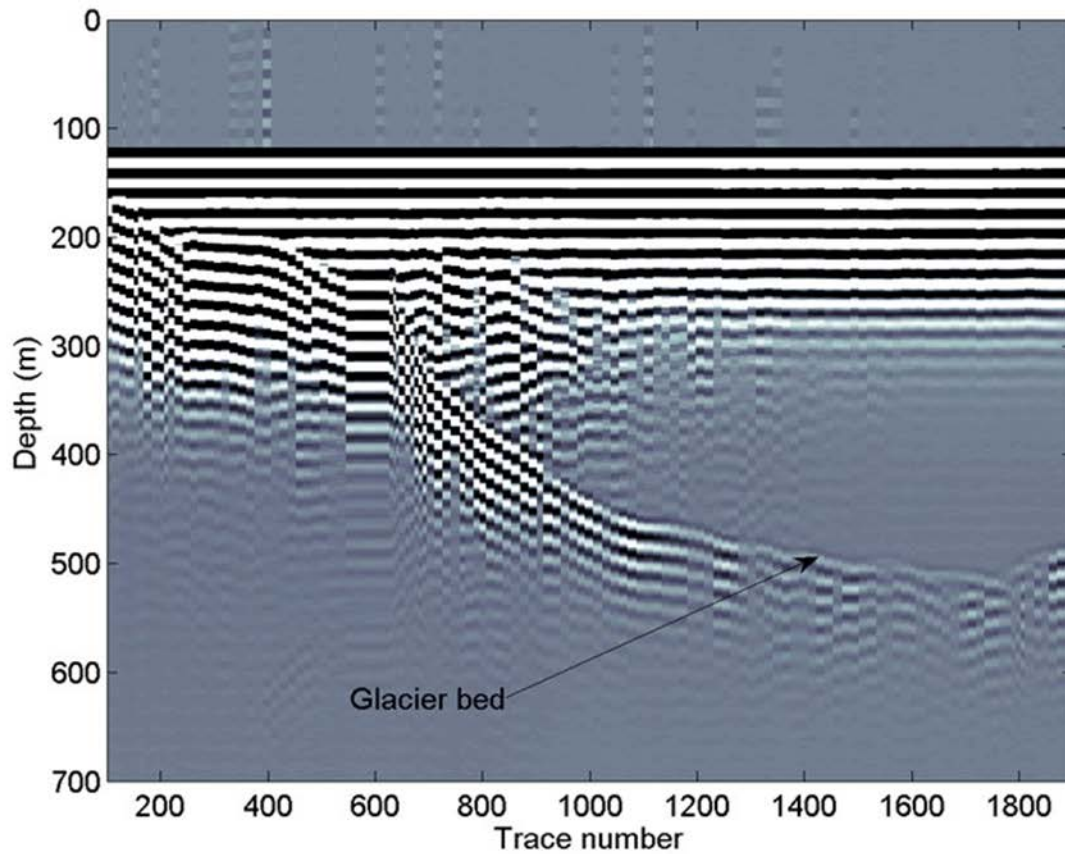


Figure 3. Radargram showing wave intensity versus depth for a series of 1900 traces on the upper Exit Glacier. The upper flat line marks the arrival of the airwave and an arbitrary offset for the depth scale. The lower line marks the location of the glacier bed.

Results

Ground-based surveys

We conducted a two-day ski survey of the upper parts of Exit Glacier in March 2010. The reduced data are shown in Figure 4. The narrow geometry of Exit Glacier makes it better suited for ground-based surveys, and we generally obtained good results. The deepest ice was recorded in the upper most areas of Exit Glacier, near the ice divide and exceeded 450 m.



Figure 4. Ice depths derived from a ground-based radar survey of the upper Exit Glacier. The background image is from Google Earth. The transects are color coded with ice depth in meters.

The ground-based survey was followed up by a much more extensive airborne survey. Results are shown in Figure 5. In one area, the airborne profile crossed a ground-based traverse with excellent agreement of the results.

