# Climate Monitoring in
# Glacier Bay National Park and Preserve:
# Capturing Climate Change Indicators

## 2010 Annual Report

***Studies Conducted As Part of Research Project:***
***Long-term tidewater and terrestrial glacier dynamics, glacier hydrology, and Holocene and historic glacier activity and climate change in Glacier Bay National Park and Preserve***

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***Cover Photo: CRREL climate station with low power usage, small footprint and multiple sensors, with imaging and Iridium SAT modem data transmission capabilities; low power consumption allows use of small lithium batteries and solar panel***

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## Executive Summary

Climate is the primary driver of the physical, hydrological and biological processes of Glacier Bay's diverse ecosystems. Because few data on the climate of the Park existed and no systematic monitoring of the climate had been performed prior to 1999, we initiated a long-term monitoring of contemporary climate in Glacier Bay in cooperation with the National Park Service (NPS). Our climate monitoring system is providing the long-term record necessary to understand the effects of global and regional changes in climate on Glacier Bay National Park and Preserve. Climate data records of sufficient length from multiple locations are necessary to calibrate Global Climate Models (GCM's) and predict how future global changes in climate will impact the environment and ecosystems of Glacier Bay. Knowledge of the likely short- and long-term responses will be important in the future for utilizing and protecting Park resources while accommodating visitors.

Our climate sites are mostly located near sea level elevation at the edge of the wilderness area and designed to minimize visual and physical impacts with a small footprint. One site is at higher elevation and provides much needed information of vertical gradients in temperature; additional sites at other locations in the West Arm would be advantageous. The sites at sea level facilitate comparison of the data and analyses of the spatial and temporal variability within the Glacier Bay watershed. The complexity of the climate system of the Park is evident, and we are hoping to collaborate with NWS on climate models to try to understand where and how weather may vary between inlets and the lower bay. The temperature data provide the basis for calibrating tree-ring records and interpreting the paleoclimatic indices of interstadial wood sites and the climate of the past 10,000 years (Lawson *et al.* 2010). Combined with other measurements, such as ablation and accumulation rates and elevation and area changes, temperature and precipitation records are critical to understanding the response of glaciers and ice sheets, as well as other physical systems to regional and global climatic change.

Two primary activities have comprised most of our efforts in 2010: first, the annual servicing and maintenance of the twenty-four sites in the Glacier Bay watershed, and secondly, developing a new database of the climate records to meet a Park requirement. In addition, we continued to test and analyze data collection and transmission by low

power, small footprint and robust systems for use in remote, largely inaccessible wilderness areas. The use of Iridium satellite modems for transmitting data and digital images is being field tested with camera systems and off the shelf, simple but accurate meteorological sensors at various high and low elevation sites in Alaska. A low power, small footprint Iridium system has been set up at the Johns Hopkins site (cover photo).

At the request of the Park in 2010, we are processing the current data records of each of the twenty-four climate stations. Previously, only raw data were required for archiving and thus substantial work has been necessary to meet that request. The requested products required re-formatting of all data to Excel 2007 and text formats, with field downloads concatenated into two files for each site's precipitation and air temperature records. In addition, each file was examined in detail, an initial QA/QC performed, and meta-data including logger meta-files, assembled. We are currently finalizing this massive effort; unfortunately, the time frame set by the Park to provide this database and associated supplemental materials of mid- September 2010 could not be met. Our intention for the research component of the climate monitoring has always been to analyze the entire database after a statistically-relevant record of at least ten years was acquired in ~ 2011. This effort will be completed in spring 2011; any new data acquired after that date will be added to the database and provided as an update. As directed by the Park, the climate monitoring system will be removed beginning in 2011 and out of service after 2013. The final database will be archived on the park's server and at CRREL. We encourage collaborative efforts and welcome inquiries to use this database.

A University of Birmingham MSc student has been recruited to begin the analyses of the ten- year climate record and examine the spatial and temporal trends in climate across the Glacier Bay watershed. The results of this research will include publication in a high impact journal such as the International Journal of Climatology. In addition, we have initiated collaboration with Chris Larsen (UAF) to examine the relationship between airborne-surveyed altitudinal changes in the glaciers of the Park over the last ten years and the climatic record for the same period of time. Glacier Bay is the only location where a sufficient number of climate stations and length of record exists to permit this analysis.

