Glacial Outburst Flooding, Bear Glacier, Kenai Fjords National Park, Alaska

FINAL REPORT

Andrew C. Wilcox, Alisa A. Wade, and Elena G. Evans
Department of Geosciences
University of Montana
Missoula, MT 59812-1296

Report prepared for National Park Service, via Rocky Mountains Cooperative Ecosystem Studies Unit (Agreement Number: H2370094000)

February 2013

Executive Summary

This project investigated glacial lake outburst floods (GLOFs) on Bear Glacier in Kenai Fjords National Park and associated hazards. The broad objective of the project was to analyze and assimilate information about impacts and hazards resulting from glacial lake outburst events on Bear Glacier to assist the park in managing this resource. In this report, we review literature about GLOF dynamics to provide a basis for understanding processes at Bear Glacier. We also provide background description of the study area, including Bear Glacier, the glacially dammed lake of interest that is the source of GLOFs ("Ice Lake", which is dammed by a tributary glacier and is 17.5 km up-glacier from Bear Glacier's terminus), and Bear Glacier Lake, the receiving waters for these GLOFs. Our methods for investigating GLOF dynamics at Bear Glacier combine field observations of both the glacially dammed lake and Bear Glacier Lake, including deployment of pressure transducers to record water level fluctuations, and remote sensing methods to examine temporal changes.

Our analysis provides insights into the drainage of Ice Lake and potential effects on Bear Glacier Lake. We found evidence that in recent years, Ice Lake has drained every year or two, with likely outbursts generally following the damming of sufficient water to create a lake area of between 0.35 and 0.5 km^2. Our evidence also indicates that Ice Lake tends to drain in late summer or fall (August – October). Two recent events are especially well constrained: the mid-August 2008 event that provided some of the impetus for this study, and an early October 2010 event we recorded with pressure transducers deployed in Ice Lake and in Bear Glacier Lake. We also found that Ice Lake has migrated down-valley, to the south, since the 1990s, likely as a result of thinning of the glacier that dams it. Our data are insufficient, however, to determine trends in frequency of drainage events from Ice Lake (e.g., as a result of climate warming and changes in Bear Glacier). We observed that in October 2010, Ice Lake drained over a period of days, rather than catastrophically. At Bear Glacier Lake, we recorded the arrival of the October 2010 GLOF from Ice Lake as a gradual, multi-day increase and then decrease in water levels. We also recorded several more rapid changes in water level unrelated to the Ice Lake GLOF, one of which was larger in magnitude than the GLOF arrival, at Bear Glacier Lake in 2010. This finding suggests that processes other than GLOFs, such as calving, can cause water level changes and associated potential hazards at Bear Glacier Lake. Our report concludes with suggestions for future study to increase understanding of GLOFs, calving, glacial change, and recreation use patterns that may influence hazards associated with glacial outburst flooding at Bear Glacier.

Contents

List of Figures

List of Tables

Introduction

Concerns surrounding glacial lake outburst floods (GLOFs), their potential links to climate change, and associated hazards have grown in recent years. Glacial lake outburst floods occur when water impounded by a glacier, such as in a glacier dammed lake, drains and is routed down-glacier. Southern Alaska hosts a high concentration of glacier dammed lakes that may be susceptible to outburst events. In Kenai Fjords National Park, Alaska, the growth of sea kayaking in areas near glacial termini has heightened interest in GLOFs and their potential hazards.
On August 19, 2008 a sea kayak guiding company expressed concern to the National Park Service about unusually high water levels and standing waves at the mouth of Bear Glacier Lake, a popular sea kayaking destination in Resurrection Bay at Kenai Fjords National Park. Park staff flew over the Bear Glacier area that afternoon and determined that a small glacier-dammed lake had recently drained (Figure 1). This small lake is about 17.5 km (10 miles) up-glacier and northwest of Bear Glacier Lake, at the head of a tributary arm to the main stem of Bear Glacier (Figure 2).

Figure 1. Photographs of glacier-dammed lake on tributary to Bear Glacier, Kenai Fjords National Park. (a) Left photo, showing full lake, taken 6 August 2005 (B. Molnia). (b) Right photo, showing drained lake, taken 19 August 2008 (C. Lindsay).

NPS staff did not observe evidence for flowing water on or near the surface of Bear Glacier, suggesting that the glacier-dammed lake's water drained through the glacier. NPS staff also observed icebergs stranded above the surface Bear Glacier Lake, suggesting that these icebergs had been stranded at high-water conditions and that, at the time of NPS observations, floodwaters were subsiding. At the time of these observations, this was the first documented drainage of the glacier dammed lake. The event raised concerns about the potential for GLOFs originating from Bear Glacier to cause rapid increases in water levels in Bear Glacier Lake, standing waves and strong currents, or the redistribution of sediment and debris in channels like the one that exists at the outlet of Bear Glacier Lake, all of which could create hazardous boating conditions and/or place camps located adjacent to Bear Glacier Lake at risk of inundation.
The concern over the outburst events at Bear Glacier prompted NPS to develop a study of the area to investigate GLOFs on Bear Glacier, determine hazards, and provide management recommendations, in collaboration with the University of Montana. In particular, this study attempts to address the following questions:

1. *What is the frequency and timing of drainage of the glacier dammed lake?*
2. *By what mechanism does the glacier dammed lake drain, and what are the controls on its drainage?*
3. *How does the drainage of the glacially dammed lake propagate downstream to Bear Glacier Lake?*
4. *What are the primary hazards as a result of this GLOF?*

To address these questions, this report analyzes and assimilates information regarding outburst floods at Bear Glacier, including aerial photo and satellite imagery, field observations, and knowledge about GLOF dynamics. As a supplement to this written report, maps and remote sensing products have been assembled in ArcGIS for electronic delivery to NPS. This study ties into broader NPS efforts to understand the impacts of climate change on park resources, increases in visitor usage of the area, and potential management actions.

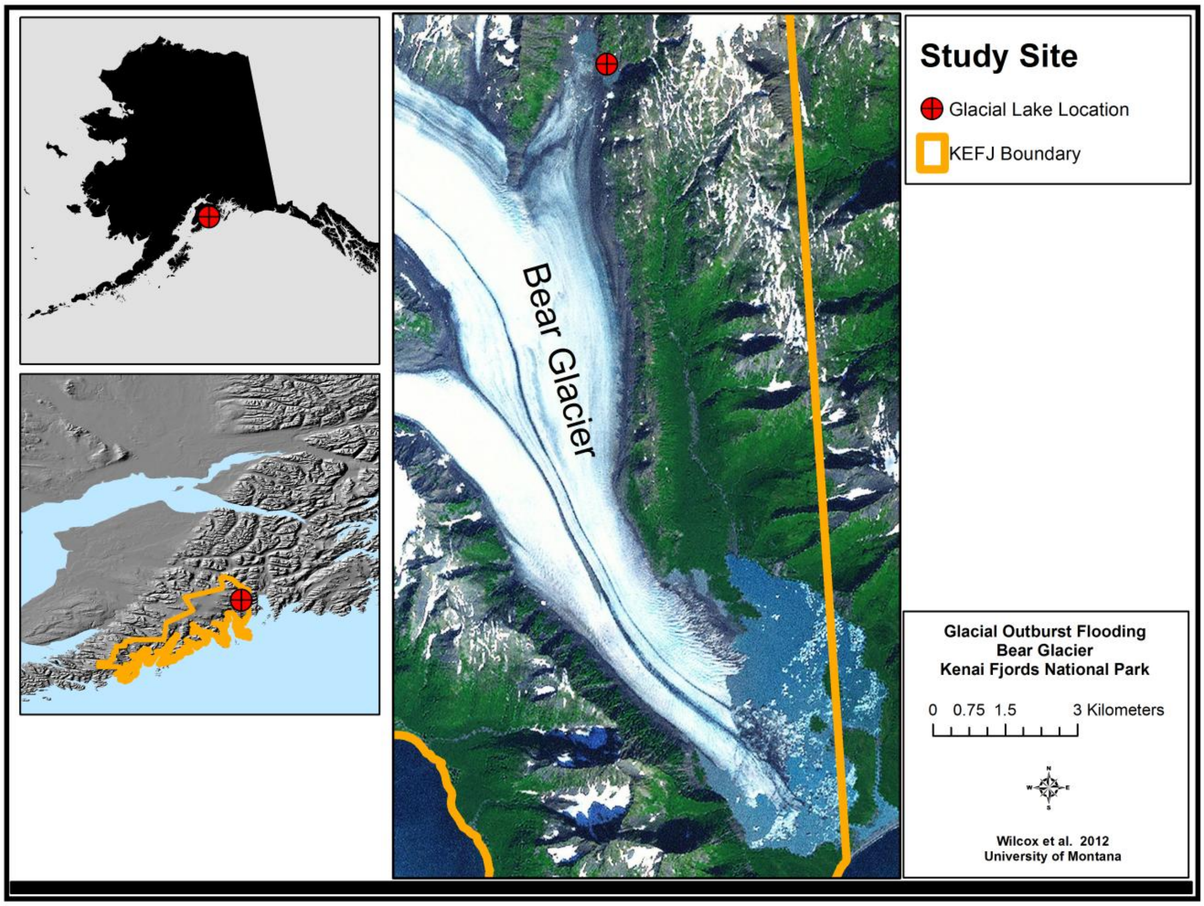


Figure 2. Study area map, showing Bear Glacier, location of glacier dammed study lake, and location within Kenai Fjords National Park (lower left) and Alaska (upper left).

Background: Glacial Lake Outburst Floods

Glacial lake outburst floods (GLOFs) occur when water impounded by a glacier drains ((Post and Mayo, 1971, Tweed and Russell, 1999). Ice-dammed lakes can occur on the surface of glaciers (i.e., supraglacially), beneath the surface (i.e., subglacially), or at the margin of a glacier (Tweed and Russell, 1999). Glacier dammed lakes (GDLs) formed at the margin of a glacier are influenced by valley topography, streamflow inputs from tributary streams, solar radiation (which influences melt rates), and changes in the dynamics of both tributary and trunk glaciers (Tweed and Russell, 1999). GDLs are dynamic features that experience cycles of filling, drainage of lake water through tunnels or drainage systems within the ice, and re-filling (Post and Mayo, 1971). The evolution of subglacial and englacial routing is important to the type and timing of floodwater discharge. GLOFs are more challenging to predict than runoff-driven floods in rivers because they are thresholded events dictated by the type of water storage, release type, and water routing.

Alaska hosts a high concentration of GDLs, and these have been inventoried by two studies. Post and Mayo (1971) mapped GDLs larger than 0.1 km^2 using topographic maps and aerial photographs. Wolfe (2008) continued this work, using remote sensing methods, to assess changes in 538 GDLs from 1971 to 2000. During that period, 263 of the lakes documented by Post and Mayo disappeared (i.e., 70% of the lakes), largely from down-wasting of the damming glaciers. Wolfe (2008) documented the appearance of 141 new lakes from 1971 to 2000.

There are two well-known GDLs that experience periodic GLOFs on the Kenai Peninsula. The Skilak glacier-dammed lake, which occurs on a lobe of the Harding Ice Field, experiences periodic GLOFs that cause rapid water level increases in the downstream Skilak River and Skilak Lake. Between 1969 and 2011, 16 GLOFs have been documented from the Skilak GDL, including winter events (National Weather Service 2012b). The Snow Glacier Dammed Lake drains subglacially to the Snow River and Kenai Lake. Records suggest that in the first half of the 20th century, the Snow GDL drained every 2 to 3 years, typically in November, December or January, causing downstream ice jams and hazards to infrastructure (Post and Mayo, 1971). Since 1953, GLOFs from this system have typically occurred from September to November (National Weather Service 2012c).

Glacier-dammed lakes and outburst events have been documented in a number of national parks in southern Alaska. In Glacier Bay National Park, Abyss Lake, is located approximately 8 km up the Brady Glacier and releases periodic GLOFs with magnitudes >1000 m^3/s (Grover 1997, as cited in Eckert et al. 2006) and a recurrence interval of between 1 and 4 years (C. Soiseth, NPS, pers. comm., as cited in Eckert et al. 2006). In Lake Clark National Park, sequences of GLOFs on the Drift River have been associated with eruptions of Mount Redoubt (Sturm et al., 1986; Nagorski et al., 2008).

In-depth studies of Hidden Creek Lake (HCL), a glacier dammed lake on Kennicott Glacier in Wrangell St. Elias National Park, Alaska, are informative with respect to the dynamics of these systems and factors explaining their drainage (e.g., Bartholomaus et al., 2008; S.P. Anderson et al. 2003; R.S. Anderson et al. 2005). Hidden Creek Lake (HCL) fills and drains annually, emptying $20–30\times10^6$ m^3 of water beneath Kennicott Glacier. Drainage of HCL requires approximately two days. Methods used to document the drainage dynamics of HCL have included deployment of pressure and submersible temperature sensors in HCL, water level surveys, and stage and electrical conductivity measurements at the Kennicott River glacier outlet, where conductivity provides insights into subglacial water residence time and routing time from HCL to the Kennicott River (Bartholomaus et al., 2008).

Post and Mayo (1971, p. 2) present seven potential mechanisms of GLOFs from GDLs, whereby the drainage of the GDL can be triggered “by the formation of a channel under, through, or over the ice in one or more of the following ways:

1. Slow plastic yielding of the ice due to hydrostatic pressure differences between the lake and the adjacent, less dense ice (Glen, 1954).
2. Raising of the ice dam by floating (Thorarinsson, 1939).
3. Crack progression under combined shear stress due to glacier flow and high hydrostatic pressure (Nichols and Miller, 1952).
4. Drainage through small, preexisting channels at the ice-rock interface or between crystals in the ice.
5. Water overflowing the ice dam, generally along the margin (Liestøl, 1956).
6. Subglacial melting by volcanic heat (Tryggvason, 1960).
7. Weakening of the dam by earthquakes (Tryggvason, 1960).”

Tweed and Russell (1999) also review triggering mechanisms for outburst events associated with ice-dammed lakes. They indicate that lakes tend to drain from either failure of a dam burst or through subglacial tunnels, and that whether subglacials tunnels stay open or close between drainage events influences GLOF hazard. Drainage of GDLs does not always occur by catastrophic draining; some GDLs may drain by slow leakage. GDLs may to drain once they reach some critical threshold. For example, the Glen (1954) mechanism suggests that GDLs drain when they reach a critical depth threshold. Flotation of ice dams may also be important; when GDLs become large enough, density differences between water and ice can produce buoyancy of the ice dam and trigger drainage (as reviewed by Tweed and Russell, 1999). In addition, crevassing reduces ice-dam density and can increases the potential for outburst events. Although early studies assumed GLOF drained through distinct subglacial conduits, more recent inquiries suggest that flood routing through glaciers is highly complex (Roberts et al. 2005).