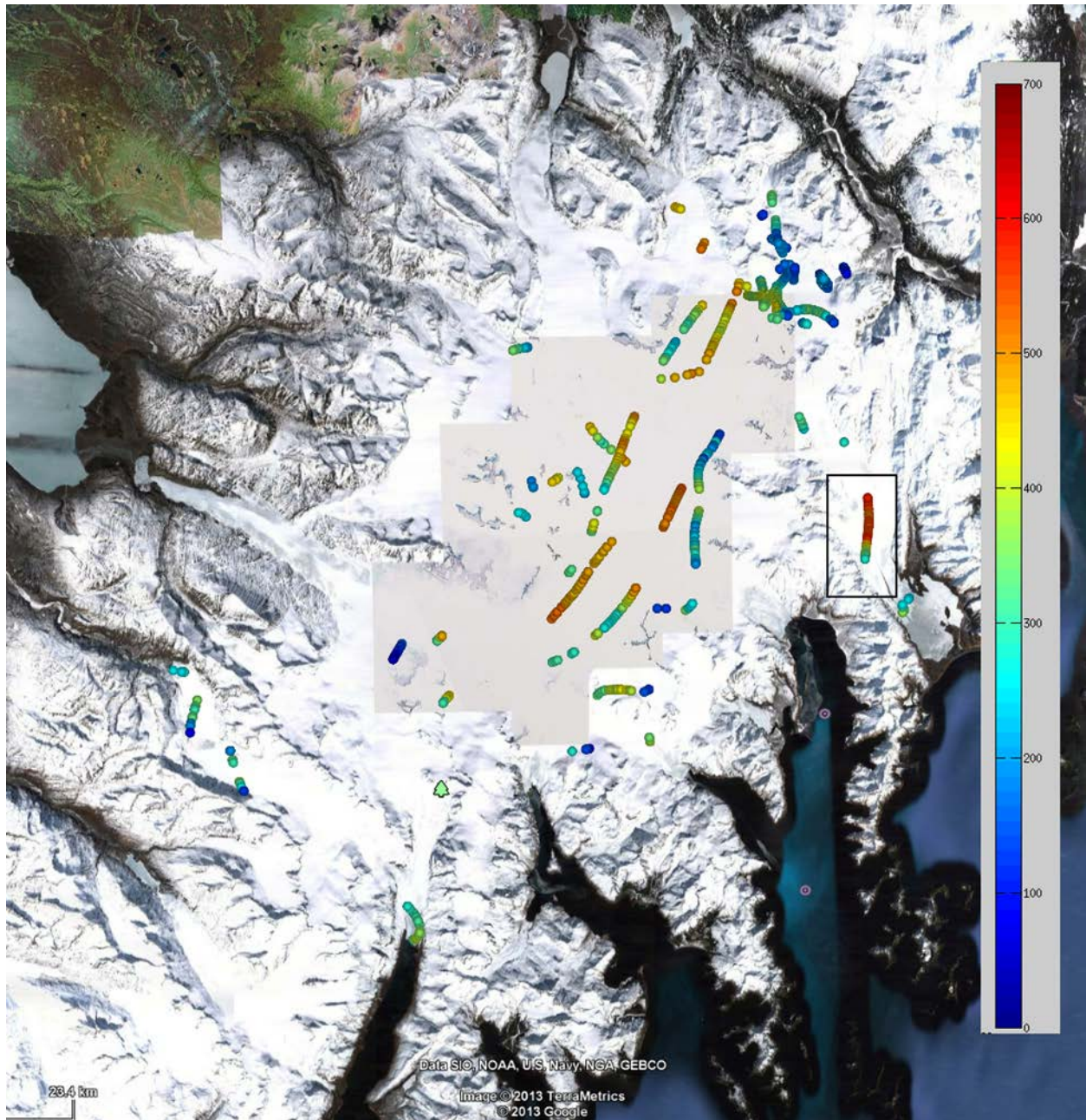


Figure 5. Ice depths derived from an airborne radar survey of the Harding Icefield. The background image is from Google Earth. The transects are color coded with ice depth in meters. The area on Bear Glacier (black box) is shown in more detail in Figure 7.

Discussion and Conclusions

We have successfully built and tested a modular radio echo sounding system that can be used in a light weight configuration by a small group on skis, or at a high data rate configuration in airborne surveys. Ground surveys resulted in nearly complete useful data recovery. Airborne surveys naturally cover a much larger area, but data interpretation is more difficult. Depending on surface conditions, bed returns can be weaker and ambiguous. In narrow valleys, the signal is routinely hampered by clutter from valley wall returns, which obscures bed returns. Figure 5 only shows data that we were certain represented bed reflections. It is possible that more advanced data processing techniques could expand that data set, particularly on the open ice field, where valley wall reflections should not be an issue. It is, however, not always clear why certain areas of the bed appear easier to image than others. In narrow valleys, experiments with flying the radar at different heights above ground might reveal at which optimal flight altitude sufficient signal strength can be obtained with minimal side valley clutter. Potentially, this could be done by simulating the radar response, using an accurate digital elevation model.