Long-term monitoring at multiple high and low elevation sites across the breadth of the Glacier Bay NP&P is essential to understanding the impacts of climate change on the Park's glaciers and ecosystems. A monitoring network that includes high and low elevation sites within the glacial and non-glacial sectors, including the outer coast, is recommended based on our experiences and records. The additional sites would fill the critical data gap that exists on the climate of the accumulation areas of the glacial systems and the region on the Gulf of Alaska which feeds the majority of precipitation for the icefields and glaciers of the Fairweather Mountains. As the regional climate continues to change and become increasingly variable in response to global warming, climate monitoring is essential to determine the impacts on Glacier Bay NP&P and provide the data needed by researchers to investigate how biological and physical systems adjust to such changes and affect ecosystems of the Park. Only through long-term monitoring can future changes in climate and its impacts be predicted. Such knowledge will be important to management in determining strategies for a park under the stress of climate change. We recommend that a monitoring system based on the results of our pioneering efforts be implemented by Park management as part of the SEAN I&M program to fill the gap left by removal of the CRREL climate network.

## Introduction

Over the last 20 years, we have conducted long-term, integrated monitoring and site-specific multidisciplinary studies of glacial, marine and terrestrial environments in Glacier Bay to improve our understanding of the physical processes and their interactions with regional and global systems. Understanding climatic change and the resulting environmental and ecosystem responses are critical to the Park's adaptive management scheme for utilizing and protecting its resources and accommodating visitors in the future. Our research investigates the processes that control physical conditions and ultimately ecosystem biodiversity along marine and terrestrial glacier margins. Sedimentologic, climatic, oceanographic and glaciohydraulic studies of glacier dynamics improve the state of knowledge of tidewater and terrestrial glacier systems. Although sediment dynamics appear to control the positions of glacier margins in fjords over the short-term, climate affects longer-term trends in tidewater glacier activity, but data to investigate the role of climate in tidewater glacier dynamics have been lacking.

Thus, climatic data are a critical component in most of our research, as well as in numerous other investigations of the marine, terrestrial and freshwater environments and ecosystems within the Park. Having a detailed, high resolution record of the air temperature and precipitation is necessary to define the daily, seasonal, annual and decadal controls on the biological and physical processes operating within each ecosystem. An important aspect of the monitoring is to provide the baseline climatic data to which future changes in climate can be compared, and ultimately applied to understanding physical and biological changes in the Park. CRREL climate sites are distributed across the Glacier Bay watershed such that regional trends can be identified and compared and correlated with temporal variations as sufficiently long records are developed. These data will allow us to analyze climatic patterns, assess differences in weather between the East and West Arms, and evaluate impacts of short-term climatic changes that result from ENSO (El Nino/La Nina), PDO (Pacific Decadal Oscillation) and AO (Arctic Oscillation). For our paleoclimate investigations, we are using these data to calibrate tree-ring records, and as the record lengthens, examine the spatial and seasonal variability that may affect how the tree-ring record is interpreted (Lawson et al. 2010).

## Reasons for Monitoring Climate

Climate is the primary driver of the physical, hydrological and biological processes of Glacier Bay's diverse marine, freshwater and terrestrial ecosystems. With the exception of historical data from Bartlett Cove and Gustavus, no systematic monitoring of the climate within the Park had been done prior to 1999, and therefore as part of our research, we initiated long-term monitoring of contemporary climate in the Glacier Bay watershed in cooperation with the Park that year.

Without a baseline for the current climate, it is impossible to know if changes in the global climate are, or will, affect southeast Alaska climate and more specifically and importantly, the climate of Glacier Bay. The CRREL climate network is the first and only detailed monitoring of climate at a scale sufficient to monitor variability within a large, natural and undisturbed watershed in southeast Alaska. It can provide an understanding of the spatial as well as temporal variability in air temperature and precipitation, perhaps the two most important climatic variables affecting the Park's environment and ecosystems. It provides the only database by which any changes may be detected, and when of sufficient length (several decades or more), it could provide valuable data that do not otherwise exist within the Gulf of Alaska and North Pacific that are required to calibrate Global Climate Models (GCM's) for this region. GCM's can then be used to predict how future global changes in climate will impact the environment and ecosystems of Glacier Bay. Our network is limited in the sense that additional data from higher elevation sites in glaciated areas and from the outer coast would provide a more complete understanding of how the Park's mountainous terrain affects temperature and precipitation, and thus the accumulation or ablation of the glacial systems and their expansion or thinning and retraction over time.

Having a detailed, high resolution record of the air temperature and precipitation is necessary to define how individual events with passage of fronts, as well as those of seasonal, annual and decadal frequency affect the biological and physical processes operating within each ecosystem. The CRREL climate sites are distributed across the large and topographically diverse Glacier Bay watershed such that spatial trends can be identified and compared and correlated with temporal variations as sufficiently long records (10 years and longer) are developed.