Many studies have drawn links between recent warming and melting of Alaskan glaciers (e.g., Arendt et al., 2002; Arendt, 2006; Arendt 2011, VanLooy et al., 2006). Warming and associated glacial melting have also influenced meltwater volumes (Arendt et al., 2002; Arendt, 2006) and meltwater storage in glaciers (as observed in Greenland by Harper et al. 2012). Changes in glacier dynamics and hydrology may have also influenced the potential for formation of glacier dammed lakes (Wolfe 2008) and hazards associated with GLOFs (e.g., Huggel et al. 2003, Wolfe 2008, Moore et al. 2009), although additional research on linkages between warming, glacial processes, GLOFs, and hazards is needed. Wolfe (2008) suggested that temperature increases of greater than 2°C were associated with loss of GDLs, while lower temperature increases correlated with lake persistence.

Tweed and Russel (1999) suggest that outburst-event magnitude and frequency can be cyclical. During periods of glacial recession, ice dams can thin to an extent that less lake water is needed to cause outbursts (Costa and Schuster, 1988; Evans and Clague, 1994; Clague and Evans, 1997). This can result in more frequent but smaller GLOFs. In contrast, when periods of glacial advance, ice dams can thicken and in turn can impound greater water volumes. Outburst events in these conditions may be less frequent but higher in magnitude.

Study Area

Bear Glacier, on the Kenai Peninsula in Kenai Fjords National Park, Alaska, is the 3rd largest outlet glacier of the Harding Icefield (Field 1975, as cited in Molnia 2008). Bear Glacier extends to the southeast from the eastern side of the Icefield toward Resurrection Bay (Figure 2). Bear Glacier has retreated substantially in recent decades. Mapping of Bear Glacier in 1909 indicated that at that time the center of the glacier's terminus was close to the shore of Resurrection Bay and that high tide reached the glacier (Grant and Higgins 1913, as cited in Molnia 2008). Other evidence suggests the glacier extended further seaward in the mid-1800s (Vierec 1967, as cited in Molnia 2008). Bear Glacier had retreated approximately 400 m by 1950 relative to 1909 (Molnia 2008). Between 1950 and the mid-1990s, Bear Glacier retreated 1.55 km, decreased in area by 8.75 km^2, and lost 9.7 km^3 of ice volume (Aðalgeirsdóttir et al. 1998, as cited in Molnia 2008). This retreat has been accompanied by thinning, which occurred at rate of 0.80±0.01 m/yr from the 1950 to the mid-1990s and 1.01±0.10 m/yr from the mid- to late-1990s (VanLooy et al., 2006). The recession rate during the 1950 to mid-1990s period was 36 /yr (Echelmeyer et al. 2001, as cited in Molnia 2008). An additional 2 km of retreat had occurred by 2004 as a result of calving of Bear Glacier's floating terminus (Molnia 2008; also see Figure 3).

Figure 3. Landsat satellite images of Bear Glacier from 1986 (left) and 2002 (right) showing glacial recession (NASA/USGS 2008). Ice Lake is faintly visible in upper center of 2002 image.

Changes in the dimensions of Bear Glacier have resulted from changing climatic conditions in the study area. KEFJ climate is strongly maritime, with relatively mild temperatures and high precipitation compared to other regions in Alaska (Figure 4). For nearby Seward, the annual mean temperature is 4.6 °C (40.3 °F) and annual average precipitation is 182 cm (71.8 in) (years 1971-2000), with the highest temperatures occurring in late July and the greatest precipitation falling in late September (Figure 5).

The last 100 years have seen a trend towards warmer temperatures in Alaska, but relatively stable precipitation (Figure 6). It is estimated that the state's annual average temperature has increased by 1.2–1.4 °C over the past 100 years, about twice the global rate (Wendler et al. 2012). Since 1977, some of this warming has been driven by the Pacific Decadal Oscillation (PDO). However, the PDO has shifted sign in the last 10 years, leading to recent cooling (Wendler et al. 2012). The last 10 years have seen an average of 1.3°C of cooling, as measured across all first-order weather stations in Alaska, with a particular cooling effect in southwestern Alaska (Wendler et al. 2012). The PDO cooling effect may last up to three decades (Wendler et al. 2012), and mask otherwise projected increasing temperatures from carbon emissions. Without PDO effects, temperatures are projected to increase approximately 0.55°C (1°F) per decade, and precipitation to increase annually, but with drier summers and autumns (on the basis of the moderate A1B carbon emissions scenario, Rupp and Loya, 2009; Figure 7).

Bear Glacier Lake is an ice-marginal lake along the glacier's eastern-southeastern margin (Figure 2, Figure 8). The evidence cited above about the extent of Bear Glacier in the 1800s and early 1900s suggest that, at that time, Bear Glacier Lake did not exist. Bear Glacier Lake was evident in 1950 mapping of Bear Glacier (Aðalgeirsdóttir et al. 1998, as cited in Molnia 2008), and it has enlarged in recent decades as a result of the retreat of Bear Glacier. Bear Glacier Lake has also become a popular sea kayaking destination in Resurrection Bay. The dynamic nature of Bear Glacier produces potential hazards to recreational users of BGL, including iceberg calving at the terminus of Bear Glacier, standing waves and strong currents, and rapid increases in water levels as a result of outburst floods from glacier dammed lakes.

One source of outburst floods is the ice-marginal glacier dammed lake that is the subject of our study. We refer to the study lake in KEFJ as Ice Lake (Figure 1, Figure 9). This lake is named Seward A7-01 in Wolfe (2008) and National Weather Service (2012a). Ice Lake is ~ 17.5 km up-glacier and northwest of Bear Glacier Lake, approximately 3.5 km up a tributary glacier to the main trunk of Bear Glacier, and approximately 11 km southwest of Seward (Ice Lake coordinates -149.60, 60.08 decimal degrees), at an approximate elevation of 260m (Figure 2). The surface elevation of the tributary glacier that impounds Ice Lake appears to be lower than the surface elevation of the adjacent trunk of Bear Glacier (Lindsey, 2008). Ice Lake has two distinct sub-areas that are often separated by surface ice but are hydrologically connected. The larger, western portion of Ice Lake is fed by an unnamed stream from the north. The smaller, eastern portion, has a small contributing area directly fed by surface runoff but likely derives most of its water from the connection to the western arm. The remainder of this report is focused on description of Ice Lake and its drainage dynamics.

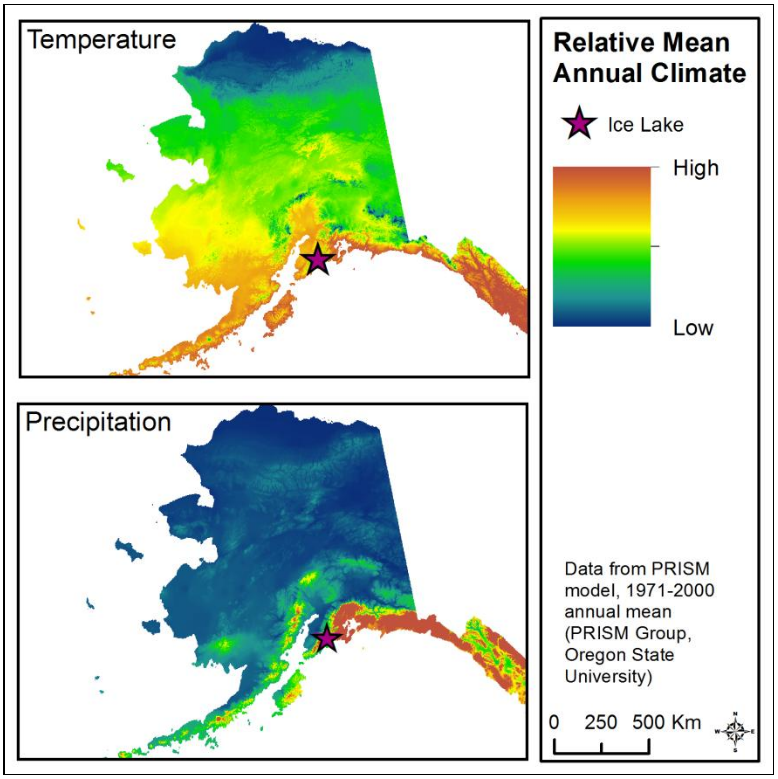


Figure 4. Mean annual temperature and precipitation for Ice Lake relative to Alaska (source: http://www.prism.oregonstate.edu/state_products/ak_maps.phtml).

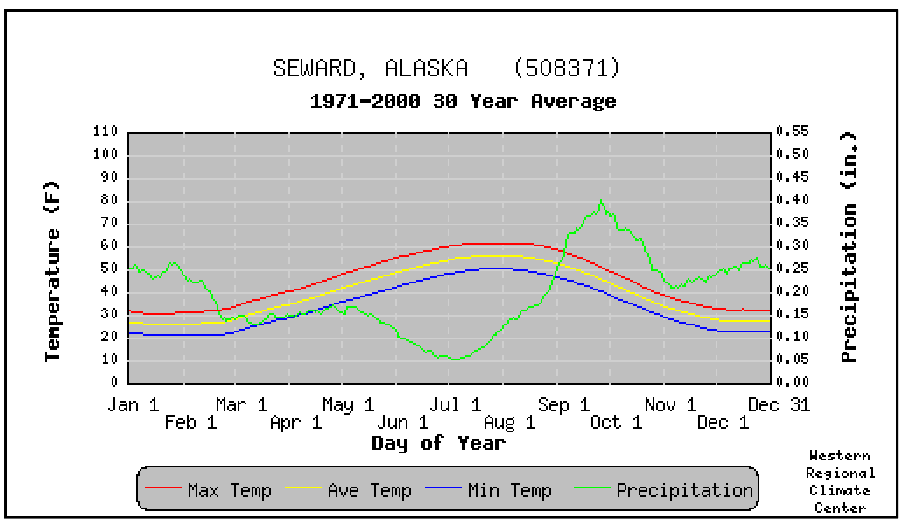
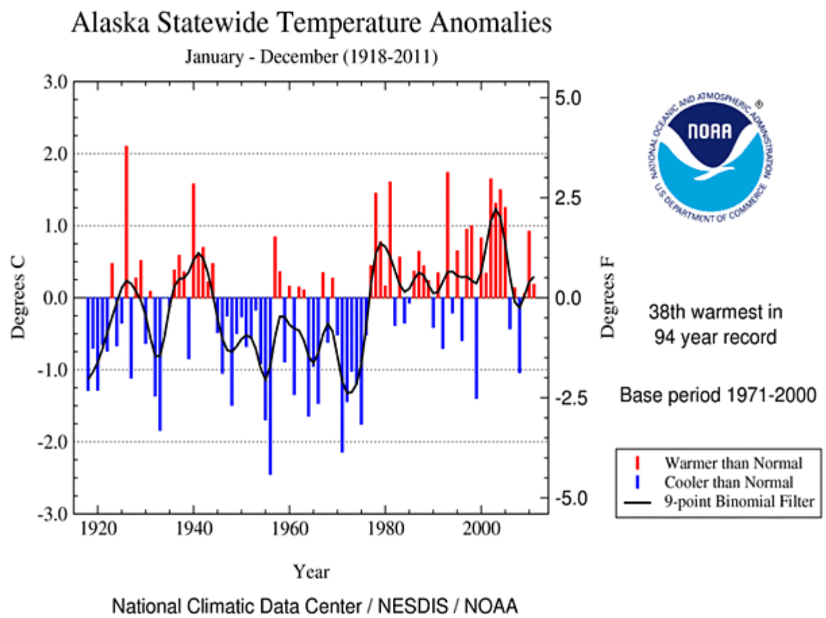
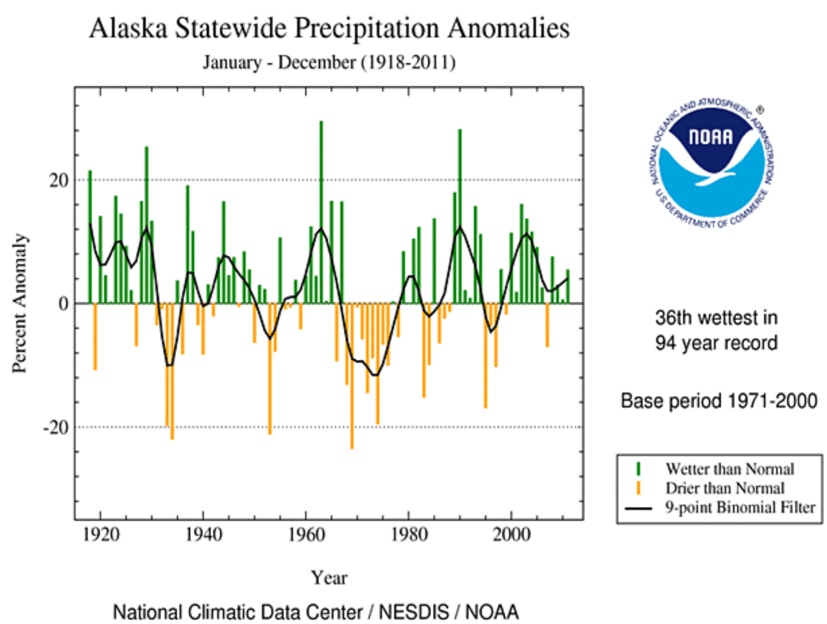


Figure 5. Mean annual temperature and precipitation for Seward, AK (1971-2000) (source: http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?aksewa).



a)



b)

Figure 6. Alaska statewide a) temperature and b) precipitation anomalies over the past 94 years, calculated from a base period of 1971-2000 (source: http://www.ncdc.noaa.gov/sotc/national/2011/13).

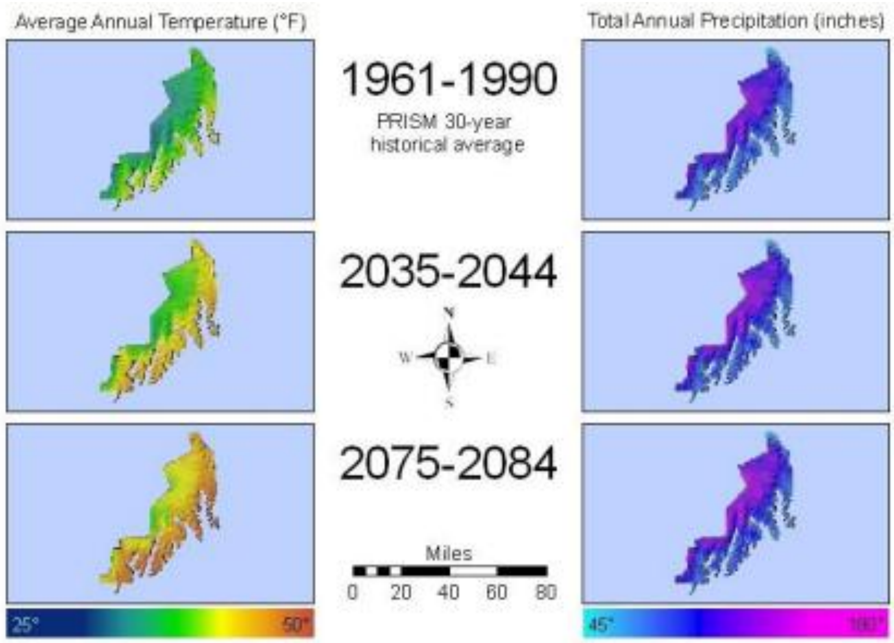


Figure 7. Projected changes in temperature and precipitation within KEFJ under the moderate A1B carbon emissions scenario (source: http://www.snap.uaf.edu/resource_page.php?resourceid=9).

