



2008 Icefield and Glacier Monitoring, Research, and Management Strategy

Kenai Fjords National Park





ON THIS PAGE

Fresh snow frosts a crevasse field on the Harding Icefield above Exit Glacier in October 2013.
NPS Photo, Deb Kurtz

ON THE COVER

The end of the ablation season on the Harding Icefield. September 2017
NPS Photo, Deb Kurtz

2008 Icefield and Glacier Monitoring, Research, and Management Strategy

Kenai Fjords National Park

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Executive Summary

In 2008 Kenai Fjords National Park held a workshop to develop a glacier monitoring and research strategy to identify issues, management objectives, and priorities associated with the Harding Icefield and glaciers; to define a ‘core’ program for recurring work; and to prioritize additional projects which further the mission of Kenai Fjords National Park. This document summarizes the results of that workshop and outlines a structured glacier monitoring program for the park.

The Harding Icefield and its outflowing glaciers are fundamental landscape components and ecosystem drivers on the southern Kenai Peninsula and are central to the mandates of Kenai Fjords National Park. In 2008, Kenai Fjords National Park held a glacier monitoring workshop to develop a strategy to address research and monitoring needs for the entire Harding Icefield, including inputs to the icefield (climate), the geometry of and changes to the ice itself, outputs (loss through melting and runoff [i.e. stream hydrology and oceanographic processes]), and influences on the terrestrial and marine environments created by the icefield and glaciers (landscape history, geomorphology, hydrology, etc.). They also sought to identify key links to other resources (e.g., fish, wildlife, and vegetation) that are dependent upon or influenced by the icefield.

The resultant 2008 glacier monitoring strategy is divided into two main components, a core and an expanded program. The ‘core’ program identifies the minimum elements that the park strives to achieve including:

- Weather and climate monitoring through establishment of weather stations
- Mass balance measurements
- Decadal icefield area and extent monitoring
- Surface elevation profiling
- Ice flow measurements
- Repeat aerial photography of Exit Glacier
- Repeat photography of coastal glaciers
- Terminus mapping

The ‘expanded’ program identifies the elements beyond the minimum that the park will strive to complete, both recurring and one-time efforts, including:

- The installation of additional weather stations for a broader geographic distribution
- Annual Equilibrium Line of Altitude mapping
- Increased frequency and extent of elevation data collection

- The installation of additional ablation stakes for a broader geographic distribution of mass balance and ice flow measurements
- Opportunistic satellite imagery acquisition

Acknowledgments

We would like to thank all of the participants of the 2008 Glacier Monitoring Workshop identified in Appendix B. We would particularly like to thank Brooke McFarland for compiling a thorough bibliography (current in 2008) of glacier research relative to the Harding Icefield.

List of Terms

¹Definitions taken directly from Cogley et al. 2011

²Definitions taken from the National Snow and Ice Data Center's *Cryosphere Glossary*
<https://nsidc.org/cryosphere/glossary>, accessed on 11/7/2018

Ablation¹: all processes that reduce the mass of a glacier

Ablation Area¹: the part of a glacier where ablation exceeds accumulation in magnitude

Accumulation¹: all processes that add to the mass of a glacier

Accumulation Area¹: the part of a glacier where accumulation exceeds ablation in magnitude

Accumulation Area Ratio (AAR)¹: the ratio, often expressed as a percentage, of the area of accumulation zone to the area of the glacier

Equilibrium Line of Altitude (ELA)¹: the spatially averaged altitude of the set of points on the surface of the glacier where the climatic mass balance is zero at a given observation

Glacier¹: a perennial mass of ice, and possibly firn and snow, originating on the land surface by the recrystallization of snow or other forms of solid precipitation and showing evidence of past or present flow

Icefield¹: a large ice body that covers mountainous terrain but is not thick enough to obscure all of the subsurface topography, its flow therefore not being predominantly radial as is that of an ice cap.

Mass Balance¹: the change in the mass of a glacier, or part of the glacier, over a stated span of time

Outburst Flood (Jokulhlaup)²: any catastrophic flooding from a glacier; may originate from trapped water in cavities inside a glacier or at the margins of glaciers or from lakes that are dammed by flowing glaciers

Surging Glacier²: a glacier that experiences a dramatic increase in flow rate, 10 to 100 times faster than its normal rate; usually surge events last less than one year and occur periodically, between 15 and 100 years

Introduction

The National Park Service (NPS) is committed to understanding the status and long-term trends of natural resource and ecosystem functions within Kenai Fjords National Park (KEFJ), including the Harding Icefield. In 2006, the NPS Southwest Alaska Network of the Inventory and Monitoring program (SWAN) identified glacier extent as a vital sign for consistent and frequent monitoring to measure and document the extent and rate of change of KEFJ's glacier margins on a decadal scale (Bennet et al 2006). Monitoring glaciers helps scientists and managers understand environmental impacts of climate change and implications of melt. It also provides information regarding management and socio-economic implications, which enhance the ability of park managers to provide a safe and educational visitor experience, a mission of the region identified by Goal #9 of the Alaska National Resource Program Implementation Plan 2013-2018 (Adema 2014). The Harding Icefield has been the focus of numerous glacier studies including changes in areal extent (Giffen et al. 2014; Loso et al. 2014; Rice 1987), surface elevation (Larsen et al. 2015; Loso et al. 2014; Arendt et al. 2002; Adalgeirsdottir et al. 1998; Sapiano et al. 1998; Van Looy et al. 2006), ice thickness (Truffer and Habermann 2011, Truffer 2014), and flow rates (Burgess et al. 2013; Rice 1987). Due to its accessibility, Exit Glacier has been the focus of additional glacier studies including terminus position monitoring (Kurtz and Baker 2016; Tetreau 2006; Tetreau 1989) and snow monitoring (Klasner 2008; Tetreau 2006).

In September 2008, KEFJ held a glacier strategy workshop with the intent to identify and prioritize glacier-related research and monitoring needs for the park and surrounding area. Proposed outcomes and products from the workshop included a final report/proceedings to address the identified objectives, a summary of project statements, and suggested parameters of an icefield program for Kenai Fjords National Park. This document serves as the final report of the workshop results.

Purpose & Need for a Strategy

Like most glaciers around the world, Alaska's glaciers are shrinking. The state's glaciers cover an area of 43,745 km², 8% less than just 60 years ago (Loso et al. 2014). Glaciers are prominent features along Alaska's southcentral and southeastern coast and in the interior mountains of the Alaska Range. Although glacial ice is unique in itself, its importance also lies in the role it plays in adjacent ecosystems. Changes in glacial mass alters water regimes in mountain watersheds and can result in sudden outburst floods as well as drought (Bliss and Radić 2014; O'Neel et al. 2014; Rhoades et al. 2008) and changes to freshwater nutrients and biodiversity (Hood and Berner 2009; Hood et al. 2009; Neal et al. 2010; Jacobsen et al. 2012; Robinson et al. 2001). In fjord ecosystems where glacial systems transition into the marine environment, impacts to a host of physical and chemical changes such as decreased iceberg production and changes to oceanographic properties such as temperature and salinity can impact marine wildlife and seabirds (O'Neel et al. 2015; Lydersen et al. 2014; Hoover-Miller et al. 2011).

Glaciers are highly sensitive to changes in precipitation and temperature and are therefore widely used as indicators of climate change (Leclercq et al. 2014, Arendt et al. 2009, Molnia 2007, Oerlemans et al. 1998). Almost all glaciers worldwide are experiencing melt as measured through

changes in length, area, volume, and mass. This diminution of glacial ice is expected to continue given current climate observations and future predictions (Vaughan et al. 2013). Perhaps one of the greatest threats of melting glaciers on a global scale is their contribution to sea level rise. Currently, 40% of the world's human population lives within 100 kilometers of the coast (CIESIN 2005), and 67 % of the megacities (defined as urban zones with more than 10 million inhabitants) are located at the coast (Von Glasow et al. 2013). Globally, glacial ice covers more than 15 million square kilometers (10% of total land surface) and provides storage for approximately 75% of the world's freshwater (NSIDC 2016). Nearly half of the glacial meltwater contributions to sea-level rise come from outside of the polar ice sheets (Meier et al. 2007) and of these nonpolar regions, Alaska's glaciers are the greatest contributors (Gardner et al. 2013).

The Harding Icefield and Grewingk-Yalik ice complex are two of the fundamental landscape components and ecosystem drivers on the Kenai Peninsula and are central to the mandates of Kenai Fjords National Park, Kenai National Wildlife Refuge, and Kachemak Bay State (Wilderness) Park. With staff turnover and the increasing prominence of issues such as climate change and coastal and ocean stewardship, it became clear that an improved awareness of past work and clearly identified existing information needs would benefit site managers. In particular, in 2008 Kenai Fjords staff set out to develop a strategy that would:

1. Apply recommendations from previous (NPS) glacier research and monitoring workshops, addressing themes of research, monitoring, ecological implications, hazard mitigation, impacts of climate change, public outreach, partnerships, etc.
2. Update existing lists of identified issues, management objectives, and project priorities focused on the Harding Icefield.
3. Incorporate management considerations of institutional and fiscal limitations—such as staff turnover, limited cyclical funding, and short-turnaround time for opportunities—to develop an applied program while fulfilling agency mandates associated with the Harding Icefield.
4. Define a 'core' glacier program for the Harding Icefield, given anticipated funding, staffing, logistical, and other constraints that could reliably be accomplished each year.
5. Prioritize elements of an expanded Harding Icefield program, including research and draft project statements (goals, objects, spatial extent, temporal frequency, methods, logistical considerations, cost estimates, etc.).
6. Identify suggested responses to funding calls, i.e. USGS partnership mapping, climate change initiatives, etc. for KEFJ, other Alaska Region National Parks, and with partner agencies.

