Climate Monitoring:
Glacier Bay National Park and Preserve

2006 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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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 previously, we initiated a long-term monitoring of contemporary climate in Glacier Bay in cooperation with the National Park Service (NPS) in 1999. This monitoring will provide data for a major research effort to understand modern climate change and utilize these data to interpret the past and predict the future of climatic change because of it critical role and resulting impacts on the environment and ecosystems of the Park.

Climate is perhaps the single most important factor in controlling the physical, marine and terrestrial environments of Glacier Bay. Climate and its variability in time and space is an overarching driver of the Park ecosystems. Thus, global changes in climate may cause significant impacts to ecosystems and their responses in the near and long-term, an understanding of which will be important considerations to management for utilizing and protecting Park resources while accommodating visitors in the future. Currently, twenty-four climate sites measuring air temperature and precipitation, including snow water equivalent gauges at three of the sites, are active. In addition, we are testing near real-time GOES satellite systems for the hourly dissemination of weather data from two sites, with the goal of establishing multiple remote sites that can be monitored by park staff and researchers via a World Wide Web site established and maintained by CRREL.

We began establishing the network of climate sites in June of 1999, completing the current network in early 2001, and distributed the sites within the interior Glacier Bay watershed to provide information on how the climate may vary spatially and temporally at the sub-regional scale. Although the planned locations include both low and high elevation sites, the initial deployment has focused on accessible locations near sea level on the edges of fjords, with only a single higher elevation site in Muir Inlet established thus far. Site distribution was done to optimize data collection and servicing of

instruments, while providing coverage of the regional variability in climate across the Park. We chose a particular site to minimize environmental and visual impact and respect park wilderness resources and ethics.

The sea level elevation of all but one site allows us a direct comparison of the measurements necessary to define the source of its variability. The data also provide the basis for calibrating tree-ring records and interpreting the paleoclimatic indices of the interstadial wood sites. These data when combined with other measurements such as ablation and accumulation rates are also critical to understanding how glaciers and other physical systems are responding to regional and global changes in climate. Comparing these data to historical records of climate from long-term meteorological sites outside Glacier Bay will indicate whether those records are representative of the climate within the bay.

The current length of record remains too short to evaluate the source and significance of variability on seasonal and annual scales, but is approaching that needed to analyze general trends over the period of record and begin to assess sub-regional changes within the Glacier Bay watershed.

Our preliminary results suggest that:

- Mean annual temperatures generally fall in the range of 4 º C to 6.5 ºC across the Glacier Bay watershed, with the coldest sites near the heads of glaciated inlets and warmest sites within mid-bay.
- Mean annual temperatures generally decrease, but not systematically, from near the entrance of Glacier Bay near Icy Strait to the inner parts of each respective inlet in the East and West Arms by as much as 2 º C
- Coldest temperatures as recorded by January mean monthly temperatures from 1999 – 2005 ranged from – 3 °C to 0 º C in January 2002, with the coldest recorded at sites from the mouth to head of Johns Hopkins inlet and secondly near the glaciated heads of Muir, McBride and Wachusett inlets.
- Warmest summer temperatures as indicated by mean July monthly temperatures occur within the mid- to lower bay; mean July temperatures are typically 1.5 to 2.5 º C colder near glacier margins at the head of each inlet
- Precipitation amounts do not appear to show consistent trends nor range in values at a particular site or area; amounts in some summers are greatest within the mid-bay area south of the mouths of the East and West Arms, but in other years are greatest near the heads of inlets occupied by glaciers.
- Monthly precipitation amounts generally follow regional trends of meteorological stations outside the Park, with the highest totals typically in October and lowest in June.

An interesting trend appears to exist in the air temperature record for the period of 1999 to 2006. We have plotted the air temperature data at the 15 or 20 minute interval for the entire period of record. These graphs suggest that the overall trend in air temperature is an increase over this time period. This trend is consistent across all sites within the Glacier Bay watershed, and it suggests a warming over this time period of ~1.5 °C. If this initial analysis proves robust and passes more detailed scrutiny, it suggests that the overall global warming in climate may be affecting the air temperature of Glacier Bay. However, caution is needed in this preliminary interpretation until further analyses of these data are completed.

As measurements continue to be obtained, the database will provide a unique and extremely valuable resource on the climate of Glacier Bay. Long-term monitoring is essential to understanding the current and future trends in climate of the Park. Expansion of the network to the outer coast and higher elevation sites would provide a more complete record and fill the critical data gap that exists on the climate of the upper accumulation areas of the glacial systems in the park. As global climate continues to warm, the monitoring will provide a glimpse into how the Glacier Bay watershed is being impacted and provide the data needed by researchers investigating biological and physical system adjustments to such changes.

Thus, we think it is imperative to continue to service and maintain the climate sites across Glacier Bay, while also upgrading systems for improved performance and reliability. We will install GOES satellite instrumentation as funding becomes available to enhance the accessibility and application of the climate data on a near real time basis. The climate database currently resides on the CRREL server and has been archived on the Glacier Bay NPS server. Updates of the archival copy will be made annually.

Introduction

For the last 15 years, CRREL has conducted long-term, integrated monitoring and site-specific multidisciplinary studies of glacial, marine and terrestrial physical systems to improve our understanding of 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 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 research 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 ecosystem and other 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. These data will allow us to analyze storm patterns in the Park, assess differences in weather between the East and West arms, and evaluate impacts of short-term climatic changes. For our paleoclimate investigations, we will use these data to calibrate tree-ring records, including any significant spatial and seasonal variability that may affect how the tree-ring record is interpreted (Lawson et al 2007)..

Project History

We began establishing test sites for monitoring climate within Glacier Bay in 1999 in response to discussion in 1998 between one of us (Lawson) and Jim Taggart (USGS-GB) about a potential collaborative project on glacial and freshwater influences on biologic activity within the fiords and bays of the Park. These discussions identified a significant data requirement for climate information for the study, but such data had not previously been monitored anywhere in the Park except at Bartlett Cove. This data gap we realized was also significant to many other possible research investigations within the Park. Although the funding for the proposal was not secured, there was an obvious need for climate data for our existing long-term studies of the glacial and hydrologic systems and to meet the apparent needs of other Park and independent researchers.