Figure 8. Resurrection Bay (foreground), Bear Glacier Lake, and Bear Glacier. (NOAA APRFC archive).

Figure 9. Ice Lake, facing toward south and down-glacier (August 2011).

Methods

Our study of glacial outburst flooding entailed both field and remote sensing investigations of Ice Lake and its drainage dynamics. In addition, we assembled anecdotal information (e.g., from sea-kayaking guides) about drainage of the Ice Lake and/or conditions at Bear Glacier Lake.

Field Methods

In August 2010, UM researchers completed initial data collection and instrument installation at Bear Glacier. Rain and low cloud cover during the UM team's visit to Alaska allowed for extremely limited helicopter access to the field site. We visited the Ice Lake field site for several hours on 5 August 2008. During this brief time at Ice Lake, we completed a reconnaissance survey of the lake using packrafts (Figure 10). We deployed a pressure transducer in the lake, suspended several meters below the surface using a system of weights and a buoy, and tethered to a boulder near the shoreline to facilitate recovery. The pressure transducer was intended to record lake level fluctuations, temperature, and draining of the lake. A second pressure transducer was installed in the stream that flows into Ice Lake from the north. A third pressure transducer was installed subaerially, adjacent to the lake, to provide barometric pressure to difference pressure changes in the lake versus climatic pressure changes. We also mounted an interval camera aimed at the lake in an effort to establish photo documentation of potential lake drainage. Deployment locations are shown in Figure 11.

Two days later, we visited Bear Glacier Lake by boat, with NPS personnel. We deployed an additional pair of pressure transducers at this site, one in the water and one in the air to provide barometric corrections. The pressure transducer installed in the lake used a similar weight and buoy system as the transducer in Ice Lake. The objective of the Bear Glacier Lake installations was to document water-level increases in Bear Glacier Lake associated with outburst floods from Ice Lake and travel time from Ice Lake to the lagoon. The pressure transducers do not directly measure depth or water surface elevation and therefore provide data on the timing and pattern of water-level changes, but not on the specific water surface elevations. All transducers were made by Onset Hobo and recorded at 15-minute intervals.

Figure 10. Field deployment at Ice Lake; left image shows helicopter landing area at head of lake, right image shows packraft used for lake travel

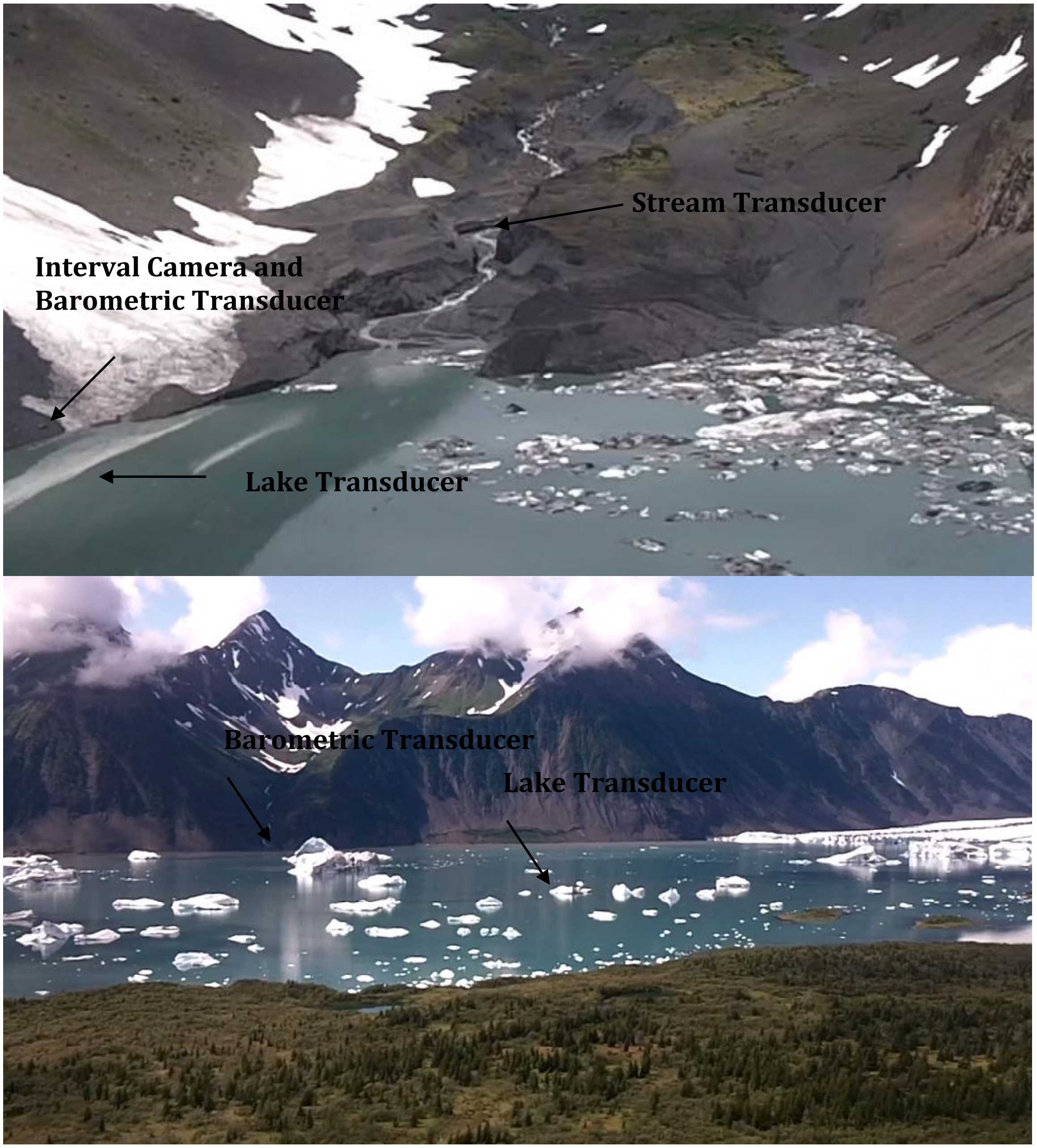


Figure 11. Instrument deployment locations at Ice Lake (top) and Bear Glacier Lake (bottom)

In 2011, UM researchers again visited Ice Lake and Bear Glacier Lake to recover instruments that had been deployed the previous summer. Ice Lake had at least partly drained since our 2010 visit and was partially filled. At Ice Lake, we recovered the lake transducer and the barometric transducer. The stream transducer could not be relocated, likely as a result of scour. The interval camera was recovered but had ceased functioning and no data were recovered. At Ice Lake, we attempted a bathymetric survey using simple sounding measurements with a weighted tape from a packraft, but a combination of safety concerns and depths exceeding the length of our tape rendered this method ineffective. At Bear Glacier Lake, we recovered the lake and barometric transducers.

After this field visit, we evaluated the need for additional field work and decided that project resources would be more effectively devoted to remote sensing analysis for addressing the project objectives. This choice was based on the longer temporal resolution offered by remote sensing work than by a single additional field visit, which was more suited to understanding the temporal element of the drainage dynamics of Ice Lake, as well as the logistical challenges of deployment to the site.

Imagery Analysis

We obtained imagery of Ice Lake to develop further insights into its drainage history and dynamics. Aerial photos or high-resolution satellite imagery (sub 20m resolution) were collected for visual inspection. We also obtained multispectral satellite imagery with sufficient bands for remote sensing of glacial lake surface area, estimated with a normalized difference water index (NDWI, methods below) (Table 1). We searched for images during months when lake was likely unfrozen (July-October) and for satellite imagery with < 40% cloud cover. We also obtained photographs from field visits and NPS reconnaissance flights (Figure 12). In total, we visually inspected 13 aerial or ground-based photos or high-resolution satellite images covering a period of 16 years (1997-2012). For four of the satellite images, we hand-digitized the estimated lake perimeter. We also reviewed 1950s images provided by Fritz Klasner (NPS), but these either had insufficient resolution or excessive snow and ice cover to permit interpretation of Ice Lake conditions.

For calculating the NDWI, we used 26 multispectral Landsat images primarily covering a period of 13 years (1999–2012 with one image from 1985). For Landsat data, we only downloaded data that were available pre-processed. Additional data could be obtained for future work from the USGS for a processing fee. There are additional ASTER multispectral data available as well, with scenes from years 2001, 2007, 2008, and 2010 that also require additional processing. These unrectified scenes are included in the GIS folder submitted with this report. Some Landsat imagery was discarded because of high shadows or cloud cover and poor NDWI estimation.

We calculated a normalized difference water index (NDWI) following the methods of Huggel (1998). Remote sensing of glacial lake characteristics is particularly applicable in relatively inaccessible locations and has been shown to be robust for glacial lake outburst flood potential hazard assessment (Huggel 2002). The methods applied are not sufficient to indicate risk -- likelihood and extent of flooding impact -- but provide a first-pass evaluation of glacial lake characteristics. The NDWI uses the spectral reflectance differences between land and water to delineate water surfaces. We calculated the maximum reflectance difference between the maximum and minimum reflectance of water, represented by the satellite sensed blue channel and a near-infared channel, respectively. Using Landsat data, this translates to the following:

NDWI = (Landsat Band 4 – Landsat Band 1)/(Landsat Band 4 + Landsat Band 1). (Equation 1)

Table 1. Data sources used in analysis and summary of lake visibility or calculated area. Aerial or ground-based images are shown below, in Figure 12.

Date	Type	Purpose	Resolution	Source
Unknown	Harding glacier Lidar DEM	basemap	2 m	NPS
6/26/1997	DOQQ (Aerial photo)	visual/digitized	1m	alaskamapped.org
9/9/2000	Color compressed Landsat7TM	visual/digitized	15m	irma.nps.gov/App/Portal
11/12/2002	Color compressed Aster L1B	visual	15m	earthexplorer.usgs.gov
8/8/2005	Color compressed IKONOS2	visual/digitized	1m	earthexplorer.usgs.gov
8/9/2005	Color compressed Aster L1B	visual	15m	earthexplorer.usgs.gov
9/4/2009	Aerial or ground-based photo	visual	NA	NPS overflight
8/5/2010	Aerial or ground-based photo	visual	NA	UM field work
8/23/2010	Color compressed Aster L1B	visual	15m	earthexplorer.usgs.gov
9/12/2010	Color compressed SPOT ortho	visual /digitized	2.5m	alaskamapped.org
9/16/2010	Aerial or ground-based photo	visual	NA	NOAA APRFC flight
8/11/2011	Aerial or ground-based photo	visual	NA	UM field work
8/21/2012	Aerial or ground-based photo	visual	NA	NPS overflight
10/9/2012	Aerial or ground-based photo	visual	NA	NPS overflight
8/10/1985	Landsat5 Bands 1-7	NDWI	30m	earthexplorer.usgs.gov
9/8/1999	Landsat7 Bands 1-8	NDWI	15 or 30m	earthexplorer.usgs.gov
9/26/1999	Landsat7 Bands 1-8	NDWI	15 or 30m	earthexplorer.usgs.gov
8/11/2000	Landsat7 Bands 1-8	NDWI	15 or 30m	earthexplorer.usgs.gov
8/21/2001	Landsat7 Bands 1-8	NDWI	15 or 30m	earthexplorer.usgs.gov
9/6/2001	Landsat7 Bands 1-8	NDWI	15 or 30m	earthexplorer.usgs.gov
9/29/2001	Landsat7 Bands 1-8	NDWI	15 or 30m	earthexplorer.usgs.gov
7/30/2002	Landsat7 Bands 1-8	NDWI	15 or 30m	earthexplorer.usgs.gov
9/14/2004	Landsat7 Bands 1-8	NDWI	15 or 30m	earthexplorer.usgs.gov
7/15/2005	Landsat7 Bands 1-8	NDWI/Climate	15 or 30m	earthexplorer.usgs.gov
8/8/2005	Landsat5 Bands 1-7	NDWI/Climate	30m	earthexplorer.usgs.gov
9/1/2005	Landsat7 Bands 1-8	NDWI/Climate	15 or 30m	earthexplorer.usgs.gov
9/18/2005	Landsat5 Bands 1-7	NDWI/Climate	30m	earthexplorer.usgs.gov
9/25/2005	Landsat5 Bands 1-7	NDWI/Climate	30m	earthexplorer.usgs.gov
7/28/2007	Landsat7 Bands 1-8	NDWI/Climate	15 or 30m	earthexplorer.usgs.gov
8/6/2007	Landsat7 Bands 1-8	NDWI/Climate	15 or 30m	earthexplorer.usgs.gov
8/30/2007	Landsat5 Bands 1-7	NDWI/Climate	30m	earthexplorer.usgs.gov
10/9/2007	Landsat7 Bands 1-8	NDWI	15 or 30m	earthexplorer.usgs.gov
8/8/2008	Landsat7 Bands 1-8	NDWI	15 or 30m	earthexplorer.usgs.gov
10/27/2008	Landsat7 Bands 1-8	NDWI	15 or 30m	earthexplorer.usgs.gov
7/9/2009	Landsat5 Bands 1-7	NDWI/Climate	30m	earthexplorer.usgs.gov
8/31/2010	Landsat5 Bands 1-7	NDWI/Climate	30m	earthexplorer.usgs.gov
9/16/2010	Landsat5 Bands 1-7	NDWI/Climate	30m	earthexplorer.usgs.gov
9/26/2011	Landsat5 Bands 1-7	NDWI/Climate	30m	earthexplorer.usgs.gov
10/12/2011	Landsat5 Bands 1-7	NDWI/Climate	30m	earthexplorer.usgs.gov
10/22/2012	Landsat7 Bands 1-8	NDWI	15 or 30m	earthexplorer.usgs.gov

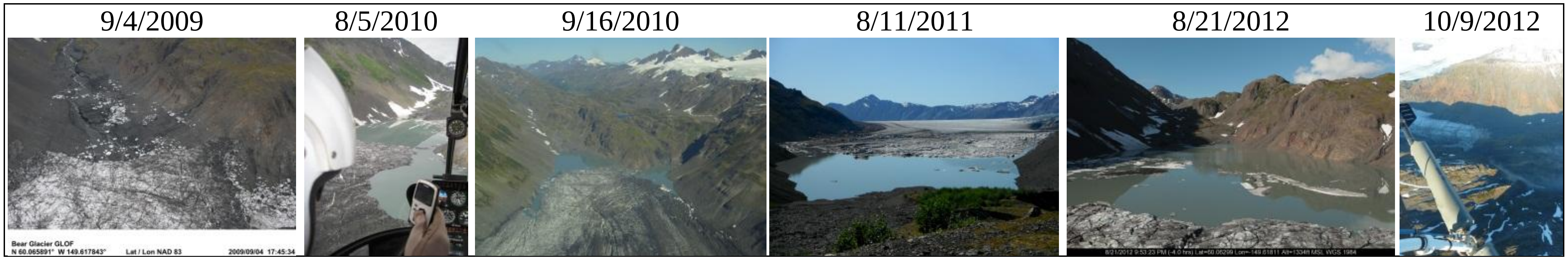


Figure 12. Aerial or ground-based photos used to assess Ice Lake drainage status.