This strategy addresses the entire icefield, including inputs (climate); the ice itself; outputs (loss through melting and runoff [i.e. stream hydrology] and calving); and the terrestrial and marine environments affected by the icefield and glaciers (landscape history, geomorphology, etc.). It also identifies key links to other resources—fish, wildlife, vegetation, and oceanography for example—that are dependent upon or influenced by the icefield. Issue scoping was accomplished through a

brainstorming session with park staff and preliminary review of a draft strategy through a workshop of NPS, US Geological Survey, and university partners; both held in fall 2008.

Resource Description

The Harding Icefield is located in the Kenai Mountains of the Kenai Peninsula in Alaska. Named for United States President Warren G. Harding, it provides spectacular scenery from the coast and interior of the Kenai Peninsula. The Harding Icefield is one of four icefields in the United States and is the largest icefield contained entirely within the United States. The Harding Icefield and surrounding glaciers encompass approximately 1,902 square kilometers with the Grewingk-Yalik complex covering an additional 424 square kilometers (as of 2000, Giffen et al. 2007). Management responsibility for these areas are primarily under jurisdiction of Kenai Fjords National Park (typically coast-terminating glaciers) and Kenai National Wildlife Refuge (typically land-terminating glaciers) with upper reaches of the icefield split between the two entities (Figure 1). Alaska State Parks has jurisdiction over portions of the Grewingk-Yalik complex.

The management purposes of these land-owning entities are defined by Federal and State law. The Alaska National Interest Lands Conservation Act (ANILCA) P.L. 96-487 (2 Dec. 1980) established Kenai Fjords National Park and expanded Kenai National Wildlife Refuge. The legislation identifies that park purposes include:

“to maintain unimpaired the scenic and environmental integrity of the Harding Icefield, its outflowing glaciers, and coastal fjords and islands in their natural state; and to protect seals, sea lions, other marine mammals, and marine and other birds and to maintain their hauling and breeding areas in their natural state, free of human activity which is disruptive to their natural processes” (ANILCA sec. 201(5)).

ANILCA (sec. 303(4, B)) identifies that refuge purposes include “to ensure, to the maximum extent practicable and in a manner consistent with the purposes set forth in paragraph (i), water quality and necessary water quantity within the refuge”; and “opportunities for scientific research, interpretation, environmental education, and land management training”. Alaska Statutes establish the purposes of Kachemak Bay State Park and Kachemak Bay State Wilderness Park to protect and preserve the land and water for its unique and exceptional scenic and wilderness value.

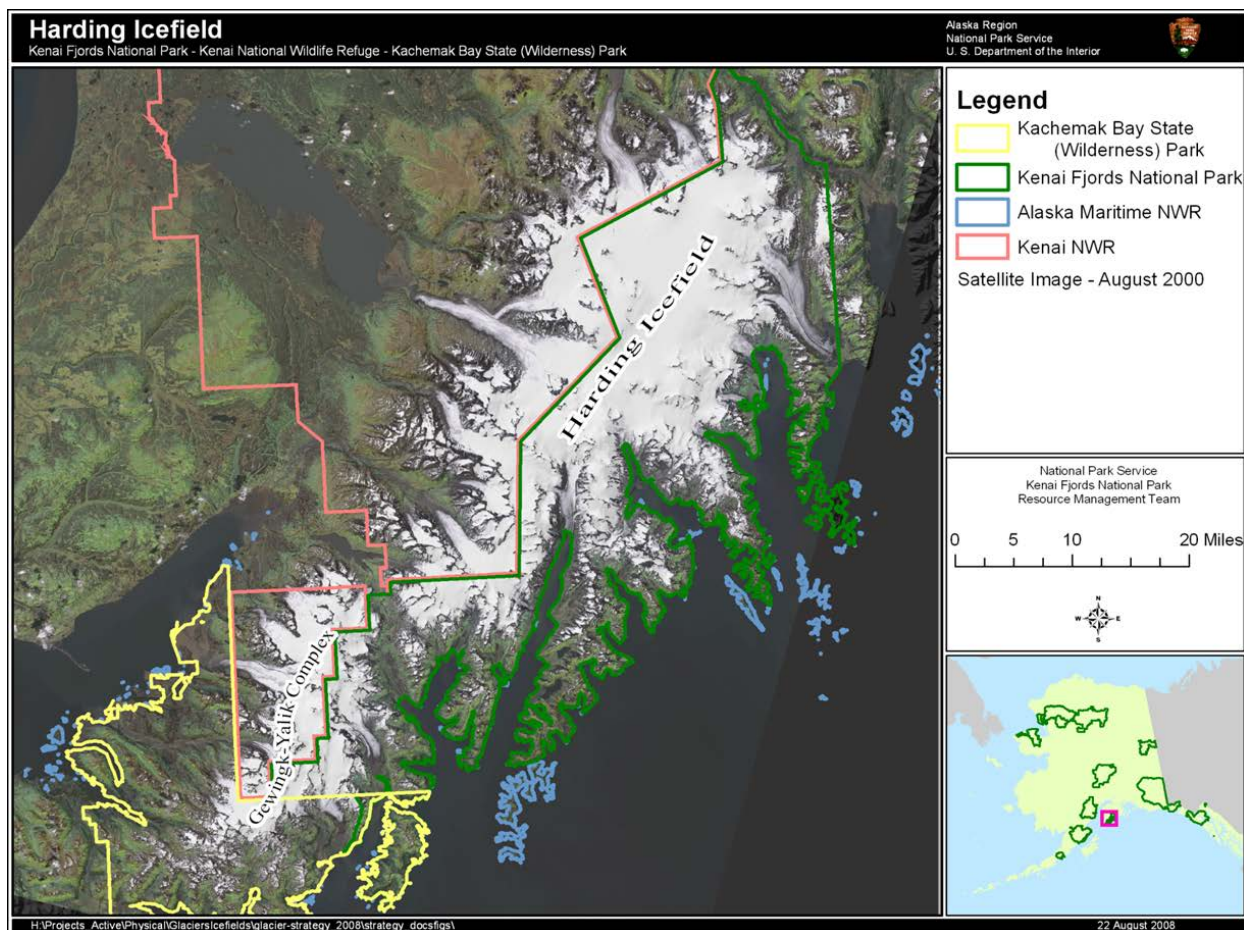


Figure 1. Map of Harding Icefield, including boundaries of Kenai Fjords National Park, Kenai National Wildlife Refuge (NWR), Alaska Maritime NWR, and Kachemak Bay State Park and State Wilderness Park.

Management Guidance

The NPS Natural Resource Reference Manual #77 provides comprehensive information in support of programmatic operations on a variety of topics, including glaciers (<http://www.nature.nps.gov/rm77/geology/ProgramGuide.cfm#Glacial>, visited 27 August 2008, excerpted below).

Table 1. NPS Natural Resource Reference Manual #77 excerpts on management relevance of glaciers.

RM 77 Section	Management Relevance
Glaciers and Glacial Features and Processes	• The primary concerns for managing glaciers and glacial processes and features are ecosystem integrity, visitor and employee safety, and visitor impacts. • Glaciers supply vast quantities of meltwater to lakes and streams (colder, turbid, and buffer low summer flows). • Glaciers are also valuable as indicators of regional climate change. • Inventories of glaciers should be conducted approximately every 10 years (form, length, surface area, top elevation, bottom elevation, and margin activity). • Monitoring should focus on two areas: marginal activity and surface mass balance.
Visitor and employee safety and impacts	• Large chunks of snow, ice, and rock commonly fall off of glaciers, particularly at their margins. • Some glaciers are also known to produce catastrophic floods known as "jokulhaups" or "outburst floods". • Glacial deposits are also hazardous because they are typically unstable. Ice cores, complex stratigraphy, a lack of vegetation cover, over-steepened slopes (caused by glacial erosion and glacier retreat, which removes lateral support to moraine deposits), and other factors contribute to the instability of glacial deposits.

Although formally no longer considered a valid guiding management document, the park's most recent "Resource Management Plan" identifies a suite of projects intended to encompass the range of glacier-related issues in the park (Kenai Fjords National Park 1999; excerpted below).

Table 2. Potential glacier-related projects identified In the Kenai Fjords National Park Resource Management Plan (1999).

RMP Section	Potential Project Title
Program Administration & Planning	• Develop a Park and Regional Glacial Resource Program • Inventory Existing Glacier Photo-documentation • Coordinate Glacial Resource Program with Others
Research	• Investigate Surge-Type Glaciers to Determine Mechanism & Periodicity • Surficial Geology Map – Glacial Geology and Glacial Histories
Mitigation	• Evaluate Glacial Flood Potential
Monitoring	• Benchmark Glacier Monitoring Network • Meteorological and Hydrological Monitoring at Benchmark Glaciers • Single-Stake Mass Balance Monitoring Sites in each Region • Remote Sensing Monitoring Program of Glacier Mass Balance • Exit Glacier Terminus Monitoring • Research and Monitoring of Additional Surge-Type Glaciers
Interpretation	• Encourage Public Awareness of Park Glaciers

In addition, Kenai Fjords National Park’s enabling legislation is unique even among ANILCA parks. Glaciers are explicitly identified as a resource, along with the connection to biological and ecological resources. In addition, to fulfill the enabling mandate of ensuring environmental integrity we need to look beyond park boundaries—to Kenai National Wildlife Refuge, Kachemak Bay State (Wilderness) Park, and beyond.