Subsequent discussions with Park staff including Mary Beth Moss, Pat Phelan, Larry Bosch, Chuck Young and Randy King indicated their desire for climatic data and an interest in establishing high resolution climate stations at several high and low elevation locations. But funding was not available to the Park to implement a climate monitoring network at that time. In order to begin some baseline monitoring, CRREL initiated the testing of small and inexpensive meteorological equipment (total costs about $200 each site) to monitor two basic parameters important for many uses: net precipitation and air temperature. These parameters were known from anecdotal evidence to be critical controls on physical and biological environments and processes in the Park.

While continuing our long-term research projects, we began deploying temperature sensors and precipitation gauges in summer 1999, initially at 14 sites across the East and West Arms. Each site was chosen to be low impact and low visibility. We learned a significant number of lessons that season on how best to deploy the equipment, what types of stands and fasteners to use or what not to use (like PVC pipe and duct tape), and the data capacity requirements (e.g. summer rainfall totals > 90 inches). Further testing of equipment and fabrication resulted in revamping of some sites, moving others, addition of recording and tipping bucket rain gauges, and addition of 12 new sites in 2000. This established a monitoring network at sea level across the full breadth of the Glacier Bay watershed. Further lessons learned in 2000 led to additional tests in the off-season and improved rain gauge sensors, mounting systems and snowfall gauges in early 2001. Although we still encountered (and today encounter) problems due to equipment failures and natural causes like avalanches, wind storms and disturbance by animals that create gaps in data records, we consider calendar year 2001 the first complete season of climate data acquisition, with incomplete or lack of records from many of the sites prior to 2001.

Following discussions with Mary Kralovec about potential future requirements for rapid access to up-bay weather data as well as additional requirements for other types of climate data, we began the testing of climate stations with near-real time data transmission capabilities during the winter of 2001-2002. The impetus for this was two-fold – provide near real time data for tracking weather on an hourly basis while at the same time, minimizing requirements for climate site access. Two stations with GOES satellite transmitters were subsequently established - at Queen Inlet in November 2002 and at Tyeen in Johns Hopkins Inlet in July 2003. Testing of components, tracking of power usage and site upgrades continue today. Data are downloaded from the GOES satellite to the COE server and uploaded to the CRREL database and web server for dissemination.

We continue to test additional sensors for barometric pressure, solar radiation and wind speed and direction in the field and laboratory, seeking robust instruments of high resolution, low power usage and small dimension. Such sensors will provide a full array of climate parameters useful to researchers, Park staff and visitors. In addition it is critical to establish additional higher elevation sites at several or more locations across the watershed. Such sites were not initially established due to requirements for remote access and unknown reliability of instrumentation for long-term deployment of battery power systems. The use of GOES and various wind generators for power may be viable at existing radio repeater sites where access may be possible during their annual servicing.

During the initial work to develop each climate site and get it running efficiently and without instrumentation and other problems, we visited sites several or more times per year. These visits allowed us to address problems, which during the first summer of 1999 were fairly extreme, with most sites needing attention after several weeks. As repeat problems were solved, such as by replacing the type of sensor or gauge, changing the mounts from PVC plastic and duct tape, both of which bears love to chew on, to metal and natural wood, or moving sites to minimize animal encounters, we have reduced requirements for site visits to twice per year, preferably in late May after snow has melted, and again late in the season after vegetation has shed its leaves and prior to snowfall, typically mid- to late September. During these visits, data are downloaded and instruments serviced.

Methods and Site Instrumentation

Climate sites are located along fiord margins, generally at or near sea level (Figure 1). Each site has a minimum of two rain gauges (for redundancy), a temperature gauge, and a bulk precipitation collector for heavy isotope analysis (Lawson *et al* 2004; Finnegan *et al* 2006). The rain gauges (Onset RG-2 Tipping Bucket; Peet Electronic) record rainfall to

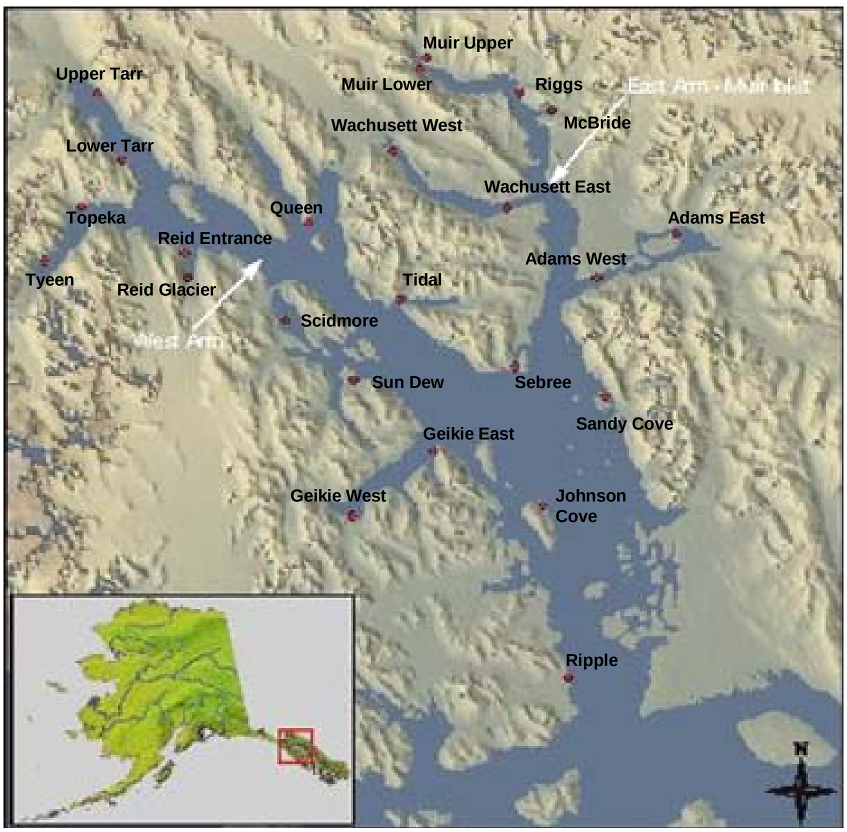


Figure 1. CRREL climate monitoring sites located within the Glacier Bay watershed.

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 repaired and upgraded and will be returned to active use in September 2007. Appendix A provides more detailed information on each site.

Figure 2. Typical monitoring set up at 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 is only used where animals are unlikely to damage rain gauges, but preferred to reduce snow cover effects early in the winter season.