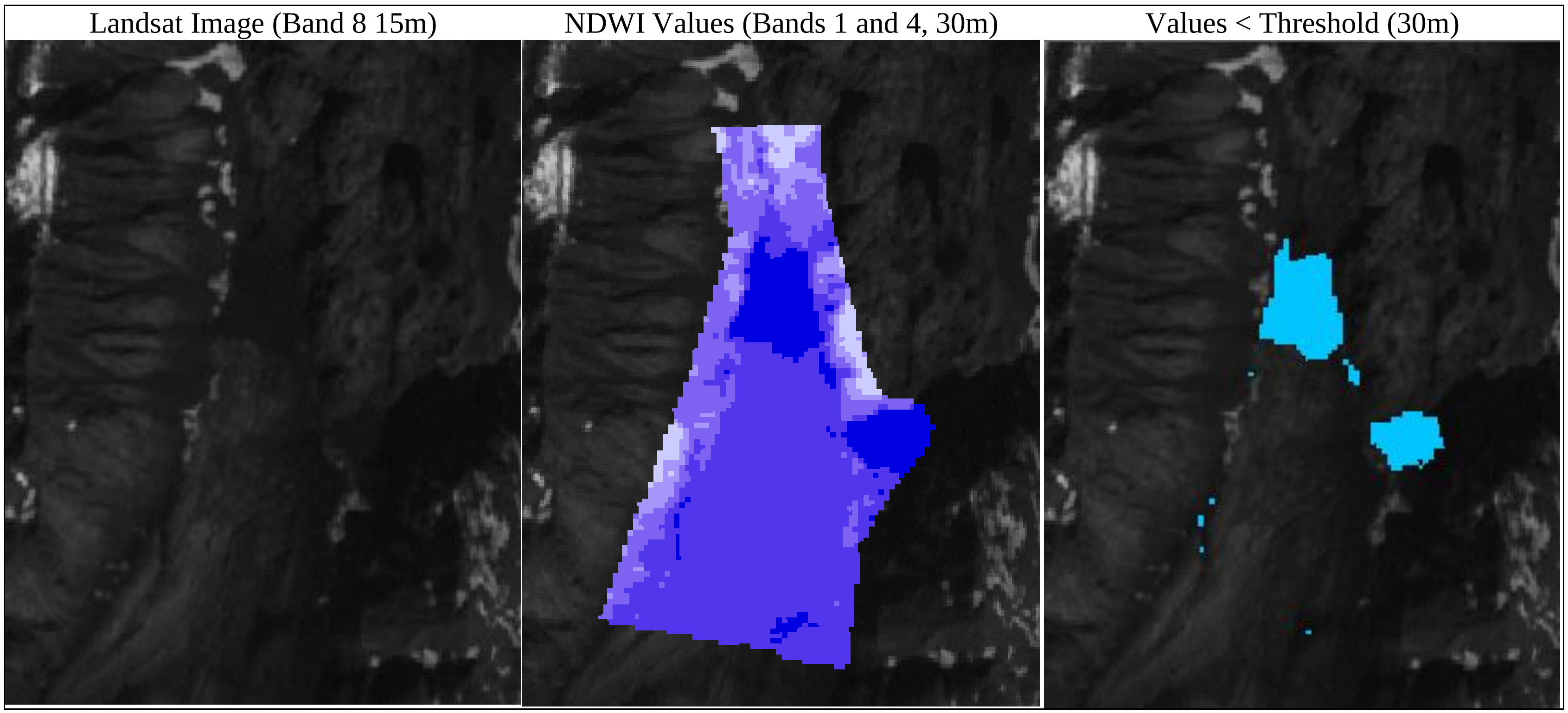


Figure 13. Example imagery and outputs from the normalized difference water index (NDWI) calculations

Huggel (2002) reports that typical NDWI values for lake surfaces are in the range between -0.60 and -0.85. We used a cutoff value of -0.55 because this tended to better represent known water (calibrated by visual inspection comparing NDWI results to high resolution imagery). Our cutoff value likely over-estimates water surface in some instances. Because areas of high-shadow in the imagery could incorrectly report water surface area, we only calculated NDWI within a small area of interest, selected to cover the maximum lake area observed in imagery while simultaneously minimizing shadows induced by steep cliff walls. We then counted the number of cells (30x30m resolution) that NDWI identified as water and translated that to estimated square kilometers of water surface area. Floating ice in the images is not recorded as water, and therefore these are not true glacial lake surface area estimates, but estimates of the area of visible surface water. We assume that area of visible surface water correlates with lake surface area and volume, however. Figure 13 shows an example of the NDWI calculation process. All analyses were conducted in ArcGIS 10.0 (ESRI), NAD83 Alaska Albers projection.

We estimated Ice Lake depth on the assumption that the change in elevation (slope) surrounding the lake is similar to the slope underlying the lake surface (sensu Hollister et al. 2011). First, we converted 24 estimated lake area polygons (4 hand-digitized from imagery, 20 derived from NWDI with lake area >0.05 km^2, which we assumed represented an un-drained lake area; we simplified NWDI rasters to polygons by eliminating any multi-polygon part that was less than 5% of the total area) to polylines in ArcGIS. We then extracted the mean elevation along each of the perimeters from the LiDar Digital Elevation Model (DEM, 2m resolution) dataset to estimate lake level elevation. We calculated the centroids of all 24 polygons, using the ArcGIS 10.0 “Feature to Point” tool, with the option “Inside” selected. This resulted in the identification of centroids within each polygon; if the lake area polygon was multi-part, the centroid was placed in the largest part. The largest part was always the northernmost area (many lake area calculations from NDWI identified two separate lakes separated by ice cover, a northern portion and smaller lake to the southeast, although we consider these both part of Ice Lake). For two of the lake area polygons that consisted of three disparate polygons, the automated process produced irregular results, and we moved the centroid to a reasonable location by hand. We then estimated average percent slope within 1km of each of the centroids, only including slope > 15 % (to avoid including areas classified as “flat” in the LiDar DEM because of glacial coverage) and within the flow contributing basin boundaries (identified by hand because of problems with automated approaches resulting from the irregularities caused by the glacier in the DEM). Finally, we calculated the distance from the centroid to the 320m contour isoline from the LiDar DEM.

We estimated depth for the lake centroid as (sensu Hollister et al. 2011):

$$\textit{Estimated depth for lake area centroid}_i = [\, C * (D_i * S_i)] - (320\text{m} - E_i) \qquad \text{Equation 2}$$

where i is the estimate for a given imagery date, C = a correction coefficient, D_i = distance of lake centroid$_i$ to the 320m isoline, S_i = average percent slope surrounding centroid$_i$, and E_i = estimated water surface elevation for lake area$_i$. We used the correction coefficient calculated as 0.553 by Hollister et al. (2011) for the Northeastern Region of the US. The coefficient is required because the approach regularly overestimates depth due to valley bottom sedimentation and other local anomalies. These are very rough estimates of lake depth: the correction coefficient is not calibrated to Alaska (we were only able to find published values for the Northeastern US), the slope estimates are biased towards steeper areas because we removed flatter slopes to avoid interference from the glacial surface in the DEM, and the centroid may represent relatively shallow or deep areas for different lake locations.

We can also empirically estimate the volume of the lake from the area estimates using equations developed by Huggel et al. (2002). Their linear regression between area and mean depth yielded the following equation for volume estimation:

$$Volume = \alpha Area^{\lambda} \qquad \text{Equation 3}$$

where they calculated $\alpha = 0.104$, and $\lambda = 1.42$. Again, this equation is calibrated to their analysis, so extension of results to our field setting requires caution. Another relationship was defined by the Canadian Inland Water Directorate (as cited in Huggel et al. 2002) as $\alpha = 0.035$, and $\lambda = 1.5$. We use the coefficients from Huggel et al. (2002) for consistency with our depth calculations, and use Equation 3 to estimate lake volume. We reiterate that these are very rough estimates that were adopted after attempts to directly measure lake depth in the field were not fruitful.

Climate Data Analysis

We obtained climate data to investigate potential correlations between glacial lake drainage and weather patterns. We sought the longest record of weather data available. Temperature and precipitation data were available for the entire year beginning in 2005 from Remote Automated Weather Station (RAWS) data from the Harding Ice Field station (Station ID FA656210). To obtain a longer period of record for summer daily maximum temperatures, we used data from the nearest RAWS station with summer temperature data dating back to 1999; the Kenai Lake station (Station ID 3246A6F0) (Figure 14). While the McArthur Pass RAWS station would have likely been a better match for the weather at the study site, data were not available for the period of interest. A new RAWS station was installed at Pedersen Lagoon, approximately 22 km from Ice Lake, in 2011, and data from that station should serve research needs into the future. We obtained data on maximum and average daily temperature and total daily precipitation. We used average and total daily temperature and precipitation data, respectively, to calculate a total “degree day” (°C) and precipitation (mm) accumulation for the year to date (starting January 1 of each year). Complete daily data were not available prior to 2005, and we therefore only calculated the accumulated degree days and precipitation for the years 2005–2012.

We explored the relationship between accumulated temperature and precipitation and lake area. There were 20 dates for which we had both NDWI area calculations and accumulated precipitation and precipitation data, 13 with lake area > .05 km^2 (which we assumed represented an un-drained lake area). We used correlation and linear regression analyses within R (R Core Team, www.R-project.org).

Figure 14. Map of local RAWS weather stations. The red "X" demarcates the approximate location of Ice Lake.

Results

Field Analysis

The pressure transducer deployed in Ice Lake in August 2010 provided insights into lake filling and drainage. After deployment of 5 August 2010, the pressure transducer recorded increases in lake levels during the following 10 days, until 15 August (Figure 15). Except for a brief drop in pressure, pressure recordings remained similar between 15 August and early October (Figure 15). We interpret this as an exceedence of the depth range of our pressure tranducer (9 m) and suspect that water levels continued to rise during this period. Drainage of the lake occurred in early October of that year. Starting on 8 October 2010, pressure began to drop sharply, indicating a drop in the amount of overlying water and the start of lake drainage. As the water level in Ice Lake declined, the transducer initially remained subaqueous. After 2 days and 3.5 hours, on 10/10/10, the transducer eventually became exposed to the air. At this time, the previously submerged transducer began recording temperature fluctuations that are consistent with air exposure (Figure 15); the diel fluctuations of air temperature are much greater than of water temperature. Exposure of the transducer to air does not necessarily signify complete lake drainage. The transducer was deployed near the edge of the lake and recovered there the following summer; additional drainage likely occurred even after 10/10/10. Regardless, these data suggest that lake drainage requires at least two days, substantially longer than a conceptual model of near-instantaneous drainage would suggest.

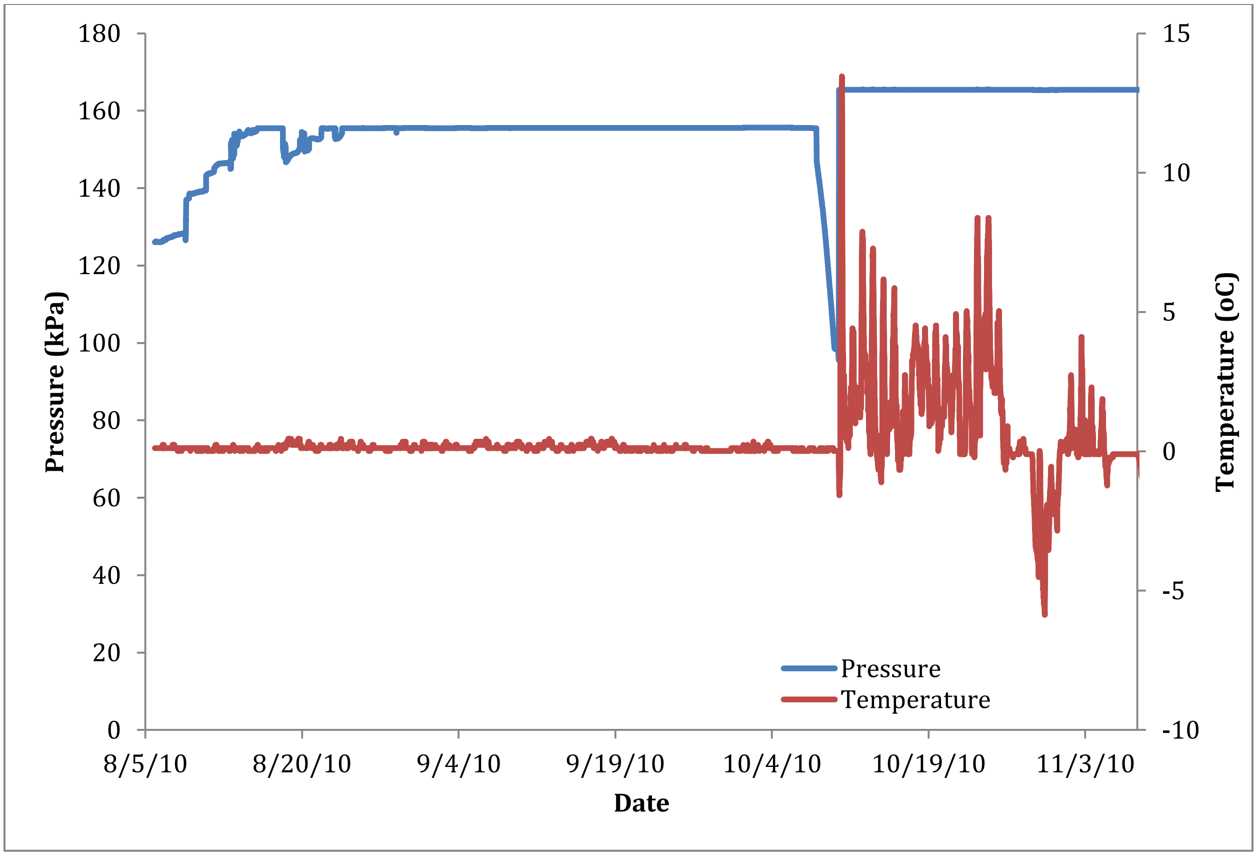


Figure 15. Pressure transducer data from Ice Lake, where blue line shows pressure and red line shows temperature. Abrupt drop in blue line in early October indicates onset of lake drainage; subsequent upward spike in pressure that coincides with increased temperature fluctuations indicates exposure of transducer to air.