Significance of the Harding Icefield

The geographic (regional, national, and international) and scientific significance and uniqueness of the Harding Icefield is an important facet for guiding research, monitoring, and communication about the resource. This significance informs park management in the broader context of National Park Service and KEFJ mandates. The following elements were identified by workshop participants:

- The icefield exhibits asymmetry, with marine-terminating glaciers to the east (including glaciers still in tidewater, tidal lake, and supra-marine stages) and land-terminating glaciers to the west (including glaciers terminating in lakes as well as on land). This affords opportunities for interpretation of glacier sensitivity to climate (change) and the influence of terminus geography on mass balance and geometry.
- The topographic orientation and size of the icefield (and Kenai Mountains)—perpendicular to the prevailing storm track, with majority of outflowing glaciers being parallel to this storm track—is not as clearly evident in other icefields and makes for a more manageable system to study.
- The geographic position of the icefield, with fjords opening directly into the Gulf of Alaska as opposed to into protected embayments such as Prince William Sound or the larger fjords of southeast Alaska, creates a strong climatic gradient from maritime to continental settings across a very compact area. This also makes tidewater glaciers accessible.
- The latitude (approximately 60° North), terrain relief, and moderating maritime influences keep the annual average air temperature close to freezing (0° C) – resulting in ice features that reflect the signals of storm tracks and latitudinal and elevation shifts in temperature while bridging continental/polar and mid-latitude glacial systems.

Other characteristics, lack of high elevation accumulation areas for example, were considered important characteristics from an analytical perspective but are not unique.

Management Goals

Five broad management goals were developed for, and are used to guide, this strategy. These goals are intended to span and inform all aspects of park (or refuge) management, including interpretation, visitor protection, science & learning, and facility management.

1. Track the environmental integrity of the Harding Icefield;
2. Inform management decisions regarding visitor use, visitor experience, and facility management;
3. Relate changes in the Harding Icefield to the status of aquatic, marine, and terrestrial ecosystems, and vice-versa;

4. Link observations of the Harding Icefield to scientific research on climate and ecosystem change occurring at regional and international scales;
5. Provide factual information on glacial processes, change, and related resources to managers and the public.

Objectives

Specific objectives were identified for initial workshop planning. These workshop objectives have been adapted to guide this strategy. These are intended to be specific, measurable conditions that can be accomplished through identifiable tasks.

- Identify index or representative glaciers and sites that can be used to characterize the larger icefield;
- Monitor icefield mass balance of index glaciers on an annual basis;
- Monitor the extent and area of the icefield and other glaciers on a decadal interval;
- Facilitate existing research and monitoring, including:
 - continued climate monitoring;
 - periodic measurements of icefield geometry;
 - repeat photography; and
 - population, distribution, and habitat characterization of ice-dependent biota; and
- Provide regular, annual at a minimum, updates useful for senior park managers and interpreters (such as a presentation, executive brief, photo pairs, or other concise summaries).

Previous Research on the Harding Icefield

A variety of entities engage in research and monitoring with the intent of better understanding the icefield and its associated resources. This section provides a brief overview of the types of recurring work that has been conducted. It is not intended to be exhaustive, but rather summarize and provide perspective on the institutional sources where such work originates.

Pre-2008 Program Efforts

Pre-2008 research and monitoring on the Harding Icefield is summarized in Appendix A “Harding Icefield 2008 Bibliography” and summarized by Tetreau (2006). The majority of work conducted by NPS staff was focused on terminus position mapping, elements of mass balance data collection, and ice flow. Exit Glacier was the most common field site, due to the convenient road access to the terminus.

2008 Program Efforts

The National Park Service, U.S. Fish & Wildlife Service, and Alaska State Parks independently administer their own research and monitoring efforts. It is anticipated that this structure will continue, albeit with improved coordination and collaboration, particularly related to icefield and glacier related projects, as a result of this strategy.

National Park Service

In 2008 Kenai Fjords National Park staff were mapping the terminus position of Exit Glacier each fall, were monitoring the annual movement of a radio transmitter on the surface of Exit Glacier, and were measuring winter snow accumulation near the upper reaches of Exit Glacier each spring. These park efforts were completed based on annual staff and fund availability, and documented and communicated on a sporadic basis. Ice flow monitoring via radio transmitter on Exit Glacier ceased in 2009 as the methods were dependent upon a 12+ year-old transmitter battery.

SWAN staff monitor icefield extent on a 5-10 year basis (in collaboration with the National Aeronautical and Space Administration (NASA), Dr. D. Hall). In July 2004 SWAN installed a weather station on a nunatak in the northeastern part of the Harding Icefield (various other entities maintain weather stations around the ice field perimeter, see Davey et al. 2007). The SWAN efforts were determined through development of a ‘Vital Signs’ monitoring plan, are documented and communicated according to standards outlined in this plan and are anticipated to continue into the foreseeable future (Bennett et al. 2006).

U.S. Fish & Wildlife Service

In 2008, no systematic or recurring icefield or glacier program existed within Kenai National Wildlife Refuge. Research and monitoring is conducted, with management support, by other federal agencies and universities.

Alaska State Parks

In 2008 no systematic or recurring icefield or glacier program existed within Kachemak Bay State Park and State Wilderness Park. Research and monitoring is conducted, with management support, by other federal agencies and universities.

Universities, Other Agencies, & Non-Profit Organizations

The U.S. Geological Survey (USGS) has no systematic program focused on the Harding Icefield, beyond regional, national, or global summaries that may be prepared. Individual USGS staff conduct various research on the icefield however, such as the work done by Bruce Molnia (see bibliography, recent efforts have emphasized repeat photography and interpretation of landscape history and vegetation succession).

The Alaska-Pacific River Forecast Center and the U.S. Geological Survey monitor hydrologic conditions in several streams flowing from Harding Icefield glaciers, with the River Forecast Center focusing more on public safety elements, and the USGS focusing on scientific uses of the information collected. Glacial outburst flood monitoring on the Snow River and Skilak Glacier are two examples of this type of work.

The University of Alaska (Fairbanks) and other universities engage in a range of research efforts. Glacier surface elevation profiles, post Ice Age uplift, terrain dating and landscape history, and stream hydrology are several examples of the types of research conducted by universities in Alaska and from ‘outside’ of Alaska.

Proposed Strategy

This strategy addresses field activities, data management, analysis and synthesis of existing data, and communication. This strategy uses the comprehensive ‘ecological monitoring framework’ (Fancy et al. 2009) as an overarching guide to ensure the full suite of environmental topics are considered (Table 1). Within this overarching framework, glacier and icefield specific issues are refined using “A Strategy for Monitoring Glaciers” (Fountain et al. 1997), and adaptations made as implemented by Adema (2008), Fagre (2008), and Riedel et al. (2007). The NPS has held several workshops to discuss glaciers and broader geologic priorities (see for example Adema and Bucki 2003 and Graham 2005). These workshops have consistently identified key scientific themes and partnership opportunities, with gradual evolution in methods with technological improvements. This strategy capitalizes on these efforts and is intended to help institutionalize the recommendations received.

The basic scientific premise of Fountain et al. (1997) and this strategy is to employ a nested approach where intensively studied glaciers are surrounded by less intensively studied glaciers and those monitored solely by remote sensing. The intensively studied sites provide a detailed understanding of the physical processes and their temporal changes. The less intensively studied glaciers are used to assess the variability of such processes within the region. The USGS already maintains nearby Wolverine Glacier as one of their intensively studied glaciers; and we hope to leverage their existing efforts and nest our work on the Harding Icefield at a regional level. Exit Glacier has the longest history of monitoring in the park and will continue to be a focus. In general, our field activities (implemented in 2009) are centered on a suite of stake-based mass balance index sites, analogous to the methods implemented by Adema (2008) in Denali National Park. After several years of monitoring we believe an analysis of site correlations will be appropriate (Harding Icefield data to Wolverine Glacier, as well as correlations of index sites within the Harding Icefield). This correlation will inform park managers of the applicability of trends in nearby sites when interpreting a specific glacier’s mass balance as well as guide decisions as to long-term levels of field data collection required.

Connecting glacial processes to fish, wildlife, and vegetation resources is accomplished largely through identification of potential collaborations. Such potential project ideas are identified, but not to the same level of detail as projects which fall under the themes highlighted in the strategy. These connections and linkages will be pursued further in the context of existing fish, wildlife, and vegetation programs. Glaciological data collected, analyzed, and reported will address these connections.

The proposed program is divided into two main components, a core and an expanded program. The ‘core’ program identifies the minimum elements that the park will strive to complete. The ‘expanded’ program identifies the elements beyond the minimum that the park will strive to complete, both recurring and one-time efforts.

Table 3. Framework for Harding Icefield and glacier program: adapted from USGS ‘Strategy for Monitoring Glaciers’ (Fountain et al. 1997) embedded within the NPS ecological monitoring framework (Fancy et al. 2009). Element(s) emphasized in this strategy are shaded blue.

Focus Area	Sub-topic	Process	Activity
Air and Climate	Air Quality		
	Weather and Climate	Weather and Climate	Weather & Climate • Station-based data • Regional climate modeling and synthesis
Geology and Soils	Geomorphology	Windblown Features and Processes	
		Glacial Features and Processes	Mass Balance • Mass balance (seasonal, net ,as function of elevation) • Equilibrium line altitude • Accumulation area ratio Geometry • Glacier area / extent • Terminus position • Surface elevation Supplementary Measurements • Underlying bed topography • Ice flow velocity
		Hillslope Features and Processes	
		Coastal / Oceanographic Features and Processes	
		Marine Features and Processes	
		Stream / River Channel Characteristics	
		Lake Features and Processes	
	Subsurface Geologic Processes	Seismic Activity	
	Soil Quality	Soil Function and Dynamics	
	Paleontology		
Water	Hydrology	Groundwater Dynamics	
		Surface Water Dynamics	Streamflow – discharge / stage height
		Marine Hydrology	
	Water Quality	Water Chemistry	Streamflow - water quality
Biological Integrity	Invasive Species		
	Infestations and Disease		
	Focal Species or Communities		
	At-risk Biota		

Table 3. Continued

Focus Area	Sub-topic	Process	Activity
Human use	Point Source Human Effects	Point Source Human Effects	
	Non-point Source Human Effects	Non-point Source Human Effects	
	Consumptive Use	Consumptive Use	
	Visitor and Recreation Use	Visitor Use	Infrastructure Commercial Use Authorization (analysis & mitigation)
	Cultural Landscapes	Cultural Landscapes	
	Hazard mitigation	Assessment Vulnerability Awareness Preparedness	Outburst floods, Icefall, Landslides
	Interpretation & Education	Interpretation Education	
Landscapes (Ecosystem Pattern and Processes)	Fire and Fuel Dynamics		
	Landscape Dynamics	Land Cover and Use	
	Extreme Disturbance Events	Extreme Disturbance Events	
	Nutrient Dynamics		
	Energy Flow		

Core Program

The core program identifies the minimum elements that the park will strive to complete. In several instances, these are elements funded and maintained through other programs, which to the best of our knowledge will be sustained. Detailed project statements were considered but rejected for inclusion in this strategy. Rather, broad goals are identified for each program element, a brief summary of how each project addresses the four Harding Icefield significance elements (1) asymmetry, with marine-terminating glaciers to the east and land-terminating glaciers to the west, 2) topographic orientation and size of the icefield (and Kenai Mountains) perpendicular to the prevailing storm track; 3) a strong climatic gradient from maritime to continental settings across a very compact area; and 4) ice features that reflect the signals of storm tracks and latitudinal and elevation shifts in temperature while bridging continental/polar and mid-latitude glacial systems). Management goals and objectives identified in this strategy will be addressed on a project-by-project basis and are not reiterated here.