Two sites (Queen Inlet, Tyeen) are utilizing GOES (Geostationary Operational Environmental Satellite) satellite transmitters for year-round, near-real time data transmission to include precipitation, temperature, solar radiation and wind measurements (Figure 3). By using the GOES transmission system, data are collected at regularly timed intervals (15 minutes) and transmitted via the GOES system for processing hourly. Once the data are transmitted, the information is decoded at a central receiving station located at the New England District Corp of Engineers Reservoir Control Center in Concord, MA. These data are quality checked and then pushed to a central database server at CRREL where the information is disseminated via the World Wide Web. The site address is: https://rsgis.crrel.usace.army.mil/ltir/GBweb.GBindex. We plan additional GOES transmitters as funds allow, reducing the need for costly site visits especially in areas where access may be limited by vessel restrictions and providing data in near real time for park managers, staff and researchers. The remote monitoring systems are ultimately expandable to include new instruments as research needs arise, and allows for collaboration with other researchers who likewise may benefit from near real-time data transmission.

We also collect bulk rainwater samples that have been analyzed for their stable isotope content (oxygen ($\delta^{18}O$), hydrogen (δD)). These data supplement those gathered from glacier ice and precipitation samples obtained from multiple locations across the Park (Lawson et al 2004). Our goal is to develop a better understanding of the sources and variability of precipitation that affect glacier activity as well as the freshwater hydrology of the Park.

Each climate site is routinely maintained during late spring or early summer and again in late summer or early fall. Typically we require 5 days to complete servicing, download, repair and maintenance of all 24 sites. 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 levelness 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, 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 the time required to service 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. 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 files on the data recorder to a folder on a portable

Figure 3. GOES test site in Queen Inlet. GOES satellite transmission system transmits hourly data on precipitation and air temperature, while also storing these data as a backup on Campbell data logger located within the grey box.

computer and as a back up onto a data key. During travel between sites, we prepare spare data loggers and instruments in case they are needed at the next climate site.

Once back at the office, all data files are archived on the CRREL server and its back up, as well as on personal computers being used to process and analyze the climate data. Water samples are logged and then stored pending analysis of their oxygen and hydrogen isotopic composition. Prior to analysis of the temperature and precipitation records, we must evaluate the data record from each individual instrument to ascertain if any problems exist. Such things as gaps in data, spurious data points and so forth must be identified and removed from the data set. In addition any situation or problems in the field that were noted in our field books must be accounted for. Such things as clogged intakes on the rain gauges or sensors knocked from their mounts to the ground will either cause records to be incomplete, or of more difficulty to recognize, be partly correct records with sections that must be removed. In the case of rain gauges, we have two gauges and we can use the two records to delineate such problems. This is commonly a tedious and lengthy job for the over 96 instrument records taken during each download period. Once problems in the data sets are removed, records are combined to develop a continuous record from which annual as well as monthly and daily information can be extracted and analyzed using standard statistical methods.

Preliminary Results and Observations

Although we now have approximately 4 to 5 years data from most of the twenty-four sites, the length of record remains too short to permit analysis of the seasonal and annual variability in climate and its significance and source. The data from the climate sites do provide some preliminary indication of sub-regional variability within the Glacier Bay watershed and observations on the range in values for air temperature and precipitation over the course of a year.

Precipitation during the period of record of 2001 to 2004 show an inconsistent spatial trend in values within the watershed (Appendix B). Rainfall amounts generally are low during the months of May through August, typically ranging from 20 to 30 inches at West Arm sites such as Topeka, to greater than 60 inches at central bay sites such as Sun Dew and Sandy. However inspection of the unprocessed rainfall data for the summer of 2006 show values ranging from only 12 to 24 inches from June to mid-September (Lawson et al 2006b), making it one of the driest summers since we began monitoring precipitation. This contrasts with anecdotal observations suggesting it was extremely rainy. This perception resulted it seems from extended cloudy periods with light mist or rain. Such types of weather could be better monitored with installation of solar radiation sensors, data which currently is non-existent for Glacier Bay.

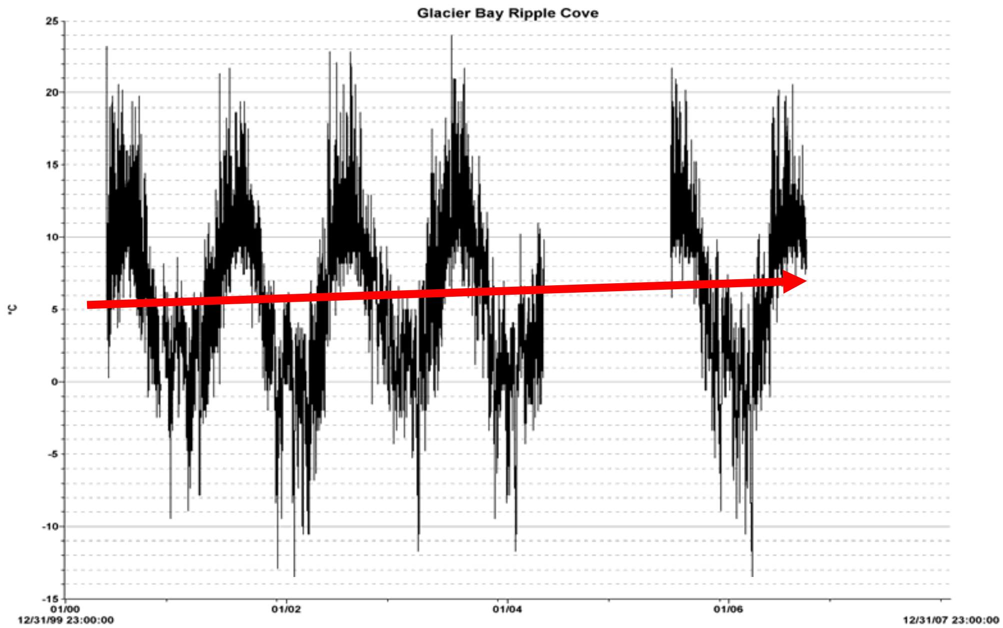
In contrast, the winter period of 2005 – 2006 was one of the wetter with a large rainfall event of 20 to 26 inches recorded at most sites within a three day period in late November 2005, and several other day events of over 8 to 10 inches during the October to December period.