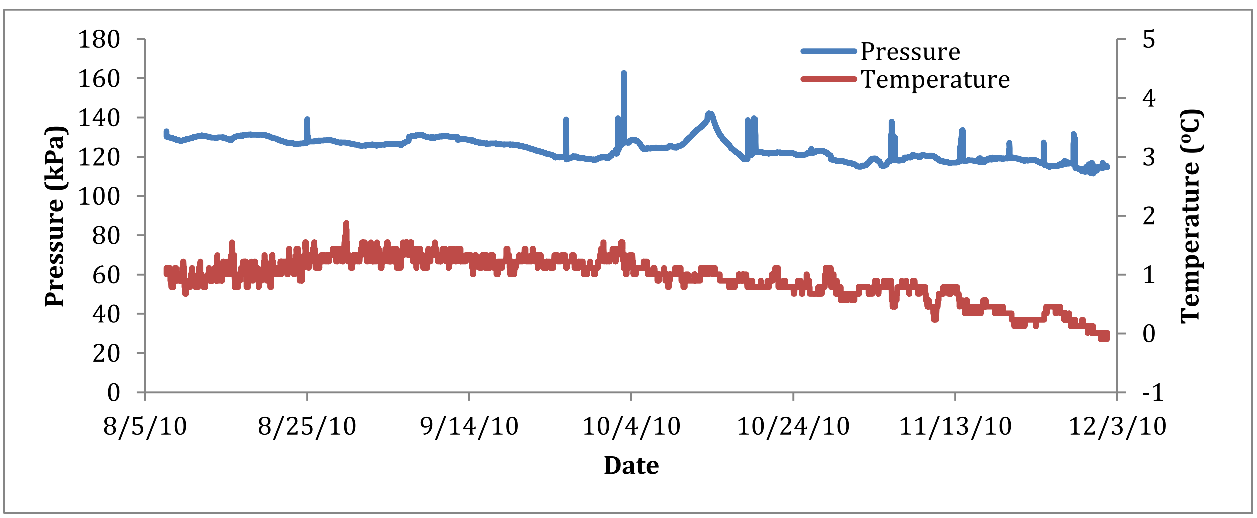


Figure 16. Bear Glacier Lake (Lagoon) pressure transducer data for August-November 2010. Pressure data illustrate that level of BGL is steady most of the time, with occasional spikes that may reflect calving at the terminus of Bear Glacier or equipment malfunction. The signature of the Ice Lake drainage event is evident as a more gradual rise in the water level starting on 9 October.

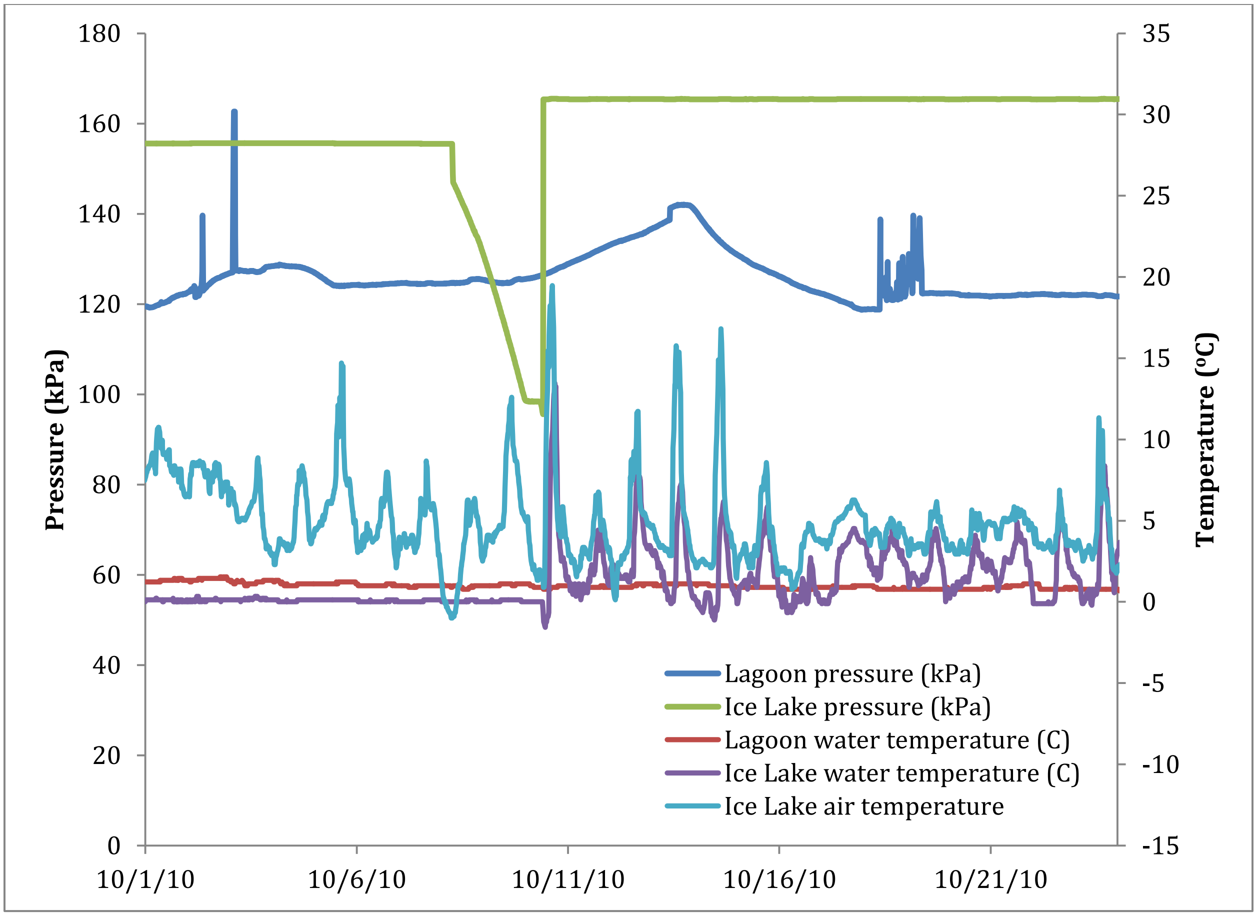


Figure 17. Pressure transducer data from October 2010 from both Bear Glacier Lake (lagoon) and Ice Lake

Analysis of the pressure transducer recovered from Bear Glacier Lake also provides insights. Several upward spikes in pressure (i.e., increases in water level) are visible that are not associated with Ice Lake drainage (Figure 16). These may reflect calving at the terminus of Bear Glacier or surges of meltwater, but they also may represent equipment malfunctions. Second, the signature of the Ice Lake drainage event is evident in BGL as a more gradual rise in the water level of BGL starting on 9 October and lasting for four days, followed by a gradual decline (Figure 16, Figure 17). The maximum water level resulting from the Ice Lake drainage is lower than from a spike recorded on 3 October.

Although Ice Lake appeared “full” at the time of our field reconnaissance, we observed geomorphic evidence of higher previous lake levels. First, multiple standlines were evident on the slopes above the lake level (Figure 18). In 2011, we counted 36 standlines, which we interpret as records of the cylical filling and drainage of the lake and the variable levels at which drainage has occurred. Second, we observed terraces above the stream that enters Ice Lake from the north and evidence of stream downcutting (Figure 19). The terraces and evidence of stream incision suggest that lake levels were higher in the past (i.e., the base level for the inlet stream has lowered), consistent with the standlines above the 2010 lake surface. These observations are also consistent with the remote sensing results presented below.

Our field visits afforded several additional observations about the Ice Lake.

- The lake has no apparent outlet and no surface channels are found on the glacier down-slope of the lake, which supports the notion that outburst flooding occurs subglacially.
- The two lobes of the lake (e.g. Figure 1a) were connected both in 2010, when lake levels were higher, and in 2011, when the lake level was lower.
- The glacier downslope of Ice Lake was heavily fractured, and standing water was visible on its surface and in crevasses in both 2010 and 2011 (Figure 20). Standing water was not visible further downglacier from Ice Lake. We suspect that the standing water was indicative of hydrologic connection with the lake.
- Floating ice accumulated near the north shore of Ice Lake in 2010. In 2011, when water levels were lower, little floating ice was observed in Ice Lake.

Figure 18. Images of standlines created by previous lake levels. In left image (August 2010), standlines are visible upslope of the large boulder found near the far shoreline, bisecting snowfields. Right image shows close up view of standlines (August 2011).

Figure 19. Ice Lake and inlet stream; terraces and fluvial incision to lowered lake level are evident (August 2010).

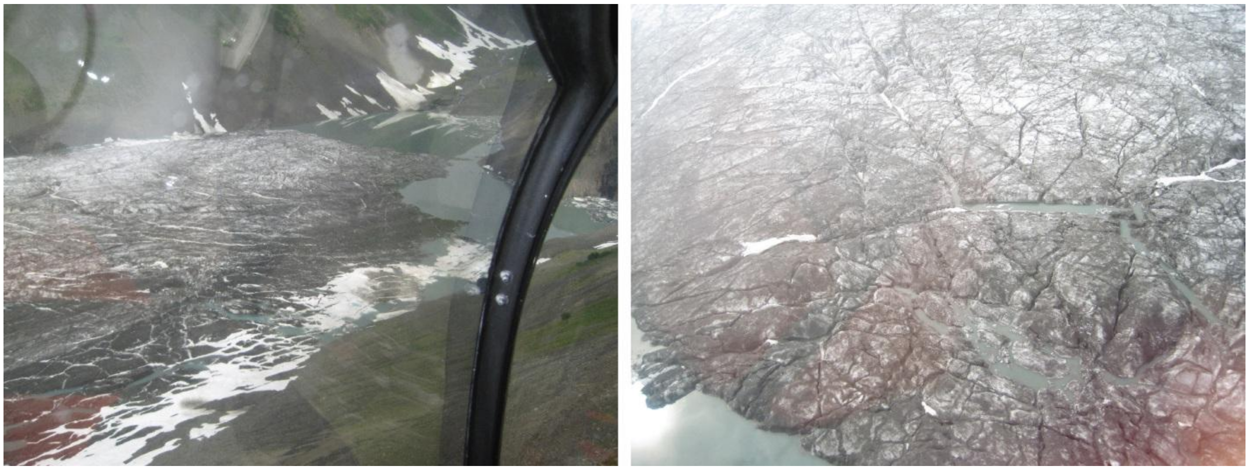


Figure 20. Images of glacier immediately down-slope from Ice Lake; standing water is evident on glacier surface and/or in crevasses (August 2010)

Anecdotal reports

Observations by sea-kayaking guides of water-level increases in Bear Glacier Lake provided some of the impetus for this study. Kenai National Park staff became aware of flooding from local residents and kayak guides when camping sites became flooded. Following the 2008 drainage event, sea kayak guides reported ~1.5 m (5 ft) water level rise in BGL (Seward City News, 08292008). In 2008, guides also reported that what they referred to as "floods" in BGL occurred every two to three years (Lindsey 2008). During some of these events, guides reported that icebergs clogged the mouth of BGL and that water overtopped the spit separating BGL and Resurrection Bay (Lindsey 2008).

Aerial reconnaissance showed that Ice Lake was full on 3 June 2009 (Klasner 2009a). Rick Brown, owner of Adventure 60 North, reported Bear Glacier outburst flooding in August 2009 that inundated the Backcountry Safari camp (Figure 21) (Klasner 2009b). Brown estimated the total water level rise in Bear Glacier Lake to be in excess of 4.5 m (15 ft) (Klasner 2009b). In 2012, two local guiding companies working near the terminus of Bear Glacier provided accounts of the BGL rising by 1.2-1.5 m (4-5 ft), starting on 28 August and lasting a few days (Kurtz 2012).

Figure 21. Photos of Backcountry Safari's camp along Bear Glacier Lake; high water is evident at top of right photo. (courtesy of Fritz Klasner email, 9/14/09)

Imagery Analysis

Table 2 identifies presence or absence of the Ice Lake and estimated surface area, elevation, and depth for 38 unique days across 28 years. A subset of these images is shown in Figure 22, which illustrates fluctuations in lake size, connectivity between the two lobes of the lake, and floating ice on the lake surface, as well as variations in image quality. The average of the maximum annual lake area across all years, calculated from NDWI analysis from available imagery, was 0.4 km^2 (Table 2). The single maximum lake area we calculated was 1.0 km^2 from imagery on 9/26/2011. This calculated area is substantially larger than any other estimated values and likely incorrectly includes topographical shading in the imagery; we therefore consider it an outlier. The second largest lake area calculation was 0.54 km^2 from imagery on 9/18/2005. The average of the estimated maximum annual lake surface elevation calculated from NDWI was 295m. The single highest estimated elevation was 342m from imagery on 8/10/1985. In general, there was a visible trend of decreasing surface elevation over time as the location of Ice Lake moved down valley as the glacial arm below the lake receded (Table 2, Figure 23).

The average of the estimated maximum annual depth calculated at the lake centroid using the NDWI analysis was 42 m, and the single maximum calculated depth was 78m on 9/26/2011; again, this outlier may be the result of an incorrect NDWI water classification. The second maximum calculated depth was 52m on 9/29/2001. The correlation between our lake area and depth estimates was 0.79. The average of the maximum annual volume from NDWI calculations was estimated at ~ 3.6×10^6 m^3 (~2,900 acre-feet), and the single maximum volume was estimated at ~1.3×10^7 m^3 (~11,000 acre-feet). We reiterate that these are very rough estimates and may not relate to potential flood volumes.

Combining all imagery analysis (visual and quantitative) we estimate that the lake has drained regularly over the period of analysis (Table 2). Our analysis suggests that for most years in which imagery data are available between 2000 and 2012, there is evidence that the lake drained each year (although we have very low confidence in the evidence of drainage in 2011).

Table 2. Identified lake presence or absence for 38 unique days across 28 years (1985-2012; there are two images for 8/8/2005). Estimated lake area, surface elevation, and depth (measured at lake centroid) estimated for 24 unique days predominantly calculated using the NDWI; elevation and depth estimates from hand-digitizing high resolution imagery are listed in bold. Dates highlighted in grey represent dates where lake was drained.