Weather & Climate

Existing data collection efforts (Harding Icefield Remote Automated Weather Station (RAWS), McArthur Pass RAWS, and Exit Glacier COOP) will continue. Upgrading the existing manual cooperative weather station at Exit Glacier to an automated Natural Resource Conservation Service (NRCS) SNOTEL site is also being pursued.

This addresses documentation of the storm track and storm signal, along with documenting potential shifts in continental and maritime climate systems. Additional detail on proximate and distal pro-glacial climate patterns in fjord systems is still desirable. This element will be conducted in close collaboration with SWAN and Kenai National Wildlife Refuge.

Mass Balance

Mass balance will be monitored on a transect of five index sites across the icefield climate gradient, from the Southeast (a marine terminating glacier) to the Northwest (a land terminating glacier). Precise site locations, to the extent possible, will be located along existing elevation profile lines as monitored by University of Alaska Fairbanks. As an example, the five sites would consist of two on Aialik Glacier, one near Harding Icefield weather station (northwest of the station), and two on the land-terminating glacier between Lowell & Skilak Glaciers. Sites will be monitored two times per year with access via aircraft. Field activities will include: spring visits (snow cores (accumulation) measured and ablation stakes placed or re-measured); fall visits (ablation stakes re-measured); and both spring and fall (precision GPS measurement of stake location and elevation to document flow). Methods will be coordinated with other regional monitoring and results reported to the World Glacier Monitoring Service.

This addresses documentation of asymmetry, topographic orientation relative to the storm track, the gradient from maritime to continental climate systems, and detection of storm signals in glaciers. This effort represents the primary field component of this strategy and will be coordinated by KEFJ staff with in-kind support sought from SWAN and Kenai National Wildlife Refuge.

Geometry

Icefield area and extent monitoring will continue on a decadal interval. This work is independently conducted by SWAN with NASA.

Elevation profiles, conducted by University of Alaska Fairbanks, should be actively supported to ensure work continues on roughly a 5-year interval using existing methods (laser altimetry or new methods that provide opportunity for comparison with historic data and research conducted by C. Larsen).

Elevation profiles for mass-balance monitoring sites will be derived from GPS data of stake location collected under the mass-balance section of this strategy. Additional fixed coordinate or repeated transects of GPS elevation data in the vicinity of these five mass balance sites may be initiated to expand upon the index (point) concept.

These three elements address all four elements of significance for the Harding Icefield. Icefield extent is supported by SWAN, elevation profiles by the University of Alaska Fairbanks (C. Larsen),

and monitoring stakes by the park. KEFJ should actively support and assist these efforts however possible.

Supplementary Measurements

- Repeat photography of glacier termini, of at least the named glaciers every ten years (icefield-wide), will be linked to logistics of other field projects as time permits. Existing databases and protocols for photography will be adapted to limit setup time.
 - Time-lapse photography of marine-terminating tidewater glaciers, already collected by the Alaska SeaLife Center, will be reviewed to document ice flux and calving rates.
- Ice Flow will be monitored through derived measurements of mass-balance stake positions with each visit to monitor mass balance.
- Exit Glacier: we will continue data collection at Exit Glacier emphasizing interpretive and education uses. This is the second element with a substantial field component; partnerships will be pursued to engage local community in these Exit Glacier activities.
 - Repeat (aerial) photography of Exit Glacier will be collected on an ad hoc basis. This need not be geo-registered photography (can be registered post-hoc from existing benchmark coordinates or assisted by ground-based photography) nor does it need to occur every year.
 - An additional mass balance stake will be added near the day-trip access location to measure flow velocity and emphasize the potential for citizen science. This will also allow for convenient training and practice with use of field equipment.
 - Terminus position will be documented each fall using GPS (and aerial photography when available). Additional (terminus position) measurements by park interpretive staff will be supported upon request.

These elements address Harding Icefield significance in slightly different ways, with the Exit Glacier emphasis providing finer-grained temporal resolution as a potential example applicable to other glaciers, a site for testing and refining methodologies, and providing desired interpretive and facility planning information. All four significance elements (asymmetry, topographic orientation, maritime to continental gradient, and storm system response) are addressed by icefield wide repeat photography and ice flow measurements at mass balance stakes. Additional ice flow (surface) documentation is still desirable to both understand topographic bounds as well as better understand ice dynamics and its ecological role.

Hydrology & Water Quality

No new data collection. We will continue existing Exit Creek data collection and coordinate with the Alaska-Pacific River Forecast Center.

Biology

No new data collection. There is an outstanding need to emphasize relevance of glacier and icefield to biological systems. These elements are not the focus of this strategy.

Human Use

No new data collection. There is an outstanding need to emphasize relevance of human use of the icefield. The KEFJ cultural resource and visitor resource and protection programs are also pursuing elements of human use knowledge acquisition. These elements are not the focus of this strategy.

Terrestrial & Marine Ecosystems

No new data collection. There is an outstanding need to emphasize relevance of the icefield and glaciers to ecological systems. These elements are not the focus of this strategy.

Expanded Program

The expanded program identifies the elements beyond the minimum that the park will strive to complete, both recurring and one-time efforts. These could be completed either on an ad hoc basis or added to the suite of regularly planned park activities. Detailed descriptions of program elements can be found in Appendix D covering draft core, expanded, and project statements.

Weather & Climate

Augment existing climate data collection with additional high-elevation stations.

Add NRCS aerial snow survey markers to monitor winter snow accumulation.

Geometry

Map glacier Equilibrium Line Altitude (ELA) once per year in fall on a minimum of eight glaciers (icefield wide). Requires a fixed wing overflight with minimum of one person to draw on maps, an extra person to do repeat photography could be included. This is not likely to be successful every year as visual interpretation is subjective and can be difficult. Photographs of the ELA region should be an integral product of the ELA mapping.

Supplementary Measurements

- Increase the extent (and frequency) of elevation data collection (i.e. LiDAR every 5-years).
- Increase ice-flow velocity (and thus ablation stake) measurements beyond core program mass-balance sites.
- Opportunistically acquire satellite imagery to be used to delineate the icefield extent; when field and weather conditions are good or in conjunction with other program efforts.

Projects

Projects are defined as one-time efforts to inform park management and ongoing monitoring (many of which could be repeated for additional value after several years). They are presented here in approximate priority order (as opposed to using the recommended framework found elsewhere in this strategy). In some cases, this information may already exist and simply needs broader awareness, or additional limited research is needed, and in other cases the information has not been previously collected.

Projects necessary for further research and interpretation of core program data, as well as general park management:

1. After sufficient data has been collected, compare (correlate) Harding Icefield and Wolverine Glacier mass balance data. This correlation will provide a scientific foundation for determining level of effort needed for Harding Icefield monitoring.
2. Map bed topography for main Harding Icefield as well as outflowing glaciers for mass balance calculations (i.e. glacier grounding line to determine calving flux-- as our tidewater glaciers are presumably grounded this would identify the potential shoreline position) as well as for modeling of ice and landscape dynamics. Initially ground-based, use ground penetrating radar; consider airborne radar for broader spatial extent. Seismic soundings are an alternative in areas where radar methods are a limitation.
3. Survey icefield biota, including both nunatak and ice-resident species. Information is needed to ensure sensitive species, critical habitat, and highly productive areas are not impacted by Commercial Use Authorizations (CUAs), and for environmental compliance (to prepare National Environmental Policy Act (NEPA) documentation associated with motorized use on the icefield for example).
4. Map surficial geology, including moraine dating. This is necessary for hazard analyses as well as general park interpretation (see also KEFJ Geologic Resource Evaluation [Graham 2005]). Hazards include mass-wasting (both land and submarine), ice fall, and outburst floods.

High Priority projects requiring prior research:

1. Evaluate calving flux and submarine melt processes. Requires bed topography data.
2. Model the icefield to illustrate past dynamics and likely future changes (see, for example, models of Mendenhall Glacier). Initial emphasis could be on Exit Glacier and other 'high-visitation' glacial fjords. These could be mass balance models to look at the history of the icefield and make rough projections into the future about sensitivity to climate change. They could also be ice dynamics models, including differentiating proportions (volume) which are land terminating versus marine terminating—requires bed topography data and general data compilation.

High Priority projects that can be conducted independent of other work:

1. Identify the relationship between glacier calving rates and seal distribution and abundance. Contact Alaska Sea Life Center to inquire of existing and/or future efforts on this topic (Hoover-Miller and Armato 2018; Hoover-Miller et al. 2011).