In general, annual rainfall (excluding snowfall amounts) generally exceeds 70 inches to over 100 inches, but highest values were recorded during 2000 – 2001 when snow water equivalents at Tyeen and Muir Glacier ranged from 48 to 65 inches and yearly totals exceeded 150 inches. We are continuing to process the climate data to better evaluate trends in precipitation, with 2005 and 2006 data now being processed, and attempt to understand the variability in rainfall spatially as well as temporally. Inconsistent data acquisition during the early years of our monitoring (Appendix B) complicate our attempts to interpret this record, but more recently, our sites have been operating more consistently and thus processing of the raw 2005 – 2006 data may help analysis and interpretation

Air temperature at the sites across the Glacier Bay watershed (Figure 1) can vary daily and monthly by as much as 2 °C from the mouth of the bay at the Ripple site, to the head of each of the major inlets including the Muir, Wachusett West, Reid Glacier and Tarr Inlet sites. The West Arm sites from Reid Entrance and up Tarr and Johns Hopkins Inlets are generally cooler overall on a daily basis in summer and winter. Annual air temperatures generally range from ~ 4 °C to 6.5 °C, with the cooler temperatures at the sites at the head of glaciated inlets (Reid Glacier, Muir, Tyeen, Wachusett West, Tarr Lower and Upper, McBride) and warmer values within the central bay sites (Sandy, Sebree, Geikie East, Tidal, Adams West, Wachusett East). In summer, Ripple tends to be a degree cooler on average than the central bay sites. July monthly averages range from about 9 °C at the cooler sites, to over 11 °C, but as noted below, with an apparent overall increase in summer temperatures at all sites of over 1 °C from 1999 to 2006. In contrast, winter average temperatures in January may vary across the watershed by as much as 3 °C, with averages ranging from -3 °C to 0 °C in 2002 for example, but the warmest January averages (excluding 2005 – 2006 which are not fully processed) recorded at the cold sites in 2001 of ~ 0.2 to 0.5 °C in contrast to the warm mid-bay sites where January averaged 2.0 to 2.5 °C. This latter winter had few days below freezing and no significant period of extended cold (Appendix C).

Preliminary processing of the air temperature database to link multi-year recordings at each site has produced an extremely interesting and potentially significant result concerning the trend for sites with the longest period of record (1999 – 2006). We have plotted the air temperature for all data points obtained at the 15 or 20 minute interval versus date and time of each measurement. Representative results from the 24 sites are displayed in Figure 4, with data displayed from Ripple near the mouth of the bay, to Muir and Topeka near the upper reaches of the East and West Arms.

The overall trend in air temperature is increasing over this time period. Arrows drawn on these records by eye show this trend, a trend that is consistent across all sites within the Glacier Bay watershed. The suggested warming over this time period appears to be ~1.5 °C. Caution must be used in placing too much significance in this observation at this time; additional processing remains to be done, but the implication of these data, should they hold up to more intensive analysis and scrutiny, is that the climate of the last 6 years has warmed significantly and follows the overall global warming trend in climate. Additional analyses are underway to examine how our records compare with long term sites such as Sitka and Juneau, as well as to evaluate whether the apparent increase is seasonally focused to winter or summer or pervasive throughout the year.



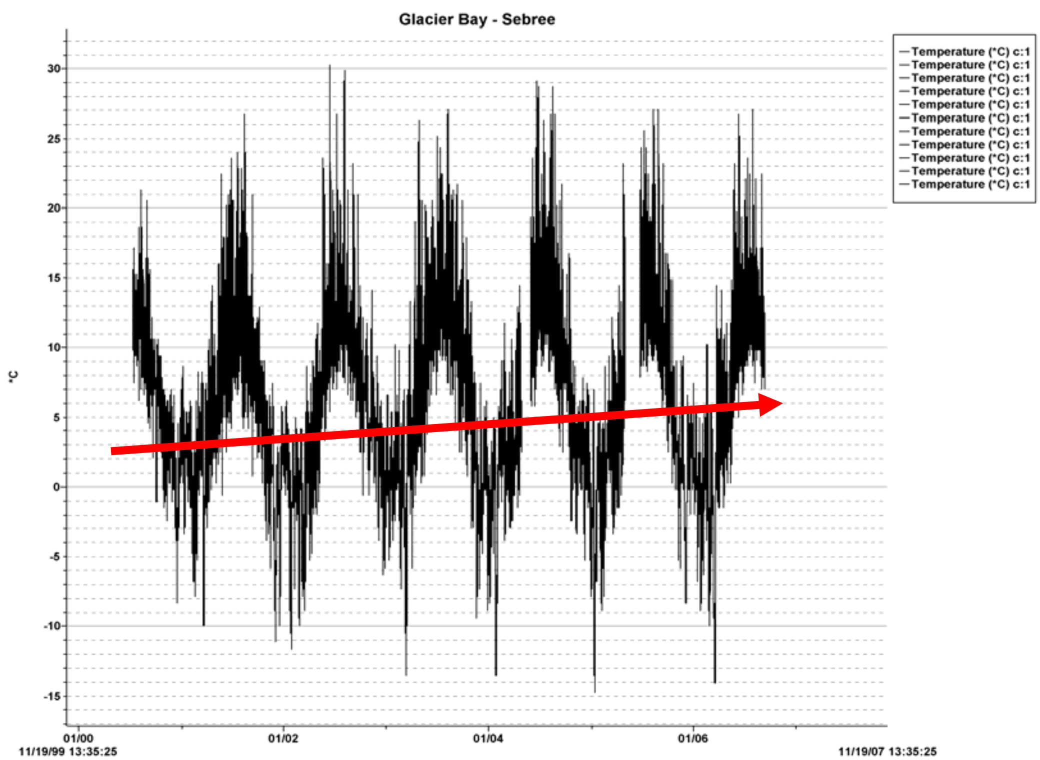
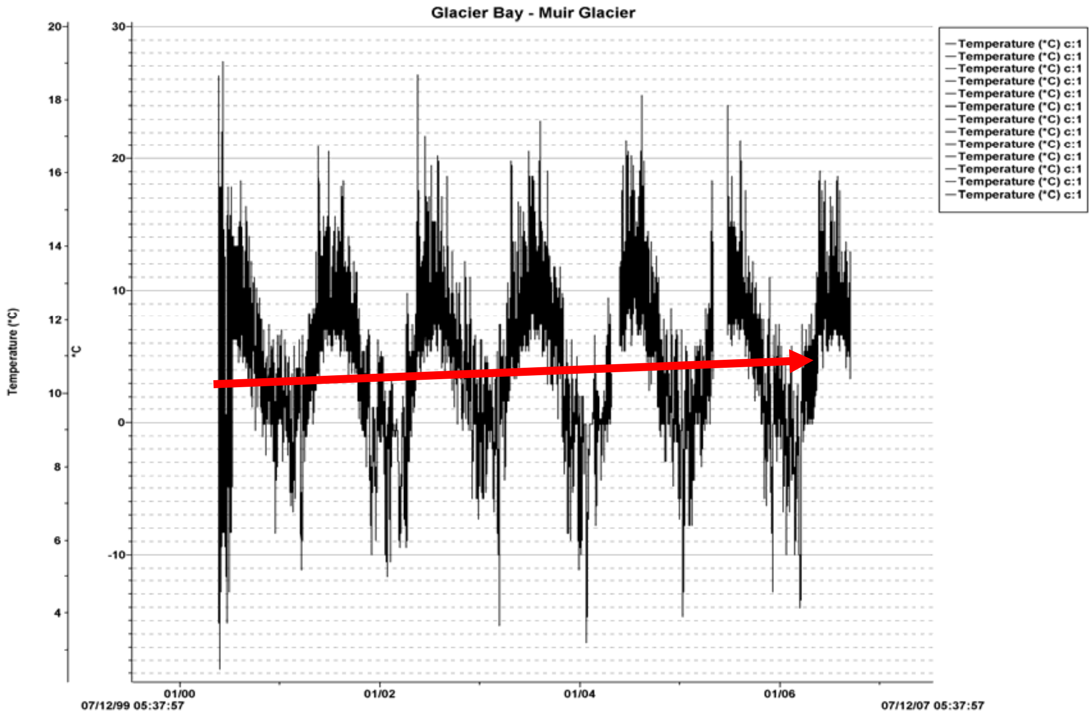