Date	Type	Purpose	Lake Area (SqKm)	Surface Elev (m)	Centroid Depth (m)
8/10/1985	Landsat5 Bands 1-7	NDWI	0.25	342	45
6/26/1997	DOQQ (Aerial photo)	visual/digitized	lake visible (0.33)	**323**	**24**
9/8/1999	Landsat7 Bands 1-8	NDWI	0.20	297	42
9/26/1999	Landsat7 Bands 1-8	NDWI	0.20	305	34
8/11/2000	Landsat7 Bands 1-8	NDWI	0.18	304	10
9/9/2000	Color compressed Landsat7TM	visual/digitized	lake visible (0.13)	**322**	**22**
8/21/2001	Landsat7 Bands 1-8	NDWI	0.02	Base	0
9/6/2001	Landsat7 Bands 1-8	NDWI	0.00	Base	0
9/29/2001	Landsat7 Bands 1-8	NDWI	0.32	306	52
7/30/2002	Landsat7 Bands 1-8	NDWI	0.09	271	22
11/12/2002	Color compressed Aster L1B	visual	lake visible	NA	NA
9/14/2004	Landsat7 Bands 1-8	NDWI	0.25	287	35
7/15/2005	Landsat7 Bands 1-8	NDWI/Climate	0.24	276	34
8/8/2005	Landsat5 Bands 1-7	NDWI/Climate	0.34	290	45
8/8/2005	Color compressed IKONOS2	visual/digitized	lake visible (0.48)	**281**	**37**
8/9/2005	Color compressed Aster L1B	visual	lake visible	NA	NA
9/1/2005	Landsat7 Bands 1-8	NDWI/Climate	0.37	295	50
9/18/2005	Landsat5 Bands 1-7	NDWI/Climate	0.54	298	47
9/25/2005	Landsat5 Bands 1-7	NDWI/Climate	0.50	283	49
7/28/2007	Landsat7 Bands 1-8	NDWI/Climate	0.20	260	28
8/6/2007	Landsat7 Bands 1-8	NDWI/Climate	0.26	273	23
8/30/2007	Landsat5 Bands 1-7	NDWI/Climate	0.33	279	46
10/9/2007	Landsat7 Bands 1-8	NDWI	0.00	Base	0
8/8/2008	Landsat7 Bands 1-8	NDWI	0.04	Base	0
10/27/2008	Landsat7 Bands 1-8	NDWI	0.01	Base	0
7/9/2009	Landsat5 Bands 1-7	NDWI/Climate	0.44	272	44
9/4/2009	Aerial or ground-based photo	visual	lake drained	NA	NA
8/5/2010	Aerial or ground-based photo	visual	lake visible	NA	NA
8/23/2010	Color compressed Aster L1B	visual	lake visible	NA	NA
8/31/2010	Landsat5 Bands 1-7	NDWI/Climate	0.44	286	34
9/12/2010	Color compressed SPOT ortho t	visual /digitized	lake visible (0.49)	**281**	**42**
9/16/2010	Landsat5 Bands 1-7	NDWI/Climate	0.45	291	44
9/16/2010	Aerial or ground-based photo	visual	lake visible	NA	NA
8/11/2011	Aerial or ground-based photo	visual	lake visible	NA	NA
9/26/2011	Landsat5 Bands 1-7	NDWI/Climate	1.01	293	78
10/12/2011	Landsat5 Bands 1-7	NDWI/Climate	0.45	289	44
8/21/2012	Aerial or ground-based photo	visual	lake visible	NA	NA
10/9/2012	Aerial or ground-based photo	visual	lake drained	NA	NA
10/22/2012	Landsat7 Bands 1-8	NDWI	0.00	Base	0

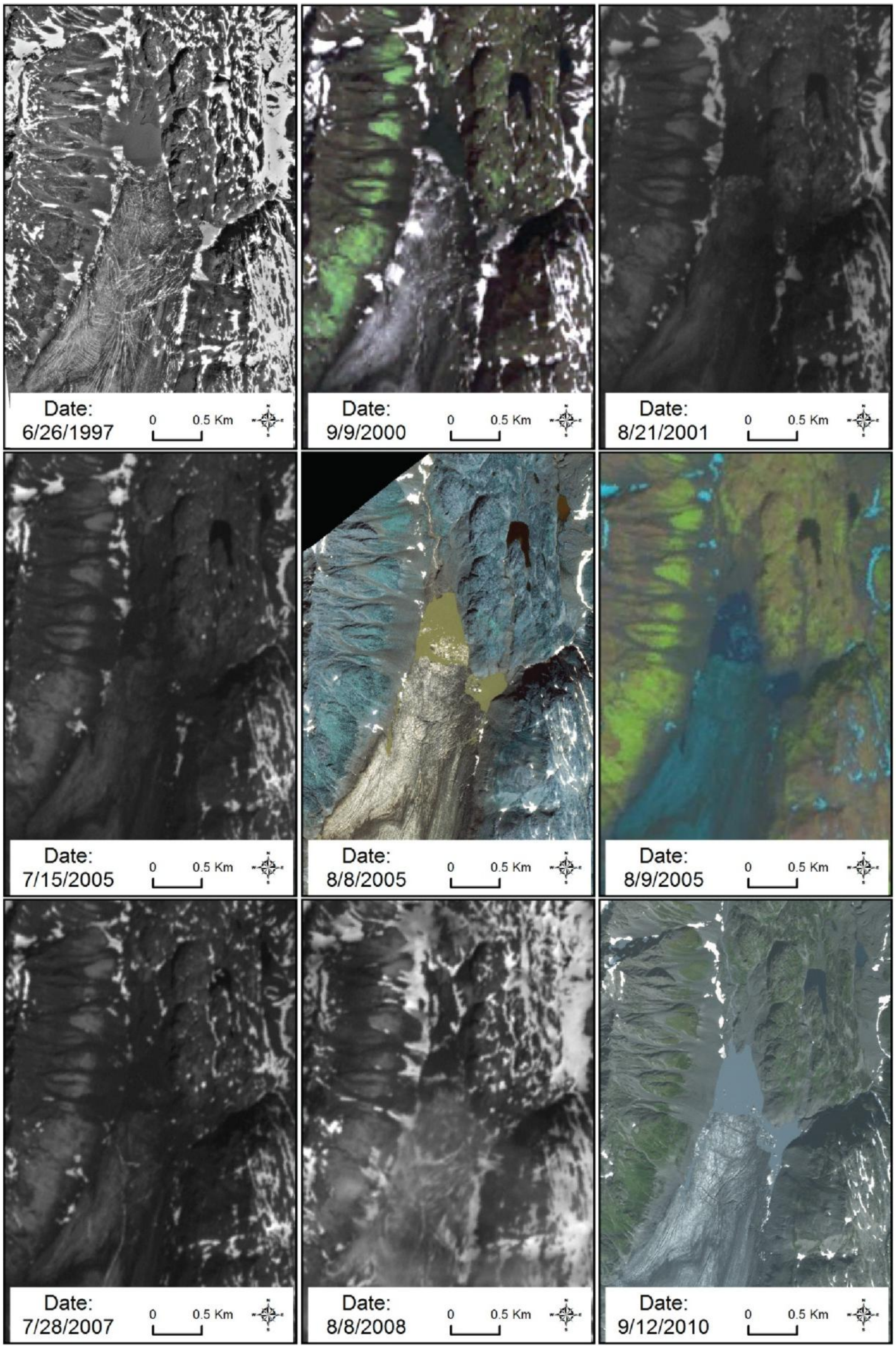


Figure 22. Remote sensing imagery of Ice Lake; specifications for all images are provided in Table 2.

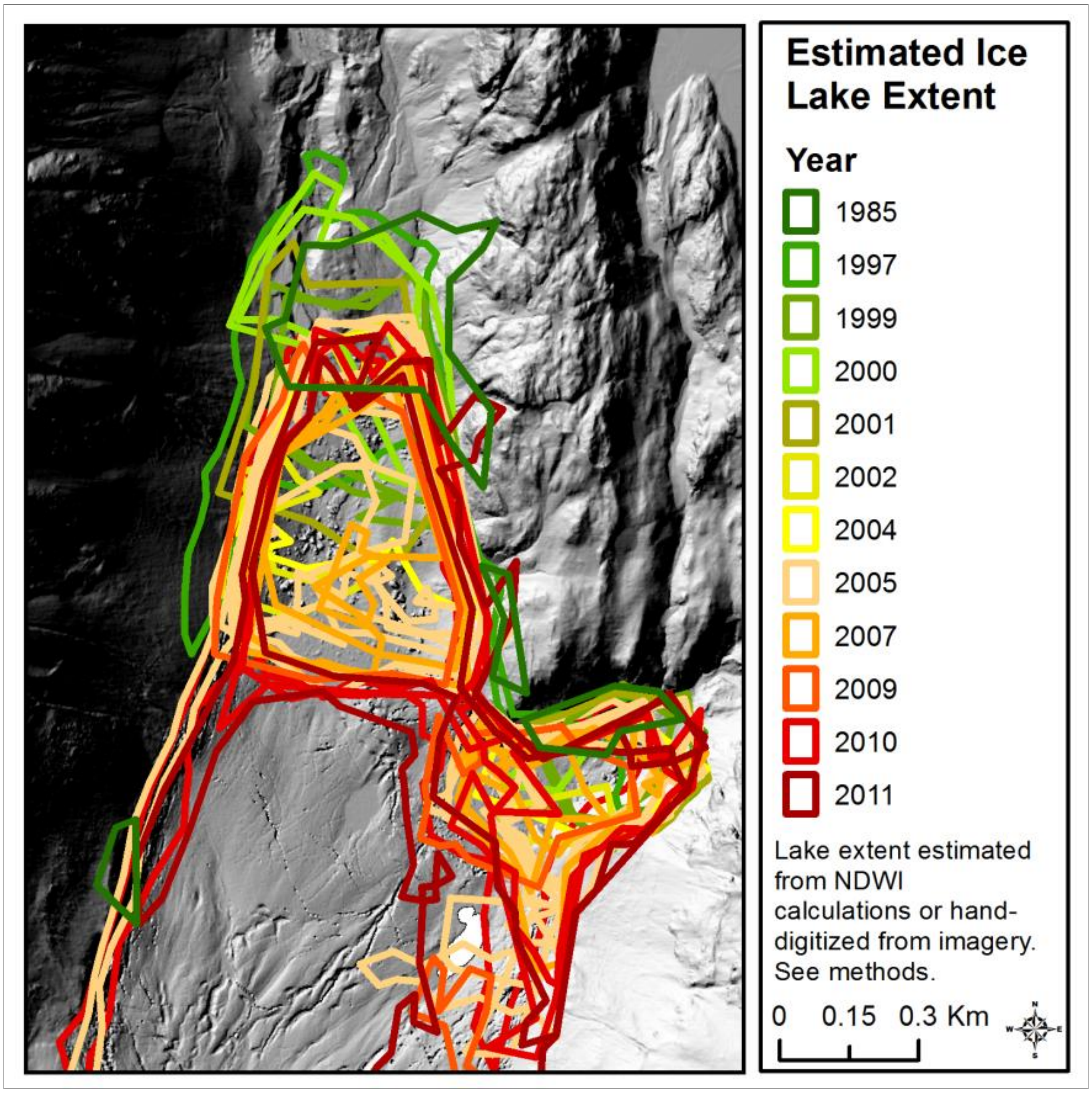


Figure 23. Estimated extent of Ice Lake, overlain on hillshade of Lidar-based DEM, in selected years between 1985 and 2011, illustrating down valley progression (note that 2011 estimates have considerable uncertainty).

Table 3. Evidence for Ice Lake drainage history.

Year	Source	Drain Certainty	Estimated Drain Date	Notes
2000	NDWI lake area calculations	Very Low	Fall 2000	NDWI estimated lake area at 0.18 km^2 on 8/11/2000 and lake was similarly sized on 9/9/2000 (from visual assessment). NDWI calculations show low to no lake area in early 2001 (0.02 on 8/21/2001 and 0.00 on 9/6/2001) and filling through the year (0.32 km^2 on 9/29/2001), suggesting drainage after 9/9/2000.
2001	NDWI lake area calculations	Very Low	9/30 - 10/31/2001	NDWI estimated lake area increasing between 9/6 (0.00 km^2) and 9/29/2001 (0.32 km^2). NDWI estimated lowered lake area (0.09 km^2) on 7/30/2002. *NOTE this could result from increased ice coverage in July 2002, masking water surface area.However, all other July area estimates were greater.*
2005-2006	NDWI lake area calculations	Low	9/26/2005 - 10/31/2006	Lake area estimates increasing through 2005 then again increasing through 2007, suggesting drainage between 9/25/2005 and 7/28/2007.
2007	NDWI lake area calculations	Low	9/1 - 10/8/2007	Lake area calculations illustrate sequence of increasing area (0.21 on 7/28, 0.26 on 8/6, 0.33 km^2 on 8/30) followed by no lake area identified from Landsat on 10/9/2007.
2008	User reports and NDWI lake area calculations	Moderate	7/15 - 8/16/2008	Kayak guides reported high water in Bear Glacier Lake on 8/19. We assume approximately 2 days for downglacial lake response (based on UM lake transducer data following 2010 GLOF). However, Landsat lake area calculations suggest low lake levels earlier and later in year (0.04 on 8/8, and remaining low throughout the fall 0.01 km^2 on 10/27), suggesting either Landsat image date was incorrectly recorded, lake drained earlier than reported by outfitters, GLOF was low-volume, or drainage conduit existed most of the summer, with continuous low-volume drainage.
2009	Aerial Photo, user reports	High	~8/15 - 9/3/2009	Aerial reconnaissance on 6/3/2009 indicated Ice Lake was full (Klasner, 2009a). Landsat lake area estimated at .44 km2 on 7/9/2009. Observations of water level increases at BGL in weeks of 8/15 and 8/23 (Klasner, 2009b) Photo of drained lake on 9/4/2009.
2010	UM Field Transducer Data	High	10/7 - 10/9/2010	Drainage of Ice Lake, starting on 10/8/10, recorded by UM pressure transducer. Landsat lake area estimates show full lake prior (.44 on 8/31 and .45 km^2 on 9/16), and photo from NOAA APRFC confirms lake existence on 9/16.
2011	NDWI lake area calculations	Very Low	9/27 - 10/11/2011	Lake area estimates show reduction from 1.0 on 9/26 to 0.45 km^2 on 10/12/2011. The NDWI lake area calculation for 9/26 is an outlier; automated area calculation may have misclassified topographical shading as water. If area calculation is correct, this suggests only partial drainage in 2011.
2012	User reports and aerial photos	High	8/24 - 8/28/2012	Aerial photos show drainage between 8/21 and 10/9. User reports state lake level rose 8/28 per Deb Kurtz. Landsat lake area estimated to be 0.0 km^2 on 10/22.

Climate Data Analysis

The average summer (7/1 -10/31) maximum air temperature, measured at the Kenai RAWS station for years 1999 – 2012 was 14.8°C. For years 2005-2012, the average was 14.6°C. The average maximum air temperature measured at the Harding Ice Field RAWS station for the same period was 4.1°C. The average total accumulated temperature by 10/31 recorded at the Harding Ice Field RAWS station between 2005 and 2012 was 529°C days. The average accumulated precipitation by 10/31 was 783 mm.