2. Prepare a GIS-based glacier inventory (set of metrics—ELA, AAR, area, watershed basins, etc.). For an example see chapter by Manley in *Glaciers of North America: Glaciers of Alaska* (<http://pubs.usgs.gov/pp/p1386k/>, http://pubs.usgs.gov/pp/p1386k/pdf/10_1386K_alaskarange.pdf#page=19).
3. Conduct an icefield dynamics research project to document ice depth, flow divides, and ice flow field and velocities. Could be completed in approximately three years duration.

Other projects (both lower priority as well as items which do not fit well in the above structure):

1. Conduct atmospheric deposition, wet and dry, in using WACAP-like methods investigations.
2. Conduct a hazard analysis (outburst flood sites, mass wasting, etc.). Requires surficial geology mapping.
3. Develop a synthesis of oceanographic data related to icefield processes. Requires bed topography data. Can use many existing oceanographic data streams.
4. Prepare time series (animations, maps) of termini since Little Ice Age, including retreat chronology of valleys (stump dating, dendrochronology, cosmogenic dating).
5. Quantify streamflow (discharge): coordinate interest and efforts with partners given high cost. This information is useful but not required for mass balance, could also be useful to answer questions of what fraction of Kenai (and other Kenai Peninsula river systems) are from the icefield.

Strategy Implementation

The following lists are steps and suggestions for implementing the strategy.

General Guidelines and/or Suggestions

- Develop desired condition and then monitor associated indicators and standards.
- Do not neglect the need for integrating physical and biological indicators (vital signs), tie glaciers to the larger ecosystem and other monitoring efforts. Illustrate how glaciers affect ecosystems.
- Keep short-term (annual) products in mind, with an interpretive element; in addition to long-term goals.
- Focus on glacier and icefield work on geographic regions which overlap with other programs (e.g., marine monitoring, climate stations, hydrologic monitoring, etc.).
- Try to anticipate (climate) changes and likely future resource conditions: what data is needed to validate these forecasts?
- Keep it simple such that the program can survive lean budget periods, staff changes, evolving park priorities, etc.
- Make it attractive for others to conduct research. Logistical help is important to bring in outside researchers (housing, transportation within the park, etc.). Even small amounts of funding can make a difference.
- Glaciology field courses at several universities rotate among sites. These represent an opportunity to have intensive research conducted at a site (e.g., Exit Glacier). The only ‘cost’ to the park would likely be logistical support, housing, etc.
- Continue to provide an opportunity for visitors to contact a glacier.

Timeframes

Specific activities are prioritized by year, beginning with 2009 as year 1. Should an activity not be accomplished in the specified year, it is intended that it will ‘roll-over’ to the following year as a priority, unless explicitly determined otherwise.

Year 1:

Equipment Procurement:

- Mass balance stakes using USGS (Wolverine Glacier) methods and materials;
- Steam drill, portable Heucke ice drill; and

- Snow corer, Kovacs drill.

Field Activities:

- Spring mass-balance measurements continue from previous years (i.e. snow pit data);
- Spring site scoping for proposed 'Core' program sites;
- Place mass balance stakes in Exit Glacier (summer or fall); and
- Additional Exit Glacier measurements (terminus position, photography) coordinated with park interpreters.

Meetings & Coordination:

- Draft complete strategy, distribute to partner agencies for review.
- Discuss and identify potential wildlife, habitat, and ecosystem linkages with KEFJ, Alaska SeaLife Center, and Kenai National Wildlife Refuge staff.

Data Management & Analysis:

- Methods and tools from existing programs in support of data collected in field activities will be acquired, revised, and used to the fullest extent possible.
- Exit Glacier terminus position geodatabase will be completed.
- Exit Glacier 2007 terminus position mapped from existing aerial photography.

Reporting:

- Annual thematic program reporting (from previous year) will be completed.
- Climate change talking points will be prepared, integrating cryosphere publications.
- Glacier strategy completed.

Projects (from Expanded Program as funding permits):

- Ice thickness (ground penetrating radar) project submitted for consideration, revised for subsequent year submission if necessary.
- Geospatial glacier inventory project proposal prepared for consideration in 2010.

Safety Considerations:

Acquire and use existing Job Hazard Analysis and other safety materials from existing programs (North Cascades, Denali, and Glacier National Parks, USGS, and University of Alaska Fairbanks).

(Annual) Work Plan

Subsequent years are defined in the annual work plan with this strategy informed and updated by completed projects.

Elements Included

The framework provides a link to the management agencies' goals, objectives, and priorities within the context of glacier and icefield efforts. Identified elements of each program activity are summarized in the format shown below. Data management, analysis, and synthesis considerations include staff time (the default estimate is that equivalent of one third of time/resources be devoted to data management, unless experience proves otherwise). Communications considerations also include staff time and cost, as well as identify target groups. Each element identifies common themes including staff time, cost estimates, opportunities for partnerships, and leveraging work of colleagues. Core and expanded options are included.

- 1) Framework topic
 - a) Justification – Link to agency policy
 - b) Objectives (tied to goals)
- 2) Field
 - a) Extent / Scope
 - b) Selected Glaciers – Sites
 - c) Temporal frequency
 - d) Methods
 - e) Parameters
 - f) Logistical Considerations
 - i) Cost
 - ii) Staff: time, expertise, training
 - iii) Environmental compliance
 - iv) Site access
 - v) Partners
- 3) Data Management
 - a) Responsibility
 - b) Time commitment
 - c) Access and Sharing
- 4) Analysis & Synthesis

- a) Extent / scope of analysis
 - b) Frequency
 - c) Logistical considerations
 - i) Who
 - ii) Cost
- 5) Communication
- a) Target groups
 - b) Frequency

Review and Revision

There will be a five-year review and data analysis of core elements. This strategy should be reviewed and updated on a decadal basis.

Literature Cited

- Adalgeirsdottir, G., K.A. Echelmeyer, W.D. Harrison. 1998. Elevation and volume changes on the Harding Icefield, Alaska. *Journal of Glaciology*. 44: 570-582.
- Adema, G. 2008. Glacier Monitoring in Denali National Park and Preserve. In: Alaska Park Science. Available from:
<http://www.nps.gov/akso/AKParkScience/symposium2006/adema.pdf> (visited 16 August 2008).
- Adema, G. 2014. The Alaska Natural Resource Program implementation plan 2013-2018. Natural Resource Report NPS/AKRO/NRR-2014/764. National Park Service, Fort Collins, Colorado.
- Adema, G. and A. Bucki. 2003. Transcripts and presentations from: National Park Service Central and Southwest Alaska Network (CAKN/SWAN) Inventory and Monitoring Program Glacier Monitoring Scoping Workshop. National Park Service, Fairbanks, Alaska, 13 November 2003.
- Arendt, A.A., K.A. Echelmeyer, W.D. Harrison, C.S. Lingle, and B. Valentine. 2002. Rapid wastage of Alaska glaciers and their contribution to rising sea level. *Science*, 297: 382-386.
- Arendt, A., J. Walsh, and W. Harrison. 2009. Changes of glaciers and climate in northwestern North America during the late twentieth century. *Journal of Climate*. 4117-4134.
- Bennett, A.J., W.L. Thompson, and D.C. Mortenson. 2006. Vital Signs Monitoring Plan, Southwest Alaska Network. National Park Service, Anchorage, AK
- Bliss, A., R. Hock, and V. Radić. 2014. Global response of glacier runoff to twenty-first century climate change. *Journal of Geophysical Research Earth Surfaces*, 119: 717–730.
- Burgess, E.W., R.R. Forster, and C.F. Larsen. 2013. Flow velocities of Alaskan glaciers. *Nature Communications*, 4:2146. DOI: 10.1038/ncomms3146.
- CIESIN, Columbia University. 2005. Percentage of total population living in coastal areas. Indicator profile for the UN Commission on Sustainable Development. Palisades NY: CIESIN.
- Cogley, J.G., R. Hock, L.A. Rasmussen, A.A. Arendt, A. Bauder, R.J. Braithwaite, P. Jansson, G. Kaser, M. Möller, L. Nicholson and M. Zemp. 2011. Glossary of glacier mass balance and related terms, IHP-VII Technical Documents in Hydrology No. 86, IACS Contribution No. 2, UNESCO-IHP, Paris.
- Davey, C.A., Redmond, K.T., Simeral, D.B. 2007. Weather and Climate Inventory, National Park Service, Southwest Alaska Network. Natural Resource Technical Report NPS/SWAN/NRTR—2007/045. National Park Service, Fort Collins, Colorado.

- Fagre, D. 2008. Glacier Monitoring Studies – Monitoring and Assessing Glacier Changes and Their Associated Hydrologic and Ecologic Effects in Glacier National Park (website); <http://www.nrmssc.usgs.gov/research/glaciers.htm> (visited 21 August 2008).
- Fancy, S.G., J.E. Gross, and S.L. Carter. 2009. Monitoring the Condition of Natural Resources in US National Parks. *Environmental Monitoring and Assessment*. 151: 161. DOI 10.1007/s10661-008-0257-y.
- Fountain, A.G., R.M. Krimmel, and D.C. Trabant. 1997. A strategy for monitoring glaciers. U.S. Geological Survey circular 1132. Available from: <http://ak.water.usgs.gov/glaciology/reports/circular1132/Circular1132.pdf> (visited 16 August 2008).
- Gardner, A.S., G. Moholdt, J.G. Cogley, B. Wouters, A.A. Arendt, J. Wahr, E. Berthier, R. Hock, W.T. Pfeffer, G. Kaser, S.R.M. Lightenberg, T. Bolch, M.J. Sharp, J.O. Hagen, M.R. van den Broeke, F. Paul. 2013. A reconciled estimate of glacier contributions to sea level rise: 2003-2009. *Science*, 340: 852-857.
- Giffen, B.A., D.K. Hall, J.Y.L. Chien. 2007. GLIMS – Chapter 12: Alaska: Glaciers of Kenai Fjords National Park and Katmai National Park and Preserve – DRAFT. http://science.nature.nps.gov/im/units/swan/Libraries/Reports/GLIMS_Chapter_12_Alaska_20071221_Compressed.pdf (visited 21 August 2008).
- Giffen, B.A., D.K. Hall, and J.Y. Chien. 2014. Alaska: Glaciers of Kenai Fjords National Park and Katmai National Park and Preserve. Pages 241-261 in Kargel, J.S., Leonard, G.J., Bishop, M.P., Kaab, A. and B.H. Raup, editors. *Global Land Ice Measurements from Space*. Springer Praxis Books, Berlin, Heidelberg.
- Graham, J. 2005. Southwest Alaska Network (SWAN) Geologic Resources Management Issues Scoping Summary. Colorado State University, Fort Collins, Colorado. Available from: http://www.nature.nps.gov/geology/inventory/publications/s_summaries/ALAG-ANIA-KATM-KEFJ-LACL_scoping_summary_20051031.pdf (visited 21 August 2008).
- Hood E. and L. Berner. 2009. Effects of changing glacial coverage on the physical and biogeochemical properties of coastal streams in southeastern Alaska. *Journal of Geophysical Research*, 114: G03001.
- Hood, E., J. Fellman, R.G.M. Spencer, P.J. Hernes, R. Edwards, D. D'Amore, and D. Scott. 2009. Glaciers as a source of ancient and labile organic matter to the marine environment. *Nature*, 462: 24-31.
- Hoover-Miller, A. and P. Armato. 2018. Harbor seal use of glacier ice and terrestrial haul-outs in the Kenai Fjords, Alaska. *Marine Mammal science*, 34(3): 616-644.