Figure 4 (cont. next page) Air temperature records from four climate sites across Glacier Bay. The red arrows mark apparent trends in temperature for the period 1999 – 2006, suggesting a significant warming took place.



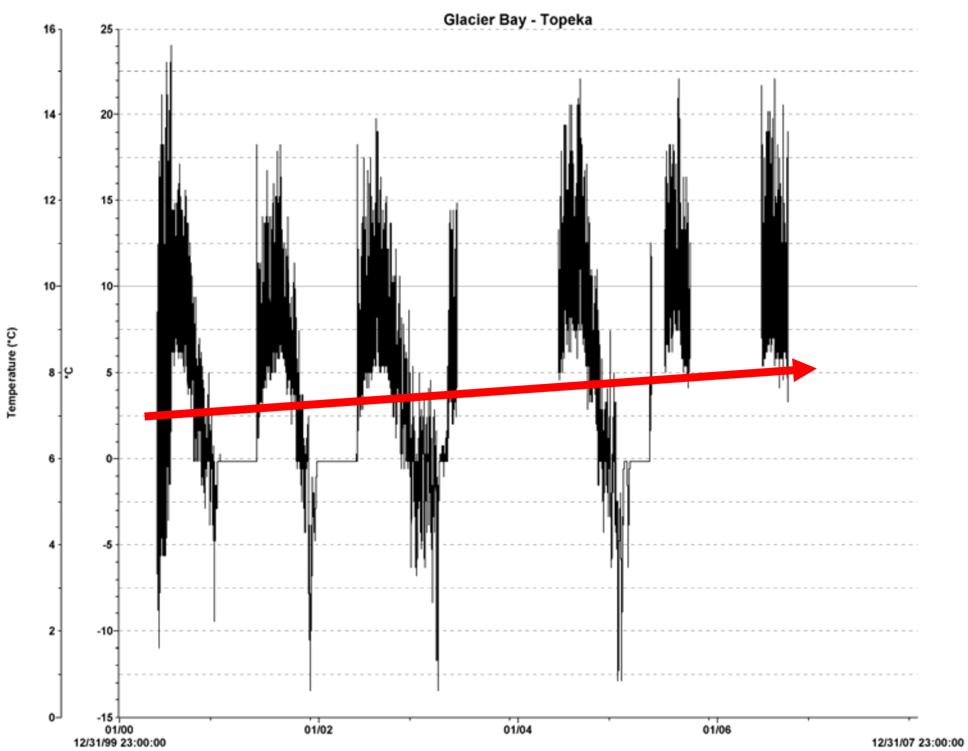


Figure 4 (cont) Air temperature records from four climate sites across Glacier Bay. The red arrows mark apparent trends in temperature for the period 1999 – 2006, suggesting a significant warming took place.

Continuing Work and Products

We plan to visit each climate site over two, 5-day periods in the spring and fall of 2007 and each year thereafter until systems are fully automated. These visits are necessary to insure that a complete record of the air temperature and precipitation from each site is acquired (barring problems over which we have no control). Additional processing and analysis of the 2005 and 2006 data will be combined with the existing database as part of a planned thesis during 2007 at Dartmouth College. We will be working to automate as much of the data processing mechanics as possible; however, the examination and assessment of each individual record will still need to be done prior to any automated processing. This will insure that data are quality and spurious information is not incorporated as this could lead to incorrect interpretations and conclusions. We have recently (July 2006) provided a DVD with all climate data acquired from 1999 through 2005 to Bill Eichenlaub for archiving on the NPS Glacier Bay server. An updated DVD to include the 2006 climate data and additional metadata is being prepared and will be sent to Bill for archiving on the Park server. The climate data are available for other researchers and park staff, but we ask that requests be made directly to us to insure no duplication of effort and that the most up-to-date and quality checked processed data are utilized.

Existing data from the climate monitoring effort will continue to be processed and analyzed through winter of 2007. As new records are acquired, we will produce continuous records, such as shown in Figure 4 for air temperature, for both the daily and monthly precipitation totals. New measurements acquired annually will eventually develop the lengthy record necessary to discern and analyze long-term trends versus short-term variability inherent in natural systems. The six year record we now have is significant, but not yet sufficiently long to analyze for multi-year (like El Nino) and longer (like Pacific Decadal and Arctic Oscillations) influences on climate, but it is approaching a length sufficient to begin to see overall trends related to global warming within the range of normal variability inherent in the regional climate. As the record develops to sufficient length and depth, we will publish our findings in prestigious professional journals.

