Assessing Contemporary and Holocene Glacial and Glacial-Marine Environments

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Abstract. Understanding tidewater and terrestrial glacier processes is critical when determining the impacts that contemporary climate and anthropogenic activities play in long-term glacier response. The primary focus of our long-term investigations in Glacier Bay is to better understand regional and global factors, such as climate, hydrology, oceanography and geophysical processes, that control terrestrial and marine-based physical systems. Our recent climatic investigations include analyzing modern climate trends at 22+ locations across Glacier Bay proper and measuring the isotopic composition ($\delta^{18}O$ and δD) of precipitation, surface water, and glacier ice to assess regional hydrologic trends. Stable isotopes from samples of glacier ice, precipitation, and meteoric waters, have provided a regional assessment of the hydrologic cycle and localized weather patterns, allowing us to examine how the current climate affects glacier activity and mass balance.

Introduction

Glacier Bay National Park, located about 140 km northwest of Juneau, Alaska, comprises 3.3 million acres, including 920 mi of coastline (fig. 1). Normally heavy snowfall in the high mountains feeds one of the larger active glacier complexes in North America, a part of the fourth largest glaciated region in the world.

With the exception of some lowlands at the southeastern and southwestern margins, Glacier Bay was inundated with ice as recently as 250 years ago. Glacier retreat since that time has been well documented, with margins that retreated as far as 90 km at some of the highest rates recorded in the world. Though ice remains in the peripheral highlands to the north and west, an extensive series of glacial and glacial-marine landforms remain, thereby providing the unusual and unique opportunity to study ice-recessional phenomena, tidewater processes and terrestrial landform development through the entirety of the Holocene.

This paper summarizes preliminary results of long-term climate and stable isotope monitoring efforts by the Cold Region Research and Engineering Laboratory (CRREL), some that have been in place for over a decade. The ultimate goal of these efforts is to quantify the physical processes of modern and historic glacial phenomena within Glacier Bay as related to the following key questions:

- What effect have contemporary and historical changes in climate had on the physical systems of the glaciers and fjords?
- As a consequence of past changes in climate, how have the physical systems responded during each successive episode of glacial advance and retreat?

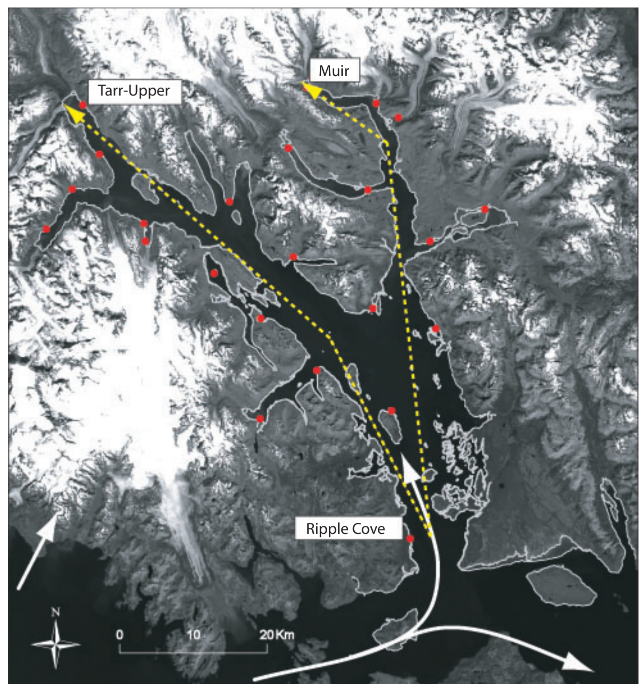

Figure 1. August 1, 1999, Landsat 7 Enhanced Thematic Mapper+satellite image overlain with long term climate monitoring sites maintained by CRREL (dots). Lines represent South to North transects in figure 3. Lines with arrows represent hypothesized dominant storm tracks off the Gulf of Alaska (after Hunter and Powell, 1993).

- What role did past climate and glacial activity have on human habitation in the Park?
- What fjord and ice marginal processes control glacial advance and retreat?
- How do terrestrial and tidewater glacial environments affect marine ecosystems?