- Hoover-Miller, A., S. Atkinson, S. Conlon, J. Prewitt, and P. Armato. 2011. Persistent decline in abundance of harbor seals *Phoca vitulina richardsi* over three decades in Aialik Bay, an Alaskan tidewater glacial fjord. *Marine Ecology Progress Series*, 424: 259-271.
- Jacobsen, D. A.M. Milner, L.E. Brown, and O. Dangles. 2012. Biodiversity under threat in glacier-fed river systems. *Nature Climate Change*, 2: 361-364.
- Kenai Fjords National Park. 1999. Resource Management Plan, Kenai Fjords National Park. National Park Service, Seward, Alaska.
- Kurtz D. and E. Baker. 2016. Two hundred years of terminus retreat at Exit Glacier: 1815 to 2015. Natural Resource Report NPS/KEFJ/NRR—2016/1341. National Park Service, Fort Collins, Colorado.
- Larsen, C.F., E. Burgess, A. A. Arendt, S. O’Neel, A. J. Johnson, and C. Kienholz. 2015. Surface melt dominates Alaska glacier mass balance. *Geophysical Research Letters*, 42: 5902–5908, doi:10.1002/2015GL064349.
- Leclercq, P.W., J. Oerlemans, H.J. Basagic, I. Bushueva, A.J. Cook, and R. Le Bris. 2014. A data set of worldwide glacier length fluctuations. *The Cryosphere*, 8: 659-672.
- Loso, M., A. Arendt, C. Larsen, J. Rich, and N. Murphy. 2014. Alaskan national park glaciers-status and trends: Final report. Natural Resource Technical Report NPS/AKRO/NRTR-2014/922. National Park Service, Fort Collins, Colorado.
- Lydersen, C. P. Assmy, S. Falk-Petersen, J. Kohler, K.M. Kovacs, M. Reigstad, H. Steen, H. Strøm, A. Sundfjord, Ø. Varpe, W. Walczowski, J.M. Weslawski, and M. Zajaczkowski. 2014. The importance of tidewater glaciers for marine mammals and seabirds in Svalbard, Norway. *Journal of Marine Systems*, 129: 452–471.
- Meier, M.F., M.B. Dyurgerov, U.K. Rick, S. O’Neel, W.T. Pfeffer, R.S. Anderson, S.P. Anderson, A.F. Glazovsky. 2007. Glaciers dominate eustatic sea-level rise in the 21st century. *Science*, 317: 1064– 1067.
- Molnia, B. 2007. Late nineteenth to early twenty-first century behavior of Alaskan glaciers as indicators of changing regional climate. *Global and Planetary Change*. 56: 23-56.
- Neal, E.G., E. Hood, and K. Smikrud. 2010. Contributions of glacier runoff to freshwater discharge into the Gulf of Alaska. *Geophysical Research Letters*, 37, L06404.
- National Snow and Ice Data Center (NSIDC). 2016. “All About Glaciers.” Accessed 9 November 2016. <https://nsidc.org/cryosphere/glaciers>.
- O’Neel, S., E. Hood, A. Arendt and L. Sass. 2014. Assessing streamflow sensitivity to variations in glacier mass balance. *Climatic Change*. DOI 10.1007/s10584-013-1042-7.
- O’Neel, S., E. Hood, A.L. Bidlack, S.W. Fleming, M. L. Arimitsu, A. Arendt, E. Burgess, C. J. Sergeant, A.H. Beaudreau, K. Timm, G.D. Hayward, J. H. Reynolds and S. Pyare. 2015.

Icefield-to-Ocean Linkages across the Northern Pacific Coastal Temperate Rainforest Ecosystem. *BioScience*, 65: 499-512.

- Oerlemans, J. B. Anderson, A. Hubbard, P. Huybrechts, T. Johannesson, W. Knap, M. Schmeits, A. Stroeven, R. van de Wal, and Z. Zuo. 1998. Modeling the response of glaciers to climate warning. *Climate Dynamics*. 14(4):267-274.
- Rhoades, R.R., X.Z. Rios and J.A. Ochoa. 2008. Mama Cotacachi: history, local perceptions, and social impacts of climate change and glacier retreat in the Ecuadorian Andes, in *Darkening Peaks: Glacier Retreat, Science, and Society*. Editors: Ben Orlove, Ellen Wiegandt and Brian H. Luckman. 2008. University of California Press.
- Riedel, J.L., R. A. Burrows, and J.M. Wenger. 2007. Long term monitoring of small glaciers at North Cascades National Park: A prototype park model for the North Coast and Cascades Network. Natural Resource Report NPS/NCCN/NRR-2007/000. National Park Service, Fort Collins, Colorado..
- Rice, B. 1987. Changes in the Harding Icefield, Kenai Peninsula, Alaska, with management implications for Kenai Fjords National Park. M.S. Thesis. University of Alaska Fairbanks. School of Agriculture and Land Resources Management, Fairbanks, AK.
- Robinson C.T., U. Uehlinger, and M. Hieber. 2001. Spatiotemporal variation in macroinvertebrate assemblages of glacial streams in the Swiss Alps. *Freshwater Biology*, 46: 1663-1672.
- Sapiano, J.J., W.D. Harrison, and K.A. Echelmeyer. 1998: Elevation, volume and terminus changes of nine glaciers in North America. *Journal of Glaciology*, 44(146):119-135.
- Tetreau M. 1989. Exit Glacier terminus monitoring: Exit Glacier, Kenai Fjords National Park. Unpublished Report. Seward, Alaska.
- Tetreau, M.D. 2006. Summary of Glacier Monitoring in Kenai Fjords National Park, Draft. US National Park Service, Kenai Fjords National Park, Seward, AK.
- Truffer M. and M. Habermann. 2011. Exit Glacier Radar Survey 2010 report. Unpublished report.
- 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.
- Van Looy, J., R. Foster and A. Ford. 2006. Accelerated thinning of Kenai Peninsula glaciers, Alaska. *Geophysical Research Letters*, 33(21): L21307.
- Vaughan, D.G., J.C. Comiso, I. Allison, J. Carrasco, G. Kaser, R. Kwok, P. Mote, T. Murray, F. Paul, J. Ren, E. Rignot, O. Solomina, K. Steffen and T. Zhang. 2013. Observations: Cryosphere. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*

[Stocker, T.F., D. Qin, G.-K. Plattener, M. Tignor, S.K. Allen, J. Boshung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Von Glasow, R., Jickells, T. D., Baklanov, A., Carmichael, G. R., Church, T. M., Gallardo, C. Hughes, M. Kanakidou, P. S. Liss, L. Mee, R. R., P. Ramachandran, R. Ramesh, K. Sundseth, U. Tsunogai, M. Uematsu, T. Zhu. 2013. Megacities and Large Urban Agglomerations in the Coastal Zone: Interactions between Atmosphere, Land, and Marine Ecosystems. *Ambio*, 42(1), 13–28. <http://doi.org/10.1007/s13280-012-0343-9>.

Appendix A: Harding Icefield 2008 Bibliography Compiled for Glacier Strategy Workshop

Mass Balance

Mass balance

Molnia, B. F. 2007. Late nineteenth to early twenty-first century behavior of Alaskan glaciers as indicators of changing regional climate. *Global and Planetary Change*. 56 (1-2): 23-56.

Equilibrium line altitude

Daigle, T. A. and D. S. Kaufman. 2008. Holocene climate inferred from glacier extent, lake sediment and tree rings at Goat Lake, Kenai Mountains, Alaska, USA. *Journal of Quaternary Science*.

Paddington, C. H. 1993. A Little ice age reconstruction for ice tongues of the Grewingk-Yalik ice complex, southern Kenai Mountains, Alaska. State University of New York, Buffalo, NY.

Geometry

Glacier area / extent

Giffen, B. A., D. K. Hall and J. Y. Chien. 2007. Chapter 12: Alaska: Glaciers of Kenai Fjords National Park and Katmai National Park and Preserve. in *Global Land Ice Measurements from Space (GLIMS)*, in progress.

Gilbert, K. G. 1904. Alaska glaciers: Harriman Alaska Expedition, 1899. Pages 96-102 in K. G. Gilbert. *Alaska: glaciers and glaciation*. Doubleday, Page and Co, New York City

Hall, D. K., B. A. Giffen and J. Y. Chien. 2005. Changes in the Harding Icefield and the Grewingk-Yalik Glacier Complex, Kenai Fjords National Park (KEFJ).