Collaborators and Synergistic Activities

We are collaborating with Justin Smith (NPS) and Tom Ainsworth (NWS) to provide a climate station at Bartlett Cove. The current plan is for CRREL to provide a GOES system, precipitation gauge and solar radiometer, while the Weather Service provides the mounting, temperature gauges, barometric pressure gauge and related equipment for local weather download. The Park will provide set up on the dock and electrical power. This climate station will provide current weather conditions for the Park staff at the Visitor Center, while the GOES transmission will provide the Weather Service data hourly via the web from the central database server at CRREL. The climate site will also provide new climate coverage for the lower eastern side of the bay, supplementing the existing CRREL sites. Additional sensors may be added, including a tide gauge, if funding can be acquired.

Our field work during the summer of 2006 relied in part on undergraduate students from The College of Wooster and Dartmouth College and high school students from Vermont. We also had significant assistance from Park volunteers in downloading data loggers and servicing the instruments.

An analysis of the climate record of the last 7 years will form the basis for a thesis by Dartmouth student Linden Mallory in 2007.

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 have extremely significant ramifications for Park management to consider and to address. Climate is the essential driver controlling physical and biological processes and environments and the feedbacks among them. The CRREL climate network is the first step toward meeting the goal of long-term monitoring and will feed directly into the SEAN Inventory and Monitoring Program. By upgrading the existing sites for additional sensors for wind, solar and barometric pressure and for satellite transmission and web access, a full suite of climatic data will be available in near real time for use by park management, rangers, naturalists and interpreters as well as researchers. Our extremely limited understanding of the climate in the Park and such basic knowledge as storm tracks and prevailing winds will be met by our climate sites and the associated studies of stable isotopes and other aspects of the hydrologic cycle.

Acknowledgements

This project has been funded in part by the US Army Cold Regions Research and Engineering Lab, the National Science Foundation, Rockefeller Center for Public Policy and Social Sciences and the Institute of Arctic Studies at Dartmouth College, and private donations. We are extremely grateful to the current and past staff and management of Glacier Bay National Park and Preserve for their logistical support, assistance and encouragement. We particularly would like to thank Tomie Lee, Superintendent, Susan Boudreau, Chief Resource Management, and Lewis Sharman, Ecologist, for their permission and encouragement to conduct the research, and in providing the continuing support of their staff and vessels, housing, office space and other facilities.

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Appendix A.

CRREL Climate Site Instrumentation Status

CRREL INSTRUMENTED SITES

UTM_E_NAD27	UTM_N_NAD27	ELEV_MSL	SITE_NAME	INSTRUMENTATION	INSTALLATION*	STATUS
421371	6549407	15	Muir Lower	T Rain, R Rain, Temp, SG, WR	1999	Fully operational
432692	6546834	21	Riggs	T Rain, R Rain, Temp, TG	1999	Fully operational
436325	6544530	9	McBride	T Rain, R Rain, Temp, WR	2000	Fully operational
418345	6539534	9	Wachusett W	T Rain, R Rain, Temp,	1999	Fully operational
431333	6532716	7	Wachusett E	T Rain, R Rain, Temp,	1999	Fully operational
441504	6524317	4	Adams W	T Rain, R Rain, Temp,	1999	Fully operational
450472	6529554	6	Adams E	T Rain, R Rain, Temp,	1999	Fully operational
432160	6513384	9	Sebree	T Rain, R Rain, Temp,	1999	Fully operational
442470	6510073	9	N. Sandy	T Rain, R Rain, Temp,	2000	Fully operational
384787	6546570	26	Tarr-Upper	T Rain, R Rain, Temp, SG	2000	Fully operational; SG upgrade needed
387487	6538546	10	Tarr-Lower	T Rain, R Rain, Temp,	1999	Fully operational
383061	6532831	17	Topeka	T Rain, R Rain, Temp	1999	Fully operational
378835	6526334	21	Tyeen	T Rain, R Rain, Temp, GOES,SG,WR(TG)	1999	Climate site fully operational; GOES, WR need repairs
394744	6527228	12	Reid Entrance	T Rain, R Rain, Temp,	1999	Fully operational
395002	6524314	28	Reid Glacier	T Rain, R Rain, Temp,	1999	Fully operational
408742	6530781	8	Queen	T Rain, R Rain, Temp, GOES,SG	2000	Fully operational
406248	6519094	3	Skidmore	T Rain, R Rain, Temp,	2000	Fully operational
419159	6521771	7	Tidal	T Rain, R Rain, Temp,	1999	Fully operational
413844	6511746	6	Sun Dew	T Rain, R Rain, Temp,	1999	Fully operational
413758	6495370	3	Geikie W	T Rain, R Rain, Temp, SG	2000	Fully operational
422979	6503247	8	Geikie E	T Rain, R Rain, Temp, TG	2000	Fully operational
435242	6496672	7	Johnson's Cove	T Rain, R Rain, Temp,	2000	Fully operational
438263	6475780	5	Ripple Cove	T Rain, R Rain, Temp, SG	2000	Fully operational; SG needs upgrade
422514	6550921	1000	Muir Upper	T Rain, R Rain, Temp, SG	2000	Fully operational; SG needs upgrade

KEY:

R Rain = Digital recording rain gauge
T Rain = Tipping bucket rain gauge
Temp = Digital temperature sensor
SG= Snow gauge
GOES = Satellite Transmitter
WR = Water Level Recorder
TG = Tide Gauge