## Research Objectives and Hypotheses

Beyond monitoring of the climate over time, the data allow multiple research questions to be addressed by us and other researchers in the park. We consider first and foremost obtaining a basic understanding of the climate across the Glacier Bay watershed as a primary goal of the network. A quantitative understanding did not exist before establishing these sites; only anecdotal observations and native legends told us about climate variability in Glacier Bay. The current ~ten year record will provide the first glimpse of the Glacier Bay watershed's temperature and precipitation trends and variability.

Our specific hypotheses are related to the continuing analyses of current and past glacial activity and associated paleoclimate. The network of climate sites as distributed across the Glacier Bay watershed allows us to address the following hypotheses on the glacial and periglacial environments. The length of record and its continuity are necessary and essential to test these hypotheses.

### *Working Hypothesis 1*.

*The climate of the East and West Arms are dissimilar and as a consequence, result in asynchronous timing of expansion and recession of glaciers into the lower bay.*

If such a regional variability exists in this large watershed, it bears directly on interpretation of the glacial record during the Holocene. Tidewater and terrestrial glaciers advance and retreat in response to changes in air temperature and precipitation, with tidewater glaciers following a cycle during which stability of the terminus is lost and retreat initiated as a probable result of decadal climatic warming. Asynchronous response is important because records of glacial activity are fragmented and only partly preserved in sediments and landforms, and thus may not faithfully and completely record the differences in advance and retreat, but this behavior would need to be modeled in the glacial history of the Park.

In addition, biological studies can use regional data; for example, Dr. Sandy Milner's research employs CRREL precipitation data as a link to discharge data for their study streams located in the lower bay and East Arm, and as such, the meteorological data are essential for understanding fluxes of nitrogen through these systems. Basic but currently unknown relationships between air temperature and water temperature can also be derived for the stream systems.

*Corollary*
*If precipitation and temperature vary significantly across the Glacier Bay watershed in response to topographic and other factors, then the establishment of forests and growth of trees will respond in kind and be reflected in tree ring records of paleoclimate.*

Such effects bear directly on our ability to crossdate ring records of similar age from different locales within the watershed using synoptic spatial modeling. The meteorological data will be valuable to compare with the tree-ring data, including the mean values at various lengths (monthly, annual) and singular "events" that may appear as significant changes recorded in ring widths over one or two year periods, and thus in each case, inform us for quantitative interpreting of paleoclimatic ring records.

***Working Hypothesis 2.***
*So-called decadal events, including ENSO (El Nino, La Nina), PDO and AO affect the magnitude and patterns of precipitation and temperature within the Glacier Bay watershed.*

If verified, freshwater, terrestrial and marine ecosystems will respond to the periodicity and magnitude of such events. These events may result in a periodic response of physical and biological processes and have currently unknown consequences for the ecosystems as a whole. For glacial systems, the periodic changes may explain the observed short term periods of advance superimposed on the overall thinning and recession now affecting most of the glaciers within the Glacier Bay watershed. In the past, decadal warming may have been responsible for initiating catastrophic retreat of the tidewater glaciers.

*Corollary*
*A strong connection and signal from decadal events will be displayed in modern and ancient tree ring records; thus studies of ring records of the Holocene will reveal their frequency and magnitude in the past.*

If true, this will allow us to address important questions about decadal events including whether ENSO existed throughout the Holocene and how influential it and other decadal events were in affecting the paleoclimate and glacial activity. The effects of decadal events on ring records require lengths of record sufficient to capture such changes; a 10-year record is a significant start to this end and it should be continued to evaluate decadal occurrences. Combined effects of the decadal events operating simultaneously may produce one or two year changes that significantly alter tree growth. Verifying that these and other extreme climatic events alter the ring record of climate will help interpret more extreme events in paleoclimatic records. An example may be the Tlingit legend of two years without summer which appears to be present within our ring record for interstadial trees of the early 1700's in the Bartlett Cove area.

***Working Hypothesis 3.***

*Extreme precipitation events characterize the Glacier Bay watershed, especially within the glaciated fjords, affecting overland flow, stream hydrology, sediment transport and freshwater flux to the marine system, as well as biological activity and productivity.*

Such extreme events are critical to shaping the landscape during and following deglaciation while modifying habitats of each ecosystem in the watershed. Calculation of glacial erosion rates from depositional volumes within fjords are in error when paraglacial climate and its physical effects are not considered such as in the recently deglaciated upper reaches of Muir Inlet. Consequences for terrestrial and freshwater ecosystems may include loss of river substrate and interruption of salmon spawning cycle and periodicity. Net and episodic flux of freshwater to the marine environment may also have important short- and long-term effects on marine populations.