Hamilton, T. D. and B. Rice. 1989. Kenai Fjords and the Harding Icefield in *Guide to the geology of the Resurrection Bay-eastern Kenai Fjords area*: Eds. S. W. Nelson and T. D. Hamilton. US National Park Service Alaska Region, Anchorage, AK Pp.22-29.

Lucas, S. 2003. Late Holocene glaciation of the McCarty and Northwestern Fjords, Southern Kenai Mountains, Alaska. Senior Independent Study Report. College of Wooster.

Mann, D. H. and T. D. Hamilton. 1995. Late Pleistocene and Holocene paleoenvironments of the North Pacific Coast. *Quaternary Science Reviews*. 14(5): 449-471.

Pewe, R. L. 1975. Quaternary Geology of Alaska. U. S. Geological Survey Professional Paper. 835.

Reyes, A. V., G. C. Wiles, D. J. Smith, D. J. Barclay, S. Allen, S. Jackson, S. Larocque, S. Laxton, D. Lewis, P. E. Calkin and J. J. Clague. 2006. Expansion of alpine glaciers in Pacific North America in the first millennium A.D. *Geology*. 34(1): 57-60.

- Rice, B. 1986. Recent changes in areal extent of glaciers on the southern Kenai Peninsula, Alaska. Report to Kenai Fjords National Park. 10pp.
- Rice, B. 1987. Changes in the Harding Icefield, Kenai Peninsula, Alaska, with management implications for Kenai Fjords National Park. M.S. Thesis. University of Alaska Fairbanks. School of Agriculture and Land Resources Management, Fairbanks, AK.
- Satin, B. 1995. Glacial advance and retreat - responses to tectonic movements: a working hypothesis for the Harding Icefield, Alaska. United States. National Park Service. Kenai Fjords National Park.
- Tarr, R. S. 1912. The Glaciers and glaciations of Alaska. *Science*. 35(894): 241-258.
- Wiles, G. C. and P. E. Calkin. 1990. Neoglaciation in the southern Kenai Mountains, Alaska. *Annals of Glaciology*. 14:319-322.
- 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: 281-303.
- Geometry – Terminus position*
- Calkin, P. E., G. C. Wiles and D. J. Barclay. 2001. Holocene coastal glaciation of Alaska. *Quaternary Science Reviews* 20:449-461.
- Cremis, L. 1993. Late Holocene glaciation of the Bear Glacier forefield, Kenai Peninsula, Alaska. M.A. Thesis. State University of New York at Buffalo, Buffalo, NY.
- Follows, D. S. 1978. Glacial landscapes and geology of the Harding Icefield complex, Southern Kenai Mountains, Alaska. Anchorage Community College, Anchorage, AK.
- Grant, U. S. and D. F. Higgins. 1913. Coastal glaciers of Prince William Sound and Kenai Peninsula, Alaska. *U. S. Geological Survey Bulletin*. 379:98-107.
- Helm, D. J. and E. B. Allen. 1995. Vegetation chronosequence near Exit Glacier, Kenai Fjords National Park, Alaska, USA. *Arctic and Alpine Research*. 27:246-257.
- Helm, D. J., E. B. Allen and J. M. Trappe. 1996. Mycorrhizal chronosequence near Exit Glacier, Alaska. *Canadian Journal of Botany* 74:1496-1506.
- Helm, D. J., E. B. Allen, J. M. Trappe. 1999. Plant growth and ectomycorrhiza formation by transplants on deglaciated land near Exit Glacier, Alaska. *Mycorrhiza*. 8:297-304.
- Tetreau, M. D. 2006. Summary of Glacier monitoring in Kenai Fjords National Park, Draft. US National Park Service, Kenai Fjords National Park, Seward, AK.
- Whitney, P. C. 1932. Recent retreat of McCarty Glacier, Alaska. *Geographical Review*. 22:389-391.

Wiles, G. C. and P. E. Calkin. 1993. Neoglacial fluctuations and sedimentation of an iceberg-calving glacier resolved with tree rings (Kenai Fjords National Park, Alaska). *Quaternary International*. 18:35-42.

Geometry – Surface elevation

Adalgeirsdottir, G., K. A. Echelmeyer and W. Harrison. 1998. Elevation and volume changes on the Harding Icefield, Alaska. *Journal of Glaciology*. 44:570-582.

Adalgeirsdottir, G. 1997. Surface elevation and volume changes on the Harding Icefield, Southcentral Alaska. Thesis..

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(5580):382-386.

Valentine, V., K. Echelmeyer, S. Campbell and S. Zirnheld. 2004. Harding Icefield's clues to climate change. *Kenai Fjords Special Issue*. 3(1):13-17.

Van Looy, J., R. Foster and A. Ford. 2006. Accelerated thinning of Kenai Peninsula glaciers, Alaska. *Geophysical Research Letters*. 33(21):L21307.

Meteorology and Streamflow

Regional climate dynamics

Mann, D. H. and T. D. Hamilton. 1995. Late Pleistocene and Holocene paleoenvironments of the North Pacific Coast. *Quaternary Science Reviews*. 14(5): 449-471.

Molnia, B. F. 2007. Late nineteenth to early twenty-first century behavior of Alaskan glaciers as indicators of changing regional climate. *Global and Planetary Change*. 56 (1-2): 23-56.

Muirhead, B. 1978. Glacier annual snow lines in the Kenai Mountains of Alaska as derived from satellite imagery: measurement, evaluation of influencing factors, and some multiple regression prediction models: Final Report.

Pewe, R. L. 1975. Quaternary Geology of Alaska. U. S. Geological Survey Professional Paper. 835.

Reyes, A. V., G. C. Wiles, D. J. Smith, D. J. Barclay, S. Allen, S. Jackson, S. Larocque, S. Laxton, D. Lewis, P. E. Calkin and J. J. Clague. 2006. Expansion of alpine glaciers in Pacific North America in the first millennium A.D. *Geology*. 34(1): 57-60.

Wiles, G. C. and P. E. Calkin. 1992. Holocene glacial fluctuation in the southern Kenai Mountains, Alaska. University at Buffalo, Buffalo, NY.

Wiles, G. C., P. E. Calkin and A. S. Post. 1995. Glacier fluctuations in the Kenai Fjords, Alaska, USA: An evaluation of controls on iceberg-calving glaciers. *Arctic and Alpine Research*. 27:234-245.

Wiles, G. C., D. J. Barclay, P. E. Calkin, T. V. Lowell. 2008. Century to millennial-scale temperature variations for the last two thousand years indicated from glacial geologic records of Southern Alaska. *Global and Planetary Change*. 60(1-2):115-125.

Stream discharge

Kenai Peninsula Borough. 2005. Skilak glacier-dammed lake outburst history. Appendix F in All-Hazard Mitigation Plan, Kenai Peninsula Borough.

Stone, K.H. 1963. Alaskan ice-dammed lakes. *Annals of the Association of American Geographers*. 53(3):332-349.

Supplementary

Underlying topography

Post, A. 1967. Effects of the March 1964 Alaska earthquake on glaciers: the Alaska earthquake, March 27, 1964: effects on the hydrologic regimen; Geological Survey paper 544-D. United Geological Survey, Washington, DC.

Reger, R. D., Sturmman, A. G., Berg, E. E., and Burns, P. A. C. 2007. A Guide to the late Quaternary history of northern and western Kenai Peninsula, Alaska. Alaska Division of Geological & Geophysical Surveys Guidebook 8, p. 3.

Tande, G. F. and J. Michaelson. 2001. Ecological subsections of Kenai Fjords National Park. US National Park Service. Kenai Fjords National Park, Seward, AK.

Von Huene, R. 1966. Glacial-marine geology of Nuka Bay, Alaska, and the adjacent continental shelf. *Marine Geology*. 4:291-304.

Ice velocity

Klasner, F. 2008. Exit Glacier - flowing at a glacial pace.

Hart, J. K. 1995. An investigation of the deforming layer/ debris-rich basal-ice continuum, illustrated from three Alaska glaciers. *Journal of Glaciology*. 41(139): 619-633.

Tetreau, M. D. 2006. Summary of Glacier monitoring in Kenai Fjords National Park, Draft. US National Park Service, Kenai Fjords National Park, Seward, AK.

Landscape change

Ahlstrand, G. M. 1983. Dendrochronological evidence of the recent history of Exit Glacier. US National Park Service Alaska Region. 10pp.

- Bailey, P. K. 1985. Periglacial landforms and processes in the southern Kenai Mountains, Alaska. Special Reports, 85-3. US Army. Cold Regions Research and Engineering Laboratory, Hanover, NH.
- Cusick, J. A. 2001. Foliar nutrients in black cottonwood and Sitka alder along a soil chronosequence at Exit Glacier, Kenai Fjords National Park, Alaska. Master's Thesis, University of Alaska Anchorage. ARLIS S596.5.C885 2001
- Flagstad, L. A. 2007. A comparison of aboveground and belowground community succession along a proglacial chronosequence in Kenai Fjords, Alaska. PhD Dissertation, University of Alaska Anchorage, 134 pp.
- Miller, A. E., P. Spencer, M. L. Carlson and R. Lipkin. 2006. Vascular plant inventory and baseline monitoring of nunatak communities 2005, Lake Clark National Park and Preserve and Kenai Fjords National Park. National Park Service, Inventory & Monitoring Program, Anchorage, AK.

Slope stability

- Wiles, G.C. and P. E. Calkin. 1992. Reconstruction of a debris-slide-initiated flood in the southern Kenai Mountains, Alaska. *Geomorphology*. 5:532-546.

Other

- Alaska Planning Group. 1973. Harding Icefield—Kenai Fjords National Monument, A Master Plan. Department of the Interior.
- Alaska Planning Group. 1975. Proposed Harding Icefield-Kenai Fjords National Monument, Alaska : Final environmental statement.