Appendix B. Precipitation Totals 2001 - 2004

Location	Year	Minimum Date	Maximum date	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Yearly Sum
Queen	2001	5/19/2001	12/31/2001					0.46	0.00	0.00	0.00	0.00	0.00	0.27	2.66	3.39
Queen	2002	1/1/2002	12/31/2002	9.29	5.52	1.03	0.57	4.27	3.73	3.42	10.23	9.04	13.47	16.65	8.78	86.00
Queen	2003	1/1/2003	7/31/2003	14.18	4.16	4.57	2.79	5.06	2.55	0.09						33.40
Riggs	2001	5/19/2001	12/31/2001					1.50	2.95	5.66	6.14	17.18	11.72	8.03	0.00	53.18
Riggs	2002	1/1/2002	12/31/2002	0.00	0.00	0.00	0.00	1.91	4.51	4.79	11.71	9.17	11.72	15.82	4.25	63.88
Riggs	2003	1/1/2003	12/31/2003	10.46	3.12	3.36	1.62	8.36	5.44	4.17	8.33	10.18	10.77	5.34	0.00	71.15
Riggs	2004	1/1/2004	5/26/2004	0.00	0.00	0.00	0.00	0.69								0.69
Tidal	2001	11/19/2001	12/31/2001											1.12	8.06	9.18
Tidal	2002	1/1/2002	12/31/2002	9.25	6.92	0.01	0.00	2.42	1.49	0.00	0.00	0.00	0.00	14.01	8.05	42.15
Tidal	2003	1/1/2003	12/31/2003	12.42	3.66	4.02	2.15	6.44	3.44	2.23	6.45	9.99	9.44	5.73	18.51	84.48
Tidal	2004	1/1/2004	7/31/2004	6.73	14.22	0.38		0.62	2.48	8.62						33.05
Sebree	2001	5/19/2001	12/31/2001					1.39	2.09	4.91	5.11	13.94	7.46	5.67	7.44	48.01
Sebree	2002	1/1/2002	12/31/2002	6.29	8.21	2.33	0.67	4.06	3.27	4.67	8.76	8.14	11.70	12.99	6.45	77.54
Sebree	2003	1/1/2003	12/31/2003	10.87	3.89	2.93	1.61	5.66	3.68	2.97	5.94	10.45	8.35	5.71	12.82	74.88
Sebree	2004	1/1/2004	7/31/2004	4.93	8.26	7.85	6.38	0.43	0.87	2.75						31.47
Topeka	2001	5/18/2001	12/31/2001					1.55	3.48	1.93	4.18	17.09	9.77	0.71	0.00	38.71
Topeka	2002	1/1/2002	12/31/2002	0.32	0.00	0.00	0.22	2.32	2.86	1.98	7.50	4.05	8.70	14.56	6.95	49.46
Topeka	2003	1/1/2003	1/20/2003	0.02												0.02
Topeka	2004	8/24/2004	8/24/2004								0.00					0.00
McBride	2001	8/12/2001	12/31/2001								6.65	16.96	12.17	8.15	4.00	47.93
McBride	2002	1/1/2002	12/31/2002	9.32	7.50	3.87	0.98	4.29	5.54	4.88	11.55	8.19	12.68	17.45	7.97	94.22
McBride	2003	1/1/2003	12/31/2003	13.37	3.06	3.97	1.17	9.30	6.15	4.74	8.05	9.57	9.67	5.32	16.50	90.87
McBride	2004	1/1/2004	2/18/2004	6.18	10.40											16.58
Sun Dew	2001	11/23/2001	12/31/2001											0.00	0.00	0.00
Sun Dew	2002	1/1/2002	12/31/2002	1.47	0.01	0.02	0.00	3.35	3.94	4.33	11.50	8.55	15.67	20.02	7.32	76.18
Sun Dew	2003	1/1/2003	12/31/2003	12.93	3.44	5.72	3.58	8.07	3.68	1.94	8.80	14.42	12.42	5.05	0.04	80.09
Sun Dew	2004	1/1/2004	5/28/2004	0.00	0.00	0.00	0.00	0.05								0.05
Scidmore	2001	11/23/2001	12/31/2001											0.00	5.93	5.93
Scidmore	2002	1/1/2002	12/31/2002	10.78	5.60	2.25	0.35	6.60	4.44	4.94	5.48	2.27	1.37	14.72	9.52	68.32
Scidmore	2003	1/1/2003	7/30/2003	12.03	3.53	4.75	4.01	2.30	3.60	1.55						31.77
Scidmore	2004	5/3/2004	5/3/2004					0.03								0.03
Adams East	2001	5/21/2001	12/31/2001					1.67	2.27	2.85	4.18	8.53	2.32	2.00	3.58	27.40
Adams East	2002	1/1/2002	12/31/2002	2.44	1.86	0.82	0.29	2.26	2.52	2.35	6.13	4.85	5.68	7.52	3.03	39.75
Adams East	2003	1/1/2003	12/31/2003	4.53	1.14	1.36	0.35	3.84	3.38	2.05	3.72	5.46	4.05	1.89	5.69	37.46
Adams East	2004	1/1/2004	5/26/2004	3.21	4.04	2.49	4.27	0.58								14.59
Adams West	2001	5/19/2001	12/31/2001					1.41	2.08	4.37	5.69	13.26	7.09	0.65	0.00	34.55
Adams West	2002	1/1/2002	12/31/2002	10.36	4.91	3.02	0.71	3.60	2.74	3.58	10.28	7.99	10.57	13.54	4.78	76.08
Adams West	2003	1/1/2003	12/31/2003	10.06	2.73	2.76	1.02	5.69	4.36	2.71	7.51	10.30	6.92	4.70	9.37	68.13
Adams West	2004	1/1/2004	5/26/2004	1.65	5.63	6.50	5.62	0.84								20.24
Sandy Cove	2001	5/24/2001	12/31/2001					0.63	2.58	4.84	5.11	9.20	4.18	3.16	4.30	34.00
Sandy Cove	2002	1/1/2002	12/31/2002	2.67	4.65	1.64	0.21	2.19	2.78	2.86	6.25	5.70	6.91	18.54	5.28	59.68
Sandy Cove	2003	1/1/2003	5/21/2003	7.40	2.27	1.69	0.85	1.18								13.39
Lower Tarr	2001	5/17/2001	12/31/2001					2.44	2.67					0.54	0.83	6.48
Lower Tarr	2002	1/1/2002	12/31/2002	9.90	0.23	0.00	0.00	7.93	3.33	3.53	11.01	6.23	10.10	14.21	6.18	72.65
Lower Tarr	2003	1/1/2003	12/31/2003	13.18	4.11	3.77	5.49	7.29	2.97	2.14	5.61	6.64	10.45	6.31	0.02	67.98