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- Is there evidence of significant climate forcing in the sedimentary and dendrochronological record and can changes in climate be related to global changes or regional phenomena?

Methods

The long-term monitoring of contemporary climate in Glacier Bay has been ongoing by CRREL in cooperation with the National Park Service since 1999 (Finnegan and others, 2003; Kopczynski and others, 2003). As of October 2004, there are 24 active climate-sites including two snow water equivalent gauges (these include a full climate site) and two realtime Geostationary Operational Environmental Satellite systems (GOES) that are maintained by CRREL within the main bay of the park (fig. 1). Each of these stations has been located to optimize data collection at approximately the same elevation (sea level) for regional comparisons. Furthermore, the locations of each site were chosen to minimize environmental and visual impact to respect park wilderness resources and ethics.

Each climate site has a minimum configuration of two rain gauges that collect data at 0.01-in. increments; a high-resolution temperature sensor sensitive to tenth of a degree; and a bulk rainwater sampler at each rain gauge for stable isotope analysis. We have collected and analyzed the bulk rainwater samples as well as precipitation (rain, snow) at re-occupied locations for oxygen ($\delta^{18}O$) and hydrogen (δD) stable isotope content over the last 10 years. Glacier ice samples also were obtained from tidewater and terrestrial glaciers throughout the Park. We have been sampling both the basal and englacial ice in systematic sampling grids to develop a better understanding of the sources of precipitation for glaciers and how these may vary across the region.

Results

Climate Data

Climate data acquired within Glacier Bay, though preliminary, is beginning to reveal trends in the local and regional climate systems. A summary of the first consistent long-term climate records to provide a holistic perspective of precipitation within Glacier Bay is shown in table 1. Overall yearly averages at each site are high (>50 in/yr) and our yearly records, indicate that precipitation levels are fairly consistent. Furthermore, the data illustrates patterns and trends which occur along the main bay, East Arm and West Arm.

As an addition to the future of climate monitoring within the park, we are developing and deploying near real-time GOES up-linked climate platforms. The GOES satellite is a geostationary imaging satellite that is primarily used for weather imaging and observations over the eastern and western continental United States. Included on the GOES platform is a one-way radio communication channel that allows for transmission of approved scientific information. Currently, most CRREL climate stations are revisited during the spring and fall seasons to calibrate instrumentation, download data, collect samples and repair damage that may have been incurred due to wildlife and environmental conditions. By using the GOES transmission system, data are collected at regularly timed intervals (15 minutes) but are transmitted via the GOES system for processing hourly. Once the data are transmitted, the information is decoded at a central receiving station at the Corp of Engineers New England District, quality checked and then sent to a central database server at CRREL.

Table 1. Summary of precipitation data for climate monitoring sites maintained in Glacier Bay by CRREL.

[in/yr, inch per year; –, incomplete data]

Location	Year	Total (in/yr)
Lower Bay		
Ripple Cove	–	–
Geikie East	2002	47.76
Geikie West	2002	71.1
Johnson’s Cove	2002	53.1
Sandy Cove	2002	59.68
Sebree	2002	77.54
West Arm		
Sundew Cove	2002	76.18
Skidmore	2002	68.32
Tidal	2002	42.15
Queen Inlet[1]	2002	86
Reid Inlet Entrance	2002	64.36
Reid Glacier	2002	57.08
Tarr Lower	2002	72.65
Tarr Upper	2002	69.88
Johns Hopkins Inlet		
Topeka	2002	49.46
Johns Hopkins[1]	2003	50.73
East Arm		
Adams East	2002	39.75
Adams West	2002	76.08
Wachusett East	2002	85.75
McBride	2002	94.22
Wachusett West	–	–
Riggs Glacier	2002	63.88
Muir Glacier	2003	88.83
Upper Muir	2002	55.9

[1]GOES near real-time data collection site.