Maps

- Alpha, T. R. 1970. Orthographic drawing of Nuka Bay, Alaska, south side of Kenai Peninsula, showing drowned cirques and glacial valleys. United States Geological Survey.
- Bradley, D. C., T. M. Kusky, P. J. Haeussler, S. M. Karl and D. T. Donley. 1999. Geologic Map of the Seldovia Quadrangle, South-Central Alaska. U.S. Geological Survey Open-File Report 99-18.
- Coulter, H. W., D. M. Hopkins, T. N. V. Karlstrom, T. L. Pewe, C. Wahrhaftig and J. R. Williams. 1965. Map showing extent of glaciations in Alaska. U. S. Geological Survey Miscellaneous geologic Investigations Map I-415, 1 sheet, scale 1:2,500,000.
- Kenai Fjords National Park. n.d. Digitized terminus of McCarty Glacier (2 maps) and Aialik Glacier. Seward, AK.

Post, A. 1980. Preliminary bathymetry of Aialik Bay and neoglacial changes of Aialik and Pederson glaciers, Alaska. Map. United States Geological Survey.

Post, A. 1980. Preliminary bathymetry of Northwestern Fiord and neoglacial changes of Northwestern Glacier, Alaska. United States Geological Survey.

Post, A. 1980. Preliminary bathymetry of McCarty Fjord and neoglacial changes of McCarty Glacier, Alaska. U.S. Geological Survey Open-File Report No. 80-424.

Appendix B: Pre-Workshop Kenai Fjords Staff Brainstorming Session Summary

This appendix summarizes the results from a brainstorming session focused on the Harding Icefield and outflowing glaciers held on 2 September 2008 at Kenai Fjords National Park. The purpose of this brainstorming session was to identify park staff priorities for information needs about the Harding Icefield and its glaciers pertaining to interpretation and management issues and concerns.

Brainstorming session participants included KEFJ staff from Resource Management, Interpretation and Education, and Visitor and Resource Protection divisions. The director of the Ocean Alaska Learning and Science Center and the Physical Scientist for SWAN were also in attendance.

Ideas and Suggestions Received

Following is a summary of suggestions received during the brainstorming session. This information was used to help guide the formal workshop. The brainstorming ideas are presented in the proposed framework (as envisioned at the time), followed by several overall recommendations to facilitate making icefield information relevant to interpretation, education, and outreach programs. No effort was made to eliminate ideas or highlight work that had already been completed or was ongoing.

Information Needs

Mass Balance

- Seasonal snow accumulation.

Geometry

Glacier area/ extent

- More frequent photos or data needed to communicate recent changes including firn line, trimlines, whole glacier, flow rates, specifically at Exit Glacier, but also at additional glaciers: Bear, Holgate, Aialik, and Northwestern.
- Icefield/glacier extent mapping is needed across the geographical extent of the park (and terminus position). Time period between mapping efforts does not need to be as frequent as for interpretive needs.

Terminus position

- Tidewater glacier extent (depth) in the water, fluctuations and effect on these glaciers.

Meteorology and Streamflow

Weather stations

- Precipitation monitoring (for multiple purposes including mass balance).

Regional climate dynamics

- Link to climate change and to regional changes.

Stream discharge

- Volume or flow rate of Exit Creek related to the processes or changes in Exit Glacier or the Icefield.

Supplementary

Underlying topography

- Topography exposed when the glacier retreats/ shrinks.
- How tidewater glaciers change the bathymetry of their bays.
- Influences/ effects of siltation.

Ice velocity

- Flow rate for Exit Glacier, determined on a finer time scale than present data.
- Causes of calving rates.

Landscape change

- Concrete examples of ecosystem change due to glacial recession.
- Comparison of current retreat to past glacial retreats.
- Predictive modeling of changes in the glacial landscape, for future management needs.
- Effects on vegetation, succession and the ability of exotics to exploit newly exposed disturbed sites.

Other

- Effect of glacial melt/ sea-level rise on our shorelines.
- Impacts on critical species habitat.
- Effect of the red algae on the snowpack.
- Influence of the glaciers and icefields on the nearshore ecosystem.
- Effect of tidewater glaciers on the physical oceanographic conditions of the park.
- Atmospheric changes/ contaminants that are identifiable in the ice composition.
- Comparability of Exit Glacier to other glaciers and icefields.
- Visitor use on the icefield, access points, changes to use/ access as the icefield changes.
- Identification of potential hazards that might change as the icefield changes.

- Identification of potential impacts on Exit Glacier infrastructure as the icefield changes. Identify data needs to determine these.
- Consider use of vessels of opportunity for collection of oceanographic data from regularly visited areas.

Other questions:

- Do we have enough information to respond to potential permit/ commercial requests? If not, what do we need to answer these questions? What data would we like to have for NEPA that we don't have?
- What are the existing Southwest Alaska Network, Inventory & Monitoring Program objectives for glacier monitoring?
- Should we be focusing some of our current monitoring efforts on other glaciers for more scientific value?
- Should we be collecting additional data for national and international-scale applications?

Overall Goal for Interpretation: make the icefield relevant for the visitor experience

Related questions/issues:

- We need to answer visitors' "so what?" questions.
- What visitor experience do we want to offer?
- What are some indicators/ information that will give us the ability to know when/ whether this experience will have to change?
- What are the different scenarios about what will happen at Exit Glacier over the next 5-10 years?
- We need to create opportunities for public/citizen science and improve virtual access to the icefield (when putting in remote stations, etc.).
- Data collection methodologies and programs should be collected with an eye for interpretation, and ideally involve someone with exhibit experience so that it can be quickly and effectively communicated to the public

Appendix C: Harding Icefield Workshop Attendees

Guy Adema, NPS, DENA

Joan Darnel, NPS, AKRO

Bruce Giffen, NPS, SWAN

Shelley Hall, NPS, KEFJ

Amy Ireland, NPS, KEFJ

Jim Ireland, NPS, KEFJ

Fritz Klasner, NPS, KEFJ

Chuck Lindsay, NPS, SWAN

Chris Larsen, UAF, Geophysical Institute

Rod March, USGS Fairbanks, Glacier Monitoring

Brooke McFarland, NPS, KEFJ

Jeff Mow, NPS, KEFJ

Jon Reidel, NPS, North Cascades

Kristy Sholly, NPS, KEFJ

Bob Winfrey, NPS. AKRO

Appendix D: Project Considerations

Core Program

1. Applied to the main body of the Harding Icefield
 - a. Extent / Scope
 - b. Selected Glaciers – Sites
 - c. Temporal frequency
 - d. Methods
 - e. Parameters
 - f. Logistical Considerations
 - g. Cost
 - h. Staff: time, expertise, training
 - i. Environmental compliance
 - j. Site access
 - k. Partners
2. Differences with land-terminating glaciers
3. Differences with coast-terminating glaciers
4. Analysis & Reporting
5. Public Education & Outreach

Expanded Program

1. Applied to the main body of the Harding Icefield
2. Differences with land-terminating glaciers
3. Differences with coast-terminating glaciers
4. Analysis & Reporting
5. Public Education & Outreach

Partnerships & Funding

1. Identify Interests (mandate, scope, geographic extent, etc.)
2. Strategies for addressing opportunities with partners and obtaining funding

Appendix E: Project Idea Outlines

Data Collection—aka monitoring

1. Mass Balance—at index or benchmark sites, as outlined in Fountain and others (1997)
 - A. Justification: NRAC-type...
 - B. Spatial Extent
 - 1) Elevation Gradient
 - 2) At Equilibrium Line Altitude (ELA)
 - C. Temporal Frequency
 - 1) Seasonally
 - 2) Net and Annual
 - D. Methods
 - 1) Parameters
 - 2) Accumulation Area Ratio
2. Glacier Area
 - A. Extent: System-wide total area, infrequent
 - 1) Method: satellite-based mapping
 - B. Extent: Terminus, frequent, selected glaciers (index sites)
 - 1) Method: Aerial photography
 - 2) Method: Oblique photography, repeated
3. Ice Surface Elevation
 - A. Extent: System-wide total area, infrequent
 - 1) Method:
 - a) Mapping (LiDAR, SRTM, ...)
 - b) Transects (Laser altimetry)
 - B. Extent: index glaciers, Local, site-specific transects
 - 1) Method: ground based, walking a route with a GPS
4. Ice Flow
 - A. Extent: System-wide
 - 1) Method: (interferometry)
 - B. Extent: Index sites
 - 1) Method: stakes, fixed objects, etc.; at estimated Equilibrium Line Altitude (ELA)
5. Hydrology
 - A. Extent: index sites
 - B. Method: gaging stations
 - C. Parameters
 - 1) Discharge Quantity
 - a) Streams
 - b) Include calving in marine environments
 - 2) Quality: suspended sediment, specific conductivity, standard I&M program parameters.
6. Meteorology
 - A. Extent: Index sites, across elevation gradient
 - B. Method: climate stations (as opposed to mapping)
 - C. Parameters: Precipitation, temperature, wind, solar

- 7. Research \ Inventories
 - A. Underlying topography \ Ice Thickness
 - 1) Extent: System-wide
 - 2) Method: Ground Penetrating Radar
 - a) Airborne
 - b) Ground-based
 - B. Tectonic rebound

Appendix F: Glacial Features and Processes

- A. Mass Balance
 - 1. Mass balance (seasonal, net, as function of elevation)
 - 2. Equilibrium line altitude
 - 3. Accumulation area ratio
- B. Geometry
 - 1. Glacier area / extent
 - 2. Terminus position
 - 3. Surface elevation
- C. Meteorology & Streamflow
 - 1. Weather stations
 - 2. Regional climate dynamics
 - 3. Stream discharge
 - 4. Water quality
- D. Research / Inventories
 - 1. Underlying topography
 - 2. Ice velocity
 - 3. Landscape change
 - 4. Slope stability

The Department of the Interior protects and manages the nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its special responsibilities to American Indians, Alaska Natives, and affiliated Island Communities.

NPS, December 2018

National Park Service
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