Lower Tarr	2004	1/1/2004	5/28/2004	0.00	0.00	0.00	0.00	0.04								0.04
Upper Tarr	2001	5/17/2001	12/31/2001					1.61	2.70	5.64	4.55	17.41	8.76	8.65	6.45	55.77
Upper Tarr	2002	1/1/2002	12/31/2002	5.07	3.18	2.60	0.62	3.95	3.63	3.77	12.24	7.12	9.32	12.41	5.97	69.88
Upper Tarr	2003	1/1/2003	12/31/2003	10.05	2.60	5.06	2.77	5.58	3.94	3.90	8.19	8.18	11.65	5.17	9.19	76.28
Upper Tarr	2004	1/1/2004	5/28/2004	0.67	5.70	6.22	4.56	0.96								18.11
Muir Upper	2001	7/17/2001	12/31/2001							1.22	6.03	14.94	6.58	4.27	2.41	35.45
Muir Upper	2002	1/1/2002	12/31/2002	4.17	0.00	0.14	1.92	4.34	4.20	3.58	7.29	6.58	9.13	11.33	3.22	55.90
Muir Upper	2003	1/1/2003	5/22/2003	6.82	1.45	2.57	1.82	1.39								14.05
Geikie East	2001	5/24/2001	12/31/2001					1.02	2.23	5.23	5.96	12.43	6.96	6.17	5.04	45.04
Geikie East	2002	1/1/2002	11/10/2002	6.85	4.47	2.51	0.15	3.88	2.61	3.34	6.10	6.34	10.62	0.89		47.76
Geikie East	2003	5/24/2003	12/31/2003					1.86	2.56	1.90	5.29	9.84	7.94	3.70	8.19	41.28
Geikie East	2004	1/1/2004	5/28/2004	2.81	7.40	5.37	1.90	0.22								17.70
Geikie West	2001	11/22/2001	12/31/2001											0.18	0.00	0.18
Geikie West	2002	1/1/2002	11/10/2002	0.05	0.02	0.00	0.00	7.99	5.07	6.23	18.09	13.44	18.33	1.88		71.10
Geikie West	2003	5/24/2003	12/31/2003					3.04	2.79	0.03	0.00	0.00	0.05	10.06	0.48	16.45
Geikie West	2004	1/1/2004	7/29/2004	0.00	0.00	0.00	0.00	0.00	0.00	0.30						0.30
Muir Lower	2001	7/18/2001	12/31/2001							0.93	6.44	20.96	12.13	12.13	0.00	52.59
Muir Lower	2002	1/1/2002	12/31/2002	10.63	0.00	0.00	1.14	1.94						17.04	6.43	37.18
Muir Lower	2003	1/1/2003	12/31/2003	13.45	2.95	5.08	2.95	8.62	4.99	4.90	11.00	12.10	11.95	9.23	1.61	88.83
Muir Lower	2004	1/1/2004	5/27/2004	0.01	0.00	0.01	0.00	0.04								0.06
Ripple Cove	2002	5/19/2002	11/10/2002					1.47	2.56	5.22	10.36	6.43	5.41	0.04		31.49
Ripple Cove	2003	5/24/2003	12/31/2003					0.51	2.22	2.17	3.29	9.55	5.50	3.33	5.49	32.06
Ripple Cove	2004	1/1/2004	1/14/2004	58.37												58.37
Reid Glacier	2001	5/18/2001	12/31/2001					2.27	2.91	3.10	6.05	18.66	8.65	0.38	0.01	42.03
Reid Glacier	2002	1/1/2002	12/31/2002	0.01	0.00	0.20	0.02	2.60	3.58	2.93	7.69	5.63	10.34	17.21	6.87	57.08
Reid Glacier	2003	1/1/2003	12/31/2003	0.03	0.01	0.00	4.14	6.47	3.13	0.99	7.94	11.80	11.83	0.56	0.00	46.90
Reid Glacier	2004	1/1/2004	7/31/2004	0.00	0.00	0.00	0.00	0.00	0.09	0.05						0.14
Tyeen	2001	7/13/2001	11/20/2001							0.10	3.63	8.63	0.00	0.02		12.38
Tyeen	2002	11/8/2002	12/31/2002											13.79	5.28	19.07
Tyeen	2003	1/1/2003	12/31/2003	10.70	1.11	0.00	7.49	5.42	1.57	0.62	4.73	8.05	9.87	1.12	0.05	50.73
Tyeen	2004	1/1/2004	7/30/2004	0.00	0.00	0.00	0.00	0.00	0.08	1.44						1.52
Johnsons Cove	2001	11/24/2001	12/31/2001											0.04	6.06	6.10
Johnsons Cove	2002	1/1/2002	11/10/2002	5.02	8.94	2.39	0.73	4.00	2.66	3.93	8.46	6.87	9.55	0.55		53.10
Johnsons Cove	2003	5/24/2003	12/31/2003					1.05	2.45	2.06	4.46	9.59	6.33	3.83	7.21	36.98
Johnsons Cove	2004	1/1/2004	5/29/2004	4.93	6.19	7.46	4.45	0.88								23.91
Reid Entrance	2001	11/21/2001	12/31/2001											0.63	0.00	0.63
Reid Entrance	2002	1/1/2002	12/31/2002	1.09	0.00	0.00	0.01	8.57	3.43	2.80	7.42	6.50	10.34	16.07	8.13	64.36
Reid Entrance	2003	1/1/2003	12/31/2003	4.34	0.31	4.70	6.11	6.61	3.33	1.22	8.09	11.35	12.28	0.74	0.00	59.08
Reid Entrance	2004	1/1/2004	5/28/2004	0.00	0.00	0.06	0.00	0.00								0.06
Wachusett East	2001	5/19/2001	12/31/2001					1.81	2.37	5.99	6.65	19.44	13.03	11.37	0.00	60.66
Wachusett East	2002	1/1/2002	12/31/2002	3.91	0.00	0.00	5.36	4.46	3.69	3.55	13.35	11.15	16.19	17.36	6.73	85.75
Wachusett East	2003	1/1/2003	5/21/2003	12.59	3.98	4.84	1.97	0.02								23.40
Wachusett West	2001	5/19/2001	12/31/2001					1.29	2.38	5.41	6.58	19.41	10.04	10.90	0.00	56.01
Wachusett West	2002	1/1/2002	11/5/2002	0.00	0.00	0.00	0.00	7.43	3.83	3.10	8.89	7.54	12.64	0.37		43.80
Wachusett West	2003	5/21/2003	12/31/2003					5.28	3.65	2.48	9.63	11.56	11.30	3.00	0.11	47.01
Wachusett West	2004	1/1/2004	5/26/2004	0.00	0.00	0.00	0.00	0.38								0.38

Appendix C.
Representative Air Temperature Records 2000 - 2002