We plotted climate variables with lake area and drainage timing over the period from 1999-2012 (Figure 24). Although lake area increased as temperature and precipitation accumulated, there was low correlation between lake area (un-drained from NDWI) and temperatures (0.22) or precipitation (0.30) calculated for the associated imagery date (Figure 25). In a linear regression of lake area ~ accumulated temperature + precipitation, no terms were significant. However, there is very little power in the regression analysis, with only 13 data points with both lake area (> 0.05 km^2) and accumulated temperature and precipitation data available. Because we did not have actual dates of drainage in most instances, we could not conduct analyses between drainage date and accumulated temperature and precipitation. However, given the available imagery dates where analysis suggested that Ice Lake was drained, accumulated temperature or precipitation was sometimes below or near the annual average accumulated temperature or precipitation (Figure 25), suggesting that any temperature- or precipitation-dependent GLOF triggers are likely to be met annually.

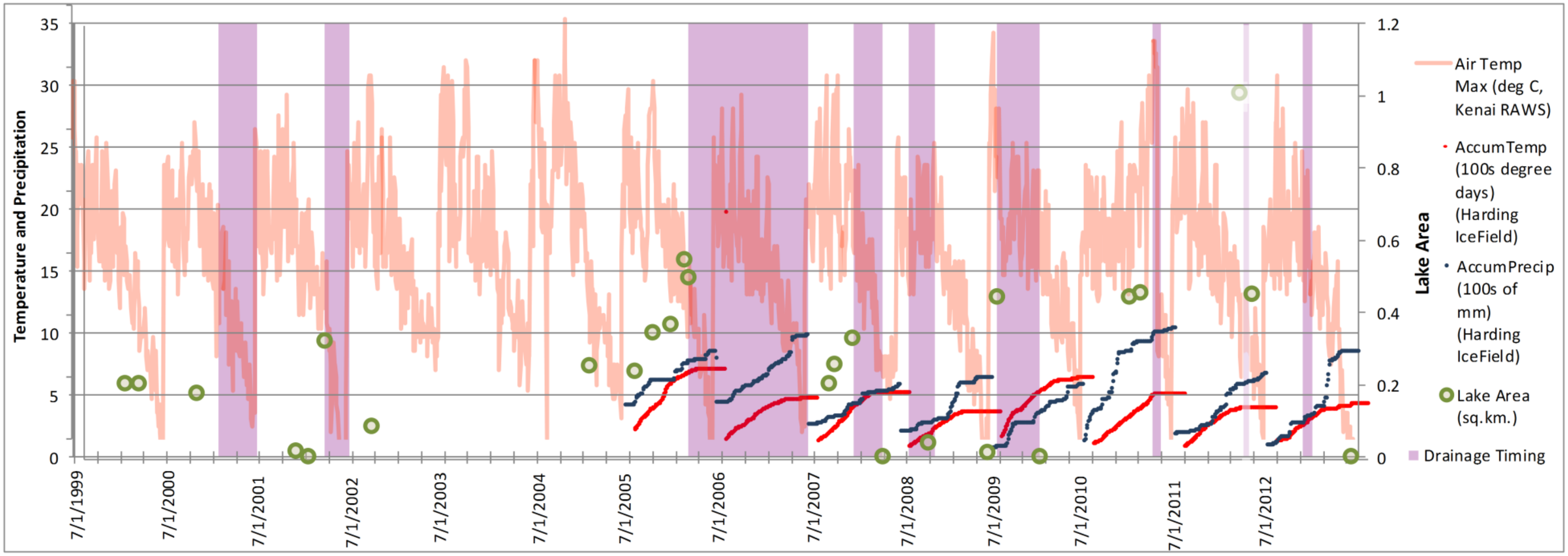


Figure 24. Summer climate variables of maximum daily temperature (orange, from Kenai RAWS station), accumulated average temperature and total accumulated precipitation (red and blue, respectively, from Harding Icefield RAWS station), and estimated lake area (green circles, from NDWI analysis) and period of timing when drainage likely occurred (purple). Calculated lake area of almost 1 km^2 in September 2011, and subsequent possible drainage, is displayed as transparent because of likely misclassification of water in NDWI analysis for that date.

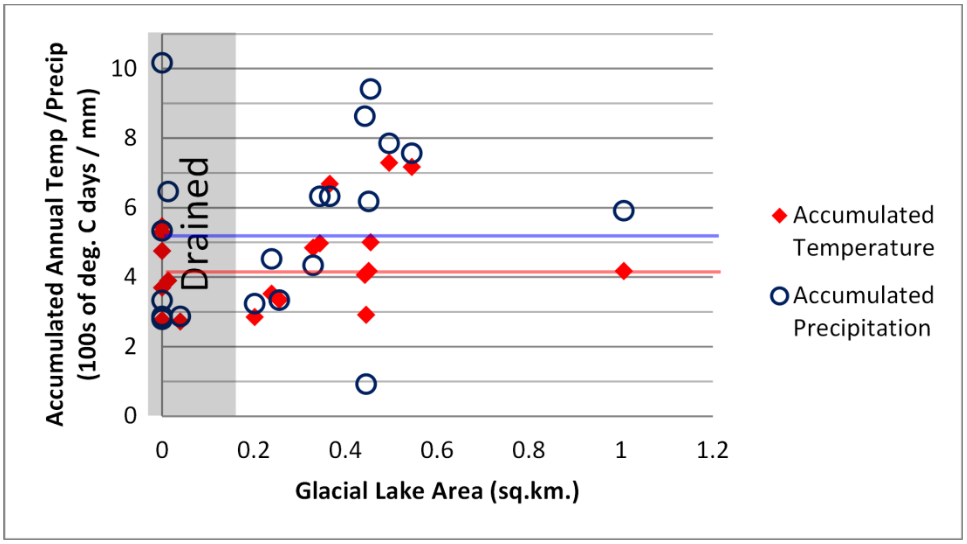


Figure 25. Relationship between climate variables and lake area estimated from NDWI analysis. There was a stronger correlation lake area (for un-drained lake estimates) and accumulated precipitation (0.30 correlation) compared to temperature (0.22 correlation). Red and blue horizontal line represents summer average accumulated temperature and precipitation, respectively (2005-2012 Harding Ice Field RAWS data).

Discussion and Conclusion

Our analysis provides insights into the drainage of Ice Lake and provides a first-pass qualitative assessment of the associated hazard potential at Bear Glacier Lake. Our analysis cannot be construed, however, as a risk assessment without further data to predict both the likelihood and magnitude of impact. Understanding the likelihood of impact requires knowledge of when kayakers and other recreational users are using Bear Glacier Lake, and understanding the magnitude of impact requires additional information concerning the amount of water released from glacial flooding and its influence on water levels in BGL relative to calving or other controls.

We found evidence that in recent years, Ice Lake has drained every year or two. There are few data sources available for estimating Ice Lake drainage frequency prior to 2005, although we found evidence for drainage in both 2000 and 2001. We also found that Ice Lake has migrated down-valley, to the south, since the 1990s (Figure 23). This result is consistent with field evidence of higher standlines and incision of the inlet stream that feeds Ice Lake (Figure 18, Figure 19). The most likely cause of these changes is thinning of the tributary glacier that blocks Ice Lake (and of the main trunk of Bear Glacier; VanLooy et al., 2006).

Our evidence also indicates that Ice Lake tends to drain in late summer or fall (August – October). Two recent events are especially well constrained: the mid-August 2008 event that provided some of the impetus for this study, and the early October 2010 event recorded with our pressure transducers. Other records of GLOFs on the Kenai Peninsula, on the Skilak and Snow Glacier glacial lakes, show that fall (September-November) drainages are most common (National Weather Service 2012b, 2012c).

Several of our results were surprising. We expected August to be the typical time of drainage events, based on the observations of the mid-August GLOF from Ice Lake in 2008 and on high temperatures and glacial melt in August relative to other times of year. Our pressure transducer documented drainage in early October 2010, and remote sensing analysis also showed evidence of drainage events later than August. We also expected that drainage events would occur rapidly (i.e., in a matter of hours), but our transducer showed that drainage from Ice Lake lasted more than two days in October 2010 (Figure 17).

A third expectation was that the largest water level increases at Bear Glacier Lake would occur as a result of down-glacier propagation of an Ice Lake GLOF. Numerous spikier (i.e., more rapid) changes in water level were recorded at Bear Glacier Lake compared to the more gradual signature of the Ice Lake GLOF, including one that caused a greater water level increase than the Ice Lake GLOF (Figure 16, Figure 17). The cause of those spikier changes in BGL's water level may be equipment malfunction, but calving from the terminus of Bear Glacier may also be recorded. Calving and associated rapid rises in water levels in BGL may also present a hazard to recreational users, in addition to Ice Lake GLOFs, which may manifest more gradually in BGL. Although the dynamics of flow routing through glaciers are extremely complex, drainage events from Ice Lake, after traveling 17.5 km through Bear Glacier to reach BGL, could be dampened by the time they reach BGL. Subglacial or englacial outburst events can, however, push out water stored within the glacier and thereby increase in volume as they propagate down-glacier (e.g., Sturm and Benson, 1985).

Our data are insufficient to determine trends in frequency of drainage events from Ice Lake. One can hypothesize that GLOF frequency has increased, for example as a result of warming temperatures and changes in Bear Glacier, but we do not have evidence to support or refute this hypothesis. Increased awareness of GLOFs may also be a function of increased recreational use of Bear Glacier Lake, rather than of any change in GLOF frequency. Warming increases the availability of meltwater for storage and transit within the glacier system (e.g., Arendt, 2011) and can cause thinning of ice blockages (Tweed and Russell 1999, VanLooy et al., 2006). Thus, the warming effect is likely non-linear, as water storage increases at the same time there is a decrease in the amount of water necessary to initiate a drainage event. Moreover, increased meltwater production under warming conditions does not necessarily correlate with increased discharge of that meltwater, because of the potential for increased water storage within glaciers (Harper et al., 2012).

As described above, the Pacific Decadal Oscillation (PDO) has been changing in phase in a manner that may produce cooling of Alaskan temperatures in the near future. As a result, trends toward increased warming-related changes in glacial activity may be temporarily tempered. Carbon emission-driven temperature increases are likely to eventually overtake PDO effects, however, which could result in continued changes in the geomorphological dynamics of Bear Glacier, Ice Lake, and Bear Glacier Lake. For example, continued thinning of the arm of Bear Glacier that blocks Ice Lake, which is ~ 3.5 km up a small arm from the main stem of Bear Glacier, could further reduce or eventually completely remove the ice blockage, allowing the current lake water to directly abut the trunk of Bear Glacier. Whether this would result in increased hazard (with substantially larger lake area covering the entire arm) or reduced hazard (changing drainage dynamics so that no water was retained in the lake) is unknown. Quincey et al. (2007) found that glacial dammed lakes are likely to persist when there is less than a 3.5%

slope between the dammed lake and glacial terminus. Although the slope between Ice Lake and the trunk of Bear Glacier is negative (there is a build-up of ice at the confluence), the slope along the trunk between the confluence and the glacial terminus is approximately 4% (over the glacial surface), and so the lake may or may not be stable without the damming ice in the sidearm channel.

Although remote sensing can provide insights into temporal changes in the size of glacial dammed lakes and into drainage history, developing quantitative understanding of glacial outbursts that are subsurface using remote sensing is extremely difficult because of their complexity (Kaab et al. 2005; Bjornsson et al., 2001). Available data were not sufficient for calculating likely flood volumes. We estimated lake volume, although these are rough, order-of-magnitude estimates with an uncertain relationship to flood quantities. Further, much of the GLOF floodwater may be stored subglacially and/or englacially (Tweed and Russell 2009). Therefore, the total flood discharge may be substantially higher than the volume stored within Ice Lake (Shuler et al. 2002 as cited in Wolfe et al. 2008). A hydrological study of Hidden Creek Lake on the Kennicott Glacier in Alaska found that up to 20% glacial flood volume came from storage within the glacier itself (Anderson et al. 2003).

Controls on and thresholds for drainage at Ice Lake remain uncertain. We found a low correlation with dates of imagery showing drainage and accumulated precipitation and temperature. This suggests that precipitation and temperature are not the direct triggers. Visual inspection of Figure 24 does suggest that lake area (which should be strongly correlated with lake volume) is related to Ice Lake drainage, with likely outbursts generally following the damming of sufficient water to create a lake area of between 0.35 and 0.5 km^2. Our rough calculations suggest that these lake-area values correspond with volumes between 3 and 5 million m^3 (~ 2400–4000 acre-feet), although as noted above, actual GLOF volumes may be greater because of subglacial water storage.

Studies of the Taku Glacier, Alaska suggest that water stage could be useful for predicting drainage dates (Neal, 2007), although our experiences revealed some of the challenges of determining lake depth and water levels in a setting such as Ice Lake. Despite our failure to find a strong relationship between climate variables, precipitation and temperature clearly influence streamflow inputs and therefore lake volume. Given the complexity of GLOF drainage dynamics (Tweed and Russell 1999), however, indirect measures of climate may be less useful than future field work to better estimate lake volume and stage. Determining the type of failure can help assess risk in the future. We suspect that Ice Lake drains via subglacial conduits, although a combination of mechanisms may contribute to drainage (reaching of some water depth threshold, ice flotation).

Suggested future work

The current report provides a preliminary investigation, yet a number of key questions remain:

- What are the discharge magnitudes of GLOFs from Ice Lake, and how do they vary between years? If Ice Lake drains at a particular water level threshold, this would suggest similar discharge magnitudes between years. Improved volume estimates could be used to estimate GLOF discharge using Clague and Mathews (1973) relation.

- How does the volume estimated based on the surface area of the lake relate to its actual volume? Is there a subglacial wedge of water beneath the ice that increases lake volume beyond what surface area would suggest, as observed by Anderson et al. (2003)?
- What controls changes in water level at Bear Glacier Lake, and what are the relative influences of GLOFs from Ice Lake, calving, and meltwater production from sources other than Ice Lake?
- Improved estimates of GLOF volume would assist risk assessment, as the volume of water not only drives the flood level, but also is likely the major trigger for GLOF events.