An example of such an impact of a precipitation event is the research Dr Sandy Milner is conducting on the effects of a major rain event on salmon habitat and spawning within the streams of Glacier Bay. Milner is using CRREL network climate data to help understand the response of streams and impacts on fauna therein, particularly the spawning of salmon and the recovery of the salmon population. Most of the climate stations within the Glacier Bay watershed recorded a major event in November 2005 of ~25 inches of rain in a 24 hour period, followed by several subsequent large events over the next several weeks. This event modified the stream substrate including woody debris distribution, changing the habitat and spawning cycle of salmon. The impact has lasted over 5 years.

Tree ring are often characterized by rapid, annual or multi-annual changes in width and density. The cause of such changes are not easy to decipher; however, such changes may be the result of storm or episodic events, and examining living tree ring records in concert with the climate data could provide a way to test whether either extreme temperature or precipitation events result in distinct changes in the ring width structure.

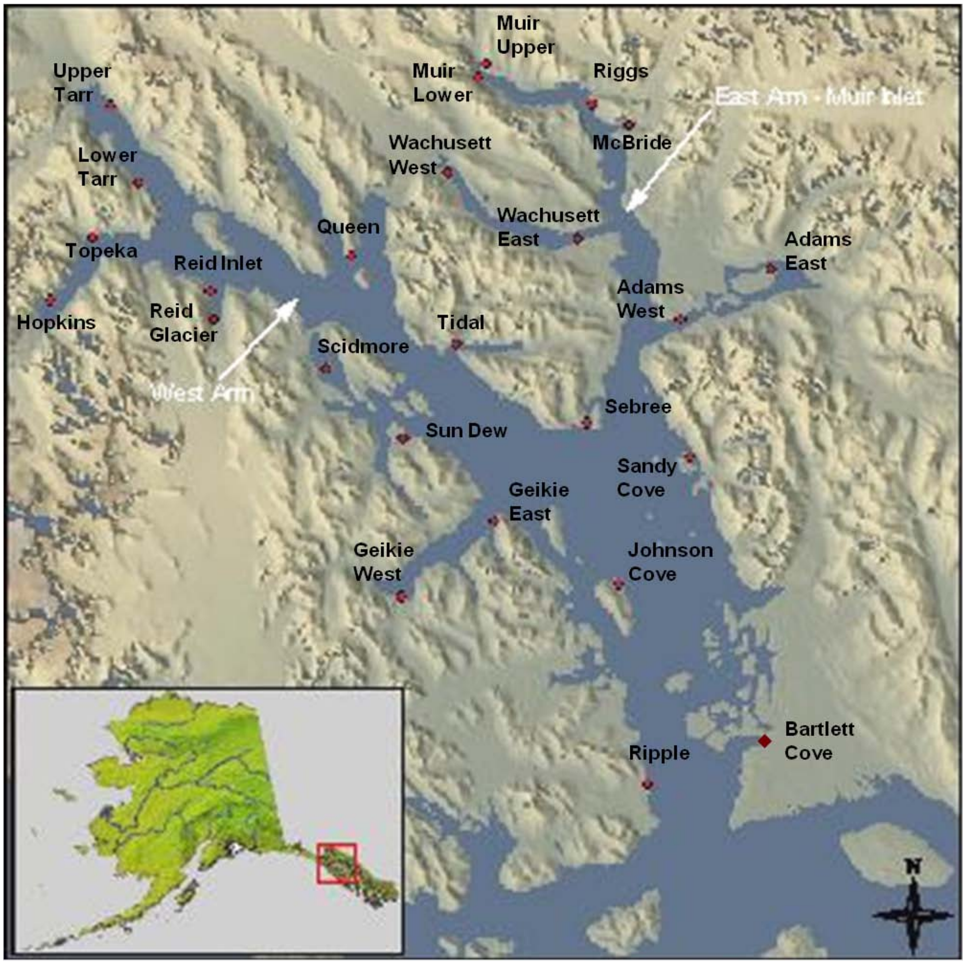

***Figure 1.*** *CRREL climate monitoring sites located within the Glacier Bay watershed. Bartlett Cove was established jointly by NWS, NPS and CRREL in December 2007 and located on the NPS fuel dock, with both local and satellite transmission capabilities.*

## Project Background

We began establishing test sites for monitoring climate within Glacier Bay in 1999. We identified the lack of any climatic data within Glacier Bay as a significant gap in knowledge about a very important and basic driver of the physical and biological systems within the Park, a sentiment echoed by many Park staff and independent researchers alike. Although specific funding for climate monitoring could not be secured, it was an obvious data gap that we have tried to fill by establishing the current network of climate sites. We initially established the network to monitor air temperature and precipitation, two primary climatic indicators that are applicable to many physical and biological research projects. The sequence of events in developing the current deployment of 24 climate sites is detailed in the 2006 annual report (Lawson *et al*. 2006a) to which the reader is referred and available at the Glacier Bay web site.