The benefits of installing these sophisticated devices include the near real-time retrieval of weather information and greatly reducing labor and resources needed to maintain a consistent, yet highly accurate accumulation of climate data. By installing the GOES systems throughout the Park, we will also reduce impact on biologically sensitive areas at critical times of the year through reduced number of visitations each season. The remote monitoring systems are capable of being expanded to include new instruments as the need arises and allows for collaboration with other researchers working in the park that likewise may benefit from near real-time data transmission. Furthermore, easy and rapid access to climate data in remote areas of the park through our web-based interface may be especially useful to Park resource managers for planning, to interpreters and naturalists for daily climate information, and to Park Rangers during emergency situations.

Isotopes

It is widely recognized that the $\delta^{18}O$ and δD isotopic compositions of precipitation are influenced by source, temperature, altitude, distance inland along storm tracks, and latitude. In Glacier Bay, our data show a trend consistent to the Global Meteoric Water Line (fig. 2), representing the average relationship between $\delta^{18}O$ and δD in meteoric waters throughout the world. Regionally, the changes exhibited in the isotopic composition of precipitation vary. For example, oxygen ratios vary by a significant 6 to 8‰ across the Park. Within the East Arm, the oxygen isotope ratio of precipitation shows seasonal variations ranging from -7 to -14.5‰, whereas in the West Arm they range from -8 to -14.5‰. The isotopic values vary significantly with location. Along north-south transects from the mouth of Glacier Bay (Ripple Cove) to the head of Muir and Tarr Inlets respectively, the $\delta^{18}O$ values for cumulative samples of precipitation decrease, becoming more negative with distance. In contrast, annual precipitation totals show an increasing trend toward the head of Muir Inlet, but a slightly erratic, mostly increasing trend into the West Arm. Combined, these trends suggest a predominance of storms tracking from the mouth of Glacier Bay to the head of Muir Inlet, but less effective movement of these storms northwestward into Tarr Inlet, inland of the Fairweather Range.

We also see isotopic differences and trends within glacial ice. Values for glaciers in the East and West Arms differ significantly from one another. These variations reflect differences in the elevation and precipitation sources of the accumulation areas. The eastern systems radiate from icefields in the Takinsha Mountains at elevations ranging from 1,200 to 1,900 m (Equilibrium Line Altitude (ELA) ~750 m), whereas those in the West Arm are fed by snow falling in the Fairweather Range at elevations of over 2,500 to 4,500 m (ELA ~1,000–1,100 m). The orogenic effect or rain shadow created by the Fairweather Range and its elevational control on the tracks of storms entering Glacier Bay appear to exert a strong regional control on the climate of the Park (fig. 3).

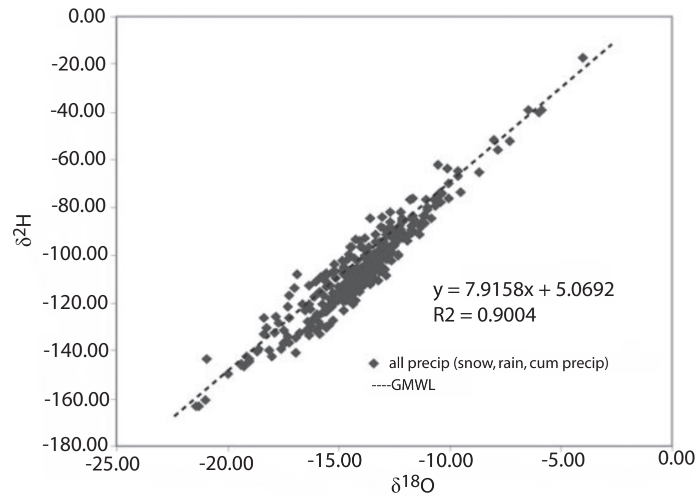

Figure 2. Relation between $\delta^{18}O$ and δD values for all precipitation and snow samples (1997–2003) collected within Glacier Bay. Samples are shown in comparison to the Global Meteoric Water Line (GMWL) where $\delta^2H = 8\ \delta^{18}O + 10‰$. Data from Glacier Bay show a reasonable fit to the GMWL.