At two locations in the upper Exit Glacier the flight line crossed the ground tracks. A direct comparison of ice thickness from both surveys showed excellent agreement (Fig. 6).

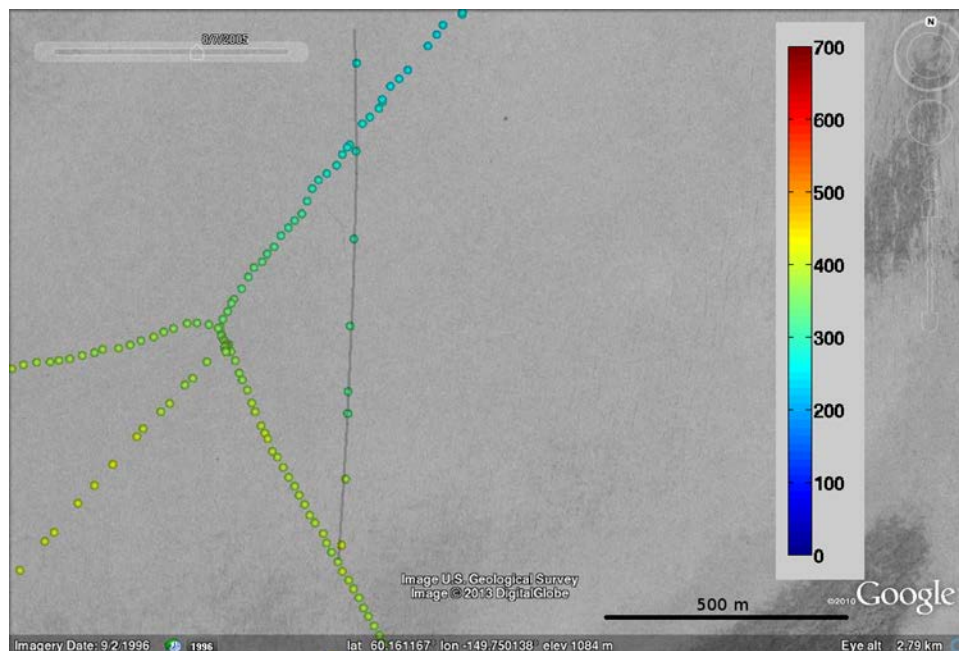


Figure 6. Comparison of ground based and airborne data. Ice depths along the light gray line were derived from an airborne radar survey, the others from the ground based survey. Depths obtained within less than 100 m agree to better than 20 m. The background image is from Google Earth. The transects are color coded with ice depth in meters.

The deepest ice recorded in the survey was on the Bear Glacier at just over 600 m depth (Fig. 7). This occurs along a line where current surface elevations are between 400 and 450 m and indicates that a continued retreat of Bear Glacier would result in a substantial lake that could more than double the size of the current lake. The maximum recorded depth on the ice field proper was 564 m at a surface

elevation of about 1,300 m a.s.l. The results indicate that the ice field is grounded well above sea level, but substantially below the current equilibrium line.