We are continuing significant effort in our lab and at field test sites in extreme environments to identify wilderness-ready systems and sensors. Our primary goal is to develop systems that have low power usage, a remote near real time capability for data transmission, minimal repair requirements, multiple meteorological sensors and minimal footprint and visual impact for wilderness deployment. In addition to increasing the suite of parameters measured, it is critical to establish higher elevation sites at several or more locations across the Glacier Bay watershed. Such sites were not initially established due to power and access requirements for these remote locations and at that time, the unknown reliability of instrumentation for long-term deployment. The use of Iridium satellite phones are being proven reliable in extreme conditions. In addition small wind generators can provide power during the often cloudy periods and short daylight of winter in appropriate locations.

The Park RM Chief has directed us to remove the entire monitoring system in stages over the next three summers. For those interested, we will be pleased to provide information on the improved monitoring systems for wilderness deployment. In addition, we would like to have our database applied to other studies and potential users should contact us for a discussion of applications and collaboration.

## Methods and Site Instrumentation

Climate sites are currently located along fjord margins, generally at or near sea level and generally within 100 m or less of the wilderness boundary (Figure 1). All climate sites were assigned names generally in keeping with their location in the Park. The description that follows provides information on the instrumentation and standard operating procedures

Each climate site has two rain gauges (for redundancy), a dual temperature sensor, and a bulk precipitation collector for heavy isotope analysis (Lawson *et al* 2004; Finnegan *et al* 2007). The rain gauges (Onset RG-2 Tipping Bucket; Peet Electronic) record rainfall to Hobo event data loggers in 0.01 inch increments (Figure 2). Temperature is measured to 0.1 ° C accuracy at a 20 minute interval using two separate thermistors that are housed within a solar radiation shield (Figure 2). Snow gauges previously used at three sites are being extensively redesigned for possible future use. As part of this effort, we have been laboratory testing systems that have better resolution and smaller footprint than the previous tower based gauges. Appendix A in Lawson *et al*. (2007) provided detailed information on each climate site.

Originally two sites (Queen, Hopkins) utilized GOES (Geostationary Operational Environmental Satellite) transmitters for year-round, near-real time data transmission including precipitation, temperature, solar radiation and wind measurements. However, the Johns Hopkins site suffered a major avalanche in winter 2007-2008 and again in 2008-2009 that destroyed all sensors, GOES transmitter and tower. The destroyed station was removed early in August, 2010, while the entire area was returned to its natural state. After significant research and testing, we established a new climate station for the Johns Hopkins site and installed it in 2010 at a previously used location removed from the avalanche path (cover photo) but close to the original site. This system includes the full suite of climate sensors and uses a modem to transmit data via an Iridium satellite phone. Power usage is extremely low, requiring only 4 AA lithium ion batteries in the data logger and an internal, sealed-cell lithium ion battery with small(~6 $in^2$) solar panel for the satellite modem, both sets of which require replacement every three years.

***Figure 2**. Typical climate sites. Upper left photo shows white solar radiation shield housing temperature sensors and a tipping bucket rain gauge installed on 1-meter tall post at Muir Glacier. Photo on lower right shows the tipping bucket and electronic rain gauges in steel housings as mounted on the ground at the Riggs site. A post can only be used where animals are unlikely to damage rain gauges, but preferred wherever possible to reduce snow cover effects on winter season data.*

We had planned additional satellite transmitters as funds allow to reduce the need for costly site visits, especially in areas where access may be limited by motorized vessel restrictions and to provide data in near real time to park managers, rangers, emergency services, interpretive staff and researchers. Our experience and knowledge could assist the I&M and RM staff in establishing new, smaller footprint systems for transmitting larger amounts of data, including digital images, via Iridium satellite modems. Testing of various components was one of our major tasks in 2009 and 2010. In addition, stations for remote, high altitude deployment are undergoing field testing at Hubbard Glacier and Columbia Glacier (Figure 3).

***Figure 3.*** *Climate station for high altitude sites shown at Columbia Glacier (photo: D. Finnegan). The Iridium satellite antenna is the ~6 in. black rod on the right side of the tower below the wind sensor. The long arm extending to left holds a snow depth sensor. Data are stored within data logger in the gray box on the mast and may be transmitted at various rates from minutes to hours. Two-way communication allows commands such as changing frequency of data collection and transmission from office computers.*

Each climate site is routinely maintained during late spring to early summer and again in early fall. We typically require five days to complete servicing, data download, repair and maintenance of all climate stations. We record the condition of the site in a field book upon arriving, sometimes photographing more serious problems such as animal or natural destruction of instruments and mounting equipment. The level of the rain gauges is measured and any deviation noted as this affects the volume recorded. The data loggers of each instrument are then downloaded to portable recorders, referred to as shuttles, and batteries and desiccant are replaced while clearing the memory of older data and reinitializing loggers to begin a new data collection cycle.