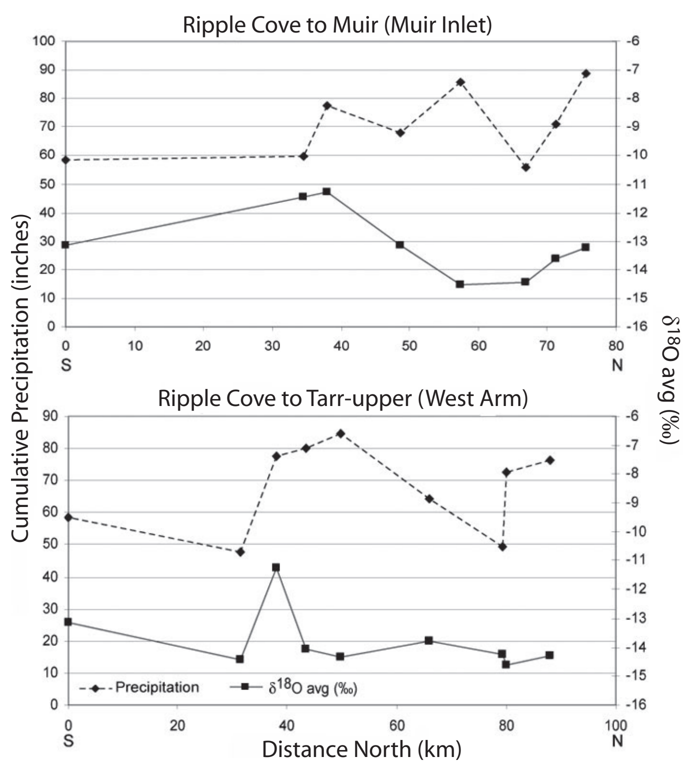

Figure 3. Spatial distribution of $\delta^{18}O$ and cumulative precipitation values derived from CRREL climate monitoring sites (up to 2004) for transects running South to North along the West and East Arms of Glacier Bay (see fig. 1 for locations). Precipitation values show an approximate increasing trend from the mouth of Glacier Bay to the head of Muir Inlet and less so towards the head of Tarr Inlet. Likewise, the isotopic values become increasing lighter with distance up each respective inlet, particularly in Muir Inlet.

Discussion and Conclusions

Understanding the modern glacial environment is essential for reconstructing the glacial history and dynamics throughout the Holocene. It also improves our understanding of the impact that climate change will have on future marine and terrestrial communities and ecosystems. Weather patterns may be highly localized, impacted by the glaciers themselves, and influenced by mountainous topography. Glaciers respond according to their location, amount of precipitation and respective source areas. The length of our records of temperature and precipitation remain too short to assess annual, seasonal and spatial variability in temperature and precipitation, but the data do suggest that trends may be present and related to both the prevailing storm tracks and local topography. The influence of other factors such as El Nino, Pacific Decadal Oscillation (PDO) and Arctic Oscillation are unknown but will be investigated as part of our paleoclimatic research (Lawson and others, this volume).

Trends present in the preliminary bulk rainwater isotopic data lead us to believe that the storm sources are diverse, but there is a regional effect related to primary storm tracks. Storms in the Gulf of Alaska appear to move through Cross Sound and then north out of Icy Strait up the lower Bay and into the East and West Arms. There is some suggestion in the data that the storms may more commonly move into the West Arm.

Expansion of the climate network to higher elevations is essential to understanding the regional variability in climate and to provide data critical to both physical, biological and ecosystem research in the Park. The climatic network is crucial to many types of studies, but a record does not exist within the Park prior to 1999. There remains a need to install additional sensors, including those for wind speed and direction and solar radiation.

Management Implications

Climatic data provide a record of the essential elements that control the physical and biological processes of freshwater, terrestrial and marine ecosystems of the Park. It is critical to establish and maintain long-term monitoring of climatic parameters. The CRREL climatic network is the first step toward meeting this goal. By upgrading the existing sites to satellite transmission and web access, the 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 are being met by our climate sites and the associated studies of stable isotopes and other aspects of the hydrologic cycle.

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