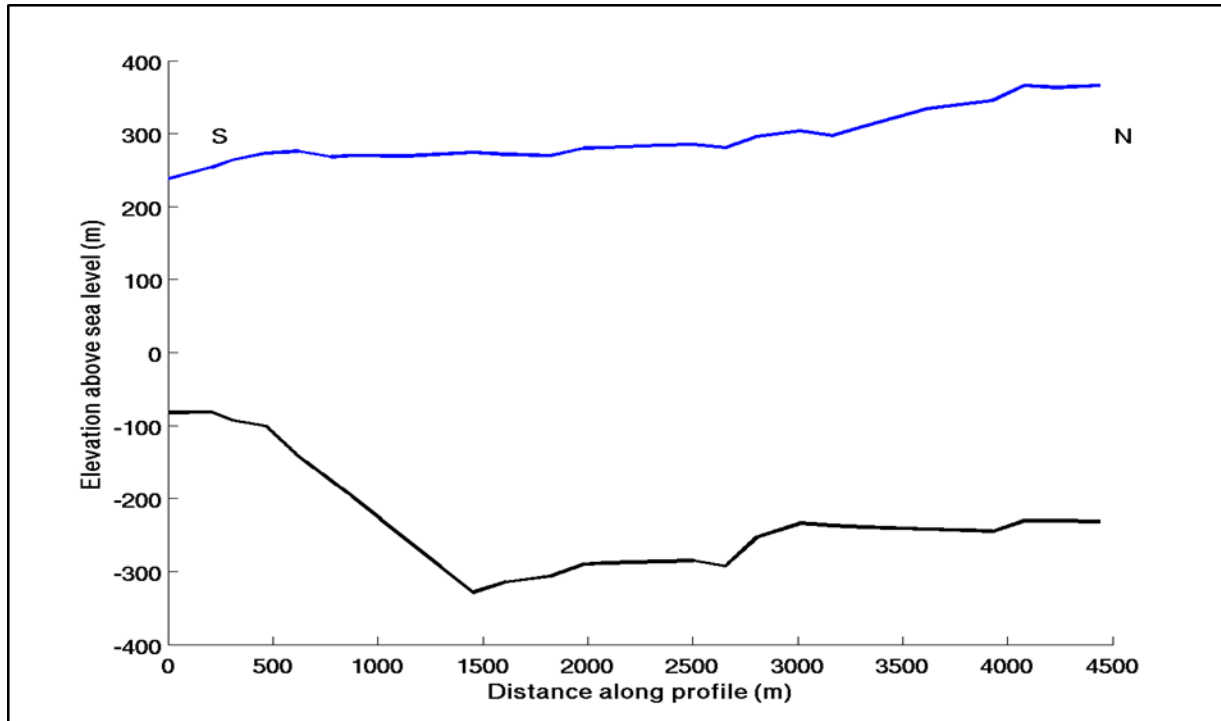


Figure 7. Transect across Bear Glacier. The area is shown in Figure 5 with a black box. The glacier bed is well below sea level at this location. Surface elevation is extracted from the ASTER Global DEM, which is a product of METI and NASA.

Low-lying ice fields are particularly vulnerable to a warming climate. Glaciers react to a warming climate both by thinning and by retreat. Glacier retreat is a stabilizing effect, because it reduces glacier area at the very lowest elevations, where the ice is subject to higher melt rates. Glacier thinning, however, leads to a lower average elevation of the glacier surface, which increases the average mass loss and therefore leads to unstable behavior (e.g. Elsberg et al., 2001). Once the equilibrium line reaches the upper parts of the ice field, the response can become unstable and the ice field will disappear entirely, even without further warming. This is believed to occur on the Yakutat Icefield, where the ice divides are located at or below 700 m a.s.l. (Truessel et al., 2013). Harding Icefield is located at higher elevation and is currently not experiencing an unstable response. However, if current warming trends persist, the equilibrium line could reach the elevation of the plateau. At that point the glacier response to climate would become unstable. Since much of the ice fields base is situated below the current ELA, most of the ice field would disappear under such a scenario, with the exception of small glaciers on higher elevation bedrock outcrops.

Generally, the ice thickness results on the various outlet glaciers are sparse, but those from Bear Glacier indicate a grounding well below sea level. This indicates that the retreat of the glacier could be unstable, because a retreat cannot reduce the exposure of ice to low elevation and high rates of surface melting (e.g. Mercer, 1961). Further conclusions about the retreat of the ice field's outlet glaciers would require additional measurements of ice thickness. These would more reliably be done

on the ground, if feasible. Combining sparse measurements with modeling, such as that of McNabb et al. (2012) is also a promising future step.