Future work could provide a more detailed understanding of GLOFs at Ice Lake and hazards at Bear Glacier Lake by implementing some combination of the following approaches, many of which would be low cost to implement and/or could be carried out by NPS interns:

- Implementing a more formal system of communication between NPS and sea-kayak guides, to provide information about potential hazards and to establish a reporting system for guides to report changes in water level at BGL.
- Implementing a more formal system of communication with bush pilots to gather information about Ice Lake drainage events.
- Interviewing past and present sea kayak guides about water level rise in BGL to learn about specific dates and magnitudes and rates of water level rise, and gathering photographic documentation from those guides. These efforts would take advantage of the substantial local knowledge that is likely available about changes at BGL, complementing what a scientific study can provide.
- An assessment of usage patterns at Bear Glacier Lake, including locations of camping areas and seasonal usage levels for comparison to potential GLOF timing. The timing of GLOFs from Ice Lake is important with respect to hazard potential. For example, if sea kayaking activity is lower in the fall, fall drainage events would cause less hazard then summer drainage. Indeed, the October 2010 GLOF documented by our pressure transducers was not reported anecdotally by recreational users. In years where overflights or anectodal information suggests that the lake is still full as of September, NPS may wish to issue additional warnings to fall users.
- Installation of a simple staff gage along the shore of BGL in the vicinity of sea-kayaking camps or at other shoreline sites commonly visited by kayakers, and implementation of a reporting system for guides or other kayakers to report water-level readings to NPS.
- Topographic surveying in the vicinity of sea-kayaking camps to determine the elevation of camps above BGL shorelines (and therefore, the water-level increase that would be required to inundate the camps). These surveys could be performed using basic level and stadia rod or total station methods.
- Establishment of a time-lapse photography program at Bear Glacier Lake. This could include (1) installation of interval cameras in the locations of camps used by kayakers and/or near the BGL shoreline (e.g., attachment of cameras to trees, as often used by hunters) to capture the timing of events that raise water levels in BGL and create inundation hazards; (2) installation of an interval camera aimed at the terminus of Bear Glacier to capture calving events; and (3) establishment of photo point stations where photos aimed at the same point on the landscape are repeated over time whenever someone is present to take the photos.

- Acquisition of higher resolution imagery (e.g., Quickbird) of Bear Glacier to develop a more accurate basis for remote sensing analysis. The work presented here relied entirely on free imagery.
- Measurements of the water chemistry at Ice Lake and BGL and associated tracer studies to understand flow routing between Ice Lake and BGL (analogous to methods used at Hidden Creek Lake on the Kennicott Glacier, e.g., Anderson et al., 2003).
- Stage and/or discharge measurements of the surface stream feeding the Ice Lake.
- Completion of a LiDAR survey at Ice Lake immediately following a drainage event, in order to determine the topography of the basin filled by Ice Lake and to determine depth-volume relationships.
- Continued remote sensing of ice thickness changes on Bear Glacier (e.g., VanLooy et al., 2006), which may influence the draining dynamics of the lake.

Regardless of what additional steps are taken to further understand Bear Glacier, Ice Lake, Bear Glacier Lake, and GLOF-related hazards, communication with the public about both current knowledge of these resources and about the uncertainties in natural-hazard forecasts (e.g., Stein and Geller, 2012) is essential.

Supplemental Data

As a supplement to this written report, maps and remote sensing products have been assembled in ArcGIS for electronic delivery to NPS.

Acknowledgments

We thank NPS personnel for their assistance, especially Fritz Klasner, Deborah Kurtz, Mark Kansteiner, and Michael Flanagan from Kenai Fjords National Park and Deanna Greco and Lisa Norby from the Geological Resources Division. We also thank Jeremy Marshment-Howell for field assistance in 2011. This work was funded by a cooperative agreement with the National Park Service via the Rocky Mountains Cooperative Ecosystem Studies Unit (Agreement Number: H2370094000)

References

Anderson, S. P., J. S. Walder, R. S. Anderson, E. R. Kraal, M. Cunico, A. G. Fountain, and D. C. Trabant (2003), Integrated hydrologic and hydrochemical observations of Hidden Creek Lake jokulhlaups, Kennicott Glacier, Alaska, *Journal of Geophysical Research-Earth Surface*, 108(F1), doi: 10.1029/2002jf000004.

Anderson, R. S., J. S. Walder, S. P. Anderson, D. C. Trabant, and A. G. Fountain (2005), The dynamic response of Kennicott Glacier, Alaska, USA, to the Hidden Creek Lake outburst flood, *Annals of Glaciology*, 40, 237-242.

Aðalgeirsdóttir, G., K. Echelmeyer, and W. Harrison (1998), Elevation and volume changes on the Harding Icefield, Alaska, *Journal of Glaciology, 44*(148), 570–582.

Arendt, A. A. (2011), Assessing the Status of Alaska's Glaciers, *Science*, *332*(6033), 1044-1045, doi: 10.1126/science.1204400.

Arendt, A. A., K. A. Echelmeyer, W. D. Harrison, C. S. Lingle, and V. B. Valentine (2002), Rapid wastage of Alaska glaciers and their contribution to rising sea level, *Science*, *297*, 382–386.

Arendt, A., K. Echelmeyer, W. Harrison, C. Lingle, S. Zirnheld, V. Valentine, B. Ritchie, and M. Druckenmiller (2006), Updated estimates of glacier volume changes in the western Chugach Mountains, Alaska, and a comparison of regional extrapolation methods, *Journal of Geophysical Research-Earth Surface*, *111*(F3), doi: 10.1029/2005jf000436.

Bartholomaus, T. C., R. S. Anderson, and S. P. Anderson (2008), Response of glacier basal motion to transient water storage, *Nature Geoscience*, *1*(1), 33-37, doi: 10.1038/ngeo.2007.52.

Bartholomaus, T. C., R. S. Anderson, and S. P. Anderson (2011), Growth and collapse of the distributed subglacial hydrologic system of Kennicott Glacier, Alaska, USA, and its effects on basal motion, *Journal of Glaciology*, 57(206), 985-1002.

Clague, J. J. and S. G.Evans (2000), A Review of Catastrophic Drainage of Moraine-Dammed Lakes in British Columbia. *Quaternary Science Reviews* 19.17–18: 1763-83.

Clague, J.J. and Evans, S.G. (1997), The 1994 jökulhlaup at Farrow Creek, British Columbia, Canada. *Geomorphology* 19, 77–87.

Clague, J.J. and Mathews, W. H . (1973), The magnitude of jökulhlaups. *Journal of Glaciology* 12, 501–504.

Costa, J.E. and Schuster, R.L. (1988), The formation and failure of natural dams. *Geological Society of America Bulletin* 100, 1054–68.

Eckert, G., E. Hood, S. Nagorski and C. Talus (2006), Assessment of coastal water resources and watershed conditions at Glacier Bay National Park and Preserve Alaska. National Park Service Technical Report NPS/NRWRD/NRTR-2006/353, http://www.nature.nps.gov/water/nrca/assets/docs/glba_coastal.pdf

Evans, S.G. and Clague, J.J. (1994), Recent climatic change and catastrophic geomorphic processes in mountain environments. *Geomorphology* 10, 107–28.

Glen, J. W. (1954), The stability of ice-dammed lakes and other waterfilled holes in glaciers: *Journal of Glaciology*, 2, 15:. 316-318.

Grover, S. (1997), An Investigation of the 1997 Abyss Lake Jökulhlaup in Glacier Bay National Park. National Park Service, Gustavus, AK.

Harper, J., N. Humphrey, W. T. Pfeffer, J. Brown, and X. Fettweis (2012), Greenland Ice-Sheet Contribution to Sea-Level Rise Buffered by Meltwater Storage in Firn. *Nature* 491, no. 7423: 240-43.

Hollister, J.W., W.B. Milstead, and M.A. Urrutia (2011), Predicting maximum lake depth from surrounding topography. PLoS ONE 6, no. 9: e25764. doi:10.1371/journal.pone.0025764.

Huggel, C., A. Kaab, W. Haeberli, B. Krummenacher (2003), Regional-scale GIS-models for assessment of hazards from glacier lake outbursts: evaluation and application in the Swiss Alps Natural Hazards and Earth System Sciences (2003) 3: 647–662.

Huggel, C., A. Kaab, W. Haeberli, P. Teysseire, and F. Paul (2002), Remote sensing based assessment of hazards from glacier lake outbursts: a case study in the Swiss Alps, *Canadian Geotechnical Journal*, *39*(2), 316-330, doi: 10.1139/t01-099.

Huggel, C. (1998), Periglaziale Seen im Luft- und Satellitenbild. Diploma thesis, Department of Geography, University of Zurich.

Kaab, A., C. Huggel, L. Fischer, S. Guex, F. Paul, I. Roer, N. Salzmann, S. Schlaefli, K. Schmutz, D. Schneider, T. Strozzi, and Y. Weidmann (2005), Remote sensing of glacier- and permafrost-related hazards in high mountains: an overview, *Natural Hazards and Earth System Sciences*, *5*(4), 527-554.

Klasner, F. (2009a), Email from Fritz Klasner, NPS, 6/5/09.

Klasner, F. (2009b), Email from Fritz Klasner, NPS, 9/14/09.

Kurtz, D. (2012), Email from Deborah Kurtz, NPS, to A. Wilcox, UM. 12/20/12.

Liestøl, O. (1956), Glacier dammed lakes in Norway, *Norsk Geog. Tidsskr.*, 15: 122-149.

Lindsey, C. (2008), Email from Chuck Lindsay to Fritz Klasner, NPS, 8/25/08.

Molnia, B.F. (2008), Glaciers of North America: glaciers of Alaska, *in* Williams, R.S., Jr., and Ferrigno, J.G., eds., Satellite image atlas of glaciers of the world: U.S. Geological Survey Professional Paper 1386-K, 525 p.

Moore, R. D., S. W. Fleming, B. Menounos, R. Wheate, A. Fountain, K. Stahl, K. Holm, and M. Jakob (2009), Glacier change in western North America: influences on hydrology, geomorphic hazards and water quality, *Hydrological Processes*, *23*(25), 3650-3650, doi: 10.1002/hyp.7575.

Nagorski, S., E. Hood, S. Pyare, and G. Eckert (2008), Assessment of Coastal Water Resources and Watershed Conditions *Lake Clark National Park and Preserve* , US Department of the Interior, National Park Service, Natural Resource Technical Report NPS/NRPC/WRD/NRTR—2008/144.

NASA and USGS (2008), Alaska's Bear Glacier: Change over time. Goddard Space Flight Center. LG-2008-3-120-GSFC. http://landsat.gsfc.nasa.gov/pdf_archive/bear_glacier_4web.pdf

National Weather Service (2012a). Selected glacier dammed lakes on the Kenai Peninsula. Alaska-Pacific River Forecast Center, NOAA, http://aprfc.arh.noaa.gov/general/bear_basin_gdl.php.

National Weather Service (2012b), Skilak Glacier Dammed Lake Dump History. Alaska-Pacific River Forecast Center, NOAA, http://aprfc.arh.noaa.gov/general/skilak_history.html

National Weather Service (2012c), Snow Glacier Dammed Lake Dump History, Alaska-Pacific River Forecast Center, NOAA, http://aprfc.arh.noaa.gov/general/snow_history.html

Neal (2007), Hydrology and glacier-lake outburst floods (1987-2004) and water quality (1998-2003) of the Taku River near Juneau, Alaska, USGS Scientific investigations report 2007-5027

Nichols, R.L., and Miller, M.M. (1952), The Moreno Glacier, Lago Argentino, Patagonia, *Journal of Glaciology*, 2: 41-50.

Post, A. and L.R. Mayo (1971), Glacier dammed lakes and outburst floods in Alaska. Department of the Interior, US Geological Survey. Hydrologic Investigations Atlas HA-455. http://ak.water.usgs.gov/glaciology/glacier_dammed_lakes/HA455/HA-455%20Text.pdf

Quincey, D. J., Richardson, S. D., Luckman, A., Lucas, R. M., Reynolds, J. M., Hambrey, M. J., & Glasser, N. F. (2007). Early recognition of glacial lake hazards in the Himalaya using remote sensing datasets. *Global and Planetary Change*, *56*(1), 137-152.

Roberts, M. J., A. J. Russell, F. S. Tweed, and O. Knudsen (2000), Ice fracturing during jokulhlaups: Implications for englacial floodwater routing and outlet development, *Earth Surface Processes and Landforms*, *25*(13), 1429-1446, doi: 10.1002/1096-9837.

Richardson, S. D., and J. M. Reynolds (2000), An overview of glacial hazards in the Himalayas, *Quaternary International*, *65-6*, 31-47, doi: 10.1016/s1040-6182(99)00035-x.

Roberts, M. J. (2005), Jokulhlaups: A reassessment of floodwater flow through glaciers, *Reviews of Geophysics*, *43*(1), doi: 10.1029/2003rg000147.

Rupp, S. and Loya, W. (2009), Scenarios Network for Alaska And Arctic Planning, Projected climate change scenarios for Alaska national parks, Kenai Fjords National Park. http://www.snap.uaf.edu/attachments/KenaiFjords_ClimSum.pdf

Stein, S. and R. J. Geller (2012), Communicating uncertainties in natural hazard forecasts. EOS Transactions American Geophysical Union 93(38).

Sturm, M., Benson, C.S., (1985), A history of jökulhlaups from Strandline Lake, Alaska. *Journal of Glaciology* 31, 272-280.

Sturm, M., Benson, C., and MacKeith, P. (1986), Effects of the 1966-68 eruptions of Mount Redoubt on the flow of Drift Glacier, Alaska, U.S.A. Journal of Glaciology **32**, no. 112: 355-362.

Thorarinsson, S. (1939), The ice dammed lakes of Iceland with particular reference to their values as indicators of glacier oscillations, *Geog. Annaler, Arg.* 21, Ht. 3-4: 216-242.

Tryggvason, E. (1960), Earthquakes, jökulhlaups and subglacial eruptions, *Jokull, Årg.* 10: 18-22.

Tweed, F. S., and A. J. Russell (1999), Controls on the formation and sudden drainage of glacier-impounded lakes: implications for jokulhlaup characteristics, *Progress in Physical Geography*, *23*(1), 79-110, doi: 10.1177/030913339902300104.

VanLooy, J., R. Forster, and A. Ford (2006), Accelerating thinning of Kenai Peninsula glaciers, Alaska, *Geophysical Research Letters*, *33*(21), doi: 10.1029/2006gl028060.

Walder, J. S., D. C. Trabant, M. Cunico, A. G. Fountain, S. P. Anderson, R. S. Anderson, and A. Malm (2006), Local response of a glacier to annual filling and drainage of an ice-marginal lake, *Journal of Glaciology*, *52*(178), 440-450, doi: 10.3189/172756506781828610.

Wendler, G., L. Chen, and B. Moore (2012), The first decade of the new century: a cooling trend for most of Alaska, Open Atmospheric Science Journal 6: 111–116.

Wiles, G. C., and P. E. Calkin (1994), Late Holocene, high-resolution glacial chronologies and climate, Kenai Mountains, Alaska, *Geological Society of America Bulletin*, *106*(2), 281-303, doi: 10.1130/0016-7606(1994)106<0281:lhhrgc>2.3.co;2.

Wolfe, D. F. G. (2008), Glacier dammed ice marginal lakes of Alaska: Changes since 1971, MS thesis, Alaska Pacific University.