Any problems with data loggers or instruments are noted in our field books, and we replace problematic loggers and broken instruments in the field with spares that we carry with us to minimize service time for each site and insure that we have fully operational equipment for the next period of monitoring. Simple repairs or download issues are addressed on board the vessel used to access the site or back in the office or lodging that night. More serious problems are repaired back at the CRREL-Hanover laboratory.

Details of each instrument recorded in the field book include condition and operation of the data loggers and any problems noted that may have affected the operation and recording of data (for example leaves or spiders in the rain gauge orifice). If data loggers or entire instruments must be replaced, the new serial numbers and time of start-up are recorded electronically. Bulk water samples are collected in 60 ml, air-tight Nalgene bottles and assigned sample numbers recorded in the notes for the particular site. On-board the vessel, we download all data files to a folder on a portable laptop computer and back-up these data on a data key.

In the office, we store all raw data files and then move the data using the Onset Computer Corporation Hobo Pro or BoxCar Pro software (depending on generation of the loggers) into Excel and text format files, which includes the basic meta-data on each logger, for later analysis. A copy of the raw data files is archived annually at the Park as required by our research permit. Prior to analysis of the temperature and precipitation records, we evaluate the data record from each individual instrument to ascertain if any problems exist such as an incomplete data stream or overlap of records when new loggers are installed. Problems such as clogged intakes on the rain gauges or sensors knocked from their mounts to the ground will cause the records to be incomplete. Duplicity of the rain gauges may in some cases fill gaps in the record. The raw data records are combined in a continuous time-series from which annual as well as monthly and daily information can be extracted and analyzed using standard statistical methods. QA/QC of these records is straightforward, generally removing of duplicate readings when loggers are replaced and identifying gaps in the records. Each of the individual Excel and Txt files are archived by site name.

### Activities in 2010

In 2010, we continued to service and acquire data from all sites across the park, with the new data processed and added to the existing record. Site access was in some cases limited by vessel availability and weather, so that data from some sites will not be available from 2009-2010 until 2011. Several loggers and instruments required repairs and replacement for a variety of reasons.

We replaced the station destroyed by avalanches at Johns Hopkins with small footprint tower with a suite of sensors (temperature, precipitation, wind speed, wind direction, solar radiation) powered by small, lithium closed-cell batteries and a Iridium modem for satellite transmission of data, powered by a internal lithium battery and small(~6 in$^2$) solar panel, a system tested previously by CRREL. This system seemed perfect for a location with limited access but within a climatically important part of the glacial systems of the Fairweather Mountains. Its dimensions and location minimize possible visual impact. The overall costs are low including monthly transmission by Iridium SAT modem.

Our primary focus the latter half of the year has been to meet the park's requirement to provide all the current records of temperature and precipitation from each site in a database. This is a new requirement which we had not planned to develop until after 2011 when a graduate student would begin thesis research on the climate of the Glacier

Bay watershed. The current collaboration between CRREL and University of Birmingham has made this effort possible now, rather than at the planned timeline. We are attempting to insure all possible data are included and have returned failed loggers to the manufacturer Onset Computer for their technicians to attempt recovery of data in their non-volatile memory. The site-by-site data are being concatenated into single file structure within Excel 2007. Any additional data acquired in 2011 will be added to the database. Thus in addition to the raw data files provided to Bill Eichenlaub annually for archiving on a Park server, we will provide the Excel 2007 database and meta data, including copies of our informal field notes on servicing of the climate network in early 2011.

The current periods of record of air temperature and precipitation for the twenty-four climate sites are shown as bar graphs in Appendices A and B. Periods of time without data, gaps in the record, are identified and briefly explained in the footnotes.

We also continued developing and testing climate system components this past year, so that an anticipated upgrade of sites within the network would have provided more reliable data collection and transmission and flexibility of operations in wilderness conditions. In particular, we have been working to develop Iridium satellite-based systems to transmit large data volumes as well as allow remote communication to query instrumentation or to modify data collection parameters.

## Continuing Work, Collaborations and Synergistic Activities

We plan to visit each climate site in 2011 to download data and service the instruments. Eight sites will be removed permanently in 2011. These visits are necessary to insure that a continuous record of the air temperature and precipitation from each site is acquired, barring any problems over which we have no control. We are continuing field testing of new systems at the Columbia and Hubbard Glacier sites, perhaps providing useful information the Park may wish to use in determining the best systems to deploy in the I&M climate network. We will continue to update the archival database of raw data files on the NPS Glacier Bay server, as well as the new Excel 2007 database.