Literature Cited

- Adalgeirsdóttir, G., K.A. Echelmeyer, and W.D. Harrison. 1998. Elevation and volume changes on the Harding Icefield, Alaska. *J. Glaciol.*, 44(148), 570–582.
- Arendt, A. A., K. A. Echelmeyer, W.D. Harrison, C. S. Lingle, and V. Valentine. 2002. Rapid Wastage of Alaska Glaciers and Their Contribution to Rising Sea Level. *Science* 297 (5580). doi:10.1126/science.1072497.
- Berthier, E., E. Schiefer, G.K.C. Clarke, B. Menounos, and F. Rémy. 2010. Contribution of Alaskan Glaciers to Sea-level Rise Derived from Satellite Imagery. *Nat. Geosci.* 3 (2) (January): 92–95. doi:10.1038/ngeo737.
- Bodvardsson, G. 1955. On the flow of ice-sheets and glaciers. *Jokull*, 5.
- Conway, H., B. E. Smith, P. Vaswani, K. Matsuoka, E. Rignot, and P. Claus. 2009. A Low-frequency Ice-penetrating Radar System Adapted for Use from an Airplane: Test Results from Bering and Malaspina Glaciers, Alaska, USA. *Ann. Glaciol.* 50 (51), 93–97. doi:10.3189/172756409789097487.
- Elsberg, D. H., W.D. Harrison, K. A. Echelmeyer, and R. M. Krimmel. 2001. Quantifying the Effects of Climate and Surface Change on Glacier Mass Balance. *J. Glaciol.* 47 (159): 649–658. doi:10.3189/172756501781831783.
- Farinotti, D., M. Huss, A. Bauder, M. Funk, and M. Truffer. 2009. A Method to Estimate the Ice Volume and Ice-thickness Distribution of Alpine Glaciers. *J. Glaciol.* 55 (191): 422–430. doi:10.3189/002214309788816759.
- Huss, M., and D. Farinotti. 2012. Distributed Ice Thickness and Volume of All Glaciers Around the Globe. *J. Geophys. Res.* 117 (F4) (October 11): F04010. doi:10.1029/2012JF002523.
- Larsen, C. F., R. J. Motyka, J.T. Freymueller, K.A. Echelmeyer, and E.R. Ivins. 2005. Rapid Viscoelastic Uplift in Southeast Alaska Caused by post-Little Ice Age Glacial Retreat. *Earth Planet. Sc. Lett.* 237 (3-4) (September): 548–560. doi:10.1016/j.epsl.2005.06.032.
- Larsen, C. F., R. J. Motyka, A. A. Arendt, K. A. Echelmeyer, and Paul E. Geissler. 2007. Glacier Changes in Southeast Alaska and Northwest British Columbia and Contribution to Sea Level Rise. *J. Geophys. Res.* 112 (F1) (February): 1–11. doi:10.1029/2006JF000586.
- Mercer, J. H. 1961. The Response of Fjord Glaciers to Changes in the Firn Limit. *J. Glaciol.* 9 (29): 850–858.
- McNabb, R.W. 2013. On the frontal ablation of tidewater glaciers. PhD Thesis. University of Alaska Fairbanks, Fairbanks, Alaska.
- McNabb, R.W., R. Hock, S. O’Neel, L.A. Rasmussen, Y. Ahn, M. Braun, H. Conway, et al. 2012. Using Surface Velocities to Calculate Ice Thickness and Bed Topography: a Case Study at Columbia Glacier, Alaska, USA. *J. Glaciol.* 58 (212): 1151–1164.

- Narod, B.B., and G.K.C. Clarke. 1994. Miniature High-power Impulse Transmitter for Radio-echo Sounding. *J. Glaciol.* 40 (134).
- Trüssel, Barbara L., R.J. Motyka, Martin Truffer, and C. F. Larsen. 2013. Rapid Thinning of Lake-calving Yakutat Glacier and the Collapse of the Yakutat Icefield, Southeast Alaska, USA. *J. Glaciol.* 59 (213): 149–161. doi:10.3189/2013J0G12J081.
- VanLooy, J., R. Forster, and A. Ford. 2006. Accelerating Thinning of Kenai Peninsula Glaciers, Alaska. *Geophys. Res. Lett.* 33 (21) (November 4): 1–5. doi:10.1029/2006GL028060.
- Viens, R.J. 1995. Dynamics and mass balance of temperate tidewater glaciers of southern Alaska. MS Thesis. University of Washington. Seattle. Washington.
- Watts, R.D., and A.W. England. 1976. Radio-echo Sounding of Temperate Glaciers : Ice Properties and Sounder Design Criteria. *J. Glaciol.* 17 (75): 39–48.
- National Park Service. 2010. Instructions to authors — Natural Resource Data Series, Natural Resource Data Series, and Natural Resource Data Series: version 3.1. Natural Resource Data Series. NPS/NPRC/IMD/NRDS—2010/256. National Park Service, Fort Collins, Colorado.