Our goal in 2011 is to begin detailed analyses of the climatic record, focusing first on basic statistical parameters and then evaluating the spatial and temporal trends across the Glacier Bay watershed. A University of Birmingham MSc. student has been recruited to begin the data analyses of the ten-year climatic record to address the working hypotheses outlined earlier, particularly hypotheses 1 and 2. In addition, one of the outcomes will include publication in a high impact journal such as the International Journal of Climatology.

We are now collaborating with Chris Larsen and his graduate student (MSc.) at UAF to examine the relationship between changes in the elevation of the glaciers and icefields of the Park and the trends in climate revealed by the CRREL climate network. The airborne altitudinal surveying of the primary glaciers within the park includes Johns Hopkins, Muir, Reid, Margerie, Carroll and McBride/Riggs as well as the Brady Icefield, exhibiting significant loss of ice in response to purported climatic warming since 2000

(Arendt *et al.* 2002; Larsen *et al.* 2007). This study will examine in a broad perspective how the elevation changes of the last ten years relate to the ten-year air temperature and precipitation record. This is the only location in southeast Alaska where there are sufficiently detailed records of climate at multiple sites in the area of the LiDAR surveying to permit such an analysis.

Collaboration is also underway on the effects of a major rain event on salmon habitat and spawning within the streams of Glacier Bay. Sandy Milner and Megan Klaar are using the climate record to help understand how geomorphic stream response to a November 2005 flood impacted salmon spawning and the subsequent recovery of the salmon population. Most of the climate stations within the Glacier Bay watershed recorded ~25 inches of rain in a 24 hour period, followed by several subsequent large events over the next several weeks. This event modified the stream substrate including woody debris distribution, changing the habitat and spawning cycle of salmon. The impact has lasted over 5 years.

We are also exploring collaboration with Dave Hill (Oregon State) to examine how the climatic data may provide insights into details on the freshwater flux to marine systems, a critical parameter driving water properties within the fjord estuarine environments of the Park (Etherington *et al.* 2007; Hill *et al.* 2009).

We will continue our collaborations with Brendan Moynihan for SEAN I&M climate monitoring and with research and interpretive staff to provide our expertise and knowledge of the climate, climate change and glacial response. It is our hope that the final results of the ten-year effort will produce climatic records as the basis for the long-term monitoring within the park and an understanding of the regional nature of the global climate signal in the Glacier Bay watershed. We remain hopeful that certain of the CRREL climate sites could ultimately be included in the SEAN I&M network to benefit directly from the current ten year record. In particular, the sites within the glaciated regions of the Fairweather Mountains and Takhinsha Mountains are critical to ascertaining changes in climate affecting glacial systems.

Our field work during the summer of 2010 relied in part on undergraduate students from The College of Wooster, Middlebury College and Dartmouth College, high school students from Vermont and significant assistance from Park volunteers in the downloading of data loggers and servicing of the instruments. Graduate students have assisted greatly in the database effort this year.

## Management Implications and Significance

Climate change is one of the most important things affecting the world today and in the future. The long-term climatic data that we are now collecting will be essential to understanding how global and regional changes in climate are affecting Glacier Bay and in predicting how such changes will impact the Park’s ecosystems. Such changes may cause significant changes in marine, terrestrial and freshwater ecosystems in the park, significant impacts that Park management may need to consider mitigating. Climate is the essential driver controlling physical and biological processes and environments and the feedbacks among them. The CRREL climate network is a first step toward meeting the goal of long-term monitoring and will hopefully feed directly into the SEAN Inventory and Monitoring Program. Additional sensors for wind, solar radiation and barometric pressure and satellite transmission with web access to the data will insure immediate and widespread distribution of the climate record. Our extremely limited understanding of the climate in the Park and such basic knowledge will be met by the enhanced climate network as collaboration with NWS comes to fruition. Emergency situations such as accidents involving cruise ships would benefit from having real time information on local meteorological conditions within the fjords.

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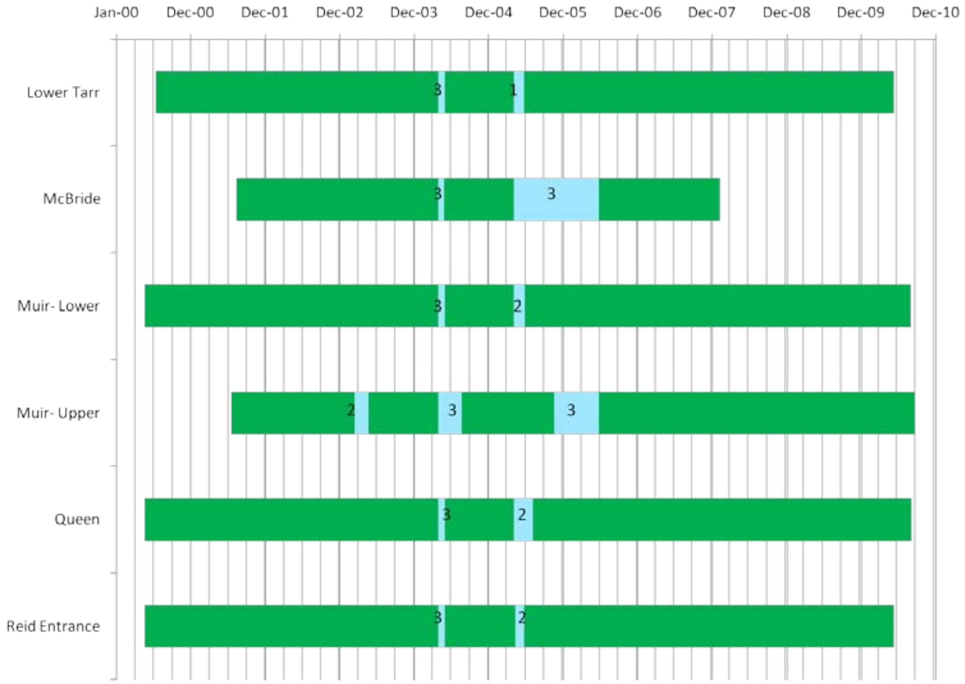
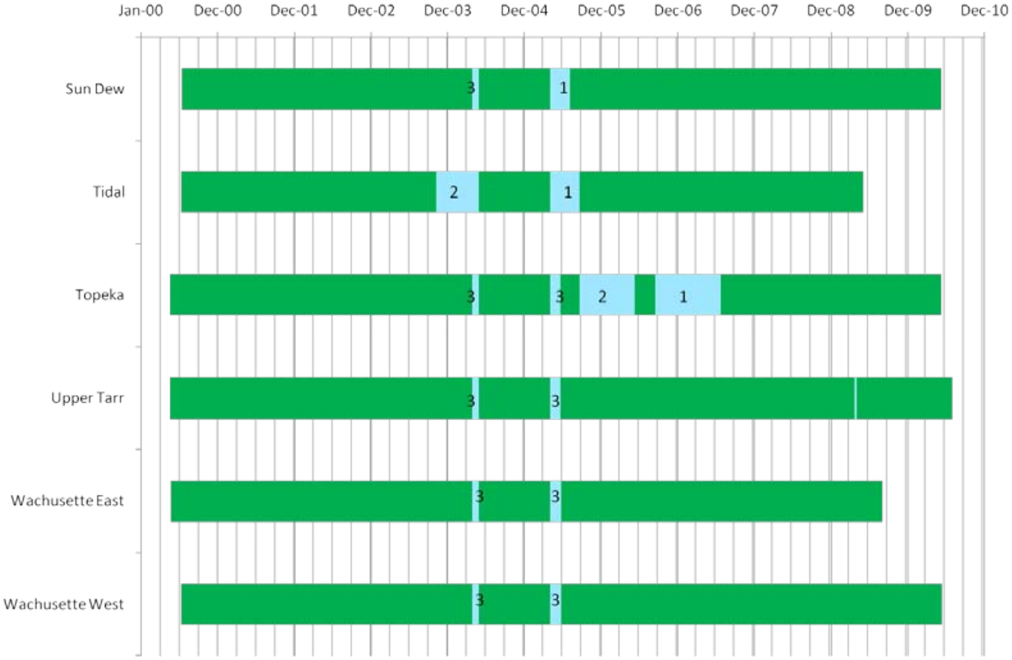
## Appendix A. Records of Air Temperature

The bar graphs show the periods of record of air temperature at each climate site. Green indicates data available; blue are gaps in the record. The numbers refer to the footnotes which briefly explain the reason why a particular gap exists.





Key: Green = data available; Blue = data missing; 1 = logger/ equipment damaged (bear, avalanche etc); 2 = equipment malfunction (battery, corrupt file etc); 3 = logger memory 'full', due to lack of access to climate station

## Appendix B.  Records of Precipitation

The bar graphs show the periods of record of precipitation at each climate site.  Green indicates data available; blue are periods of time without data recorded.  The numbers refer to the footnotes which briefly explain the reason why a particular gap in the record exists.

Key: Green = data available; Blue = data missing; 1 = logger/ equipment damaged (bear, avalanche etc); 2 = equipment malfunction (battery, corrupt file etc); 3 = logger memory 'full', due to lack of access to climate station; 4 = precipitation gauge covered to prevent snow and ice damage- practice stopped after winter 2000- 2001