Long-term Studies of Tidewater and Terrestrial Dynamics, Glacier Hydrology and Holocene and Historic Climate Activity, Glacier Bay National Park and Preserve, Southeast Alaska

Progress Report and Update
Prepared for Glacier Bay National Park and Preserve

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Abstract

Understanding tidewater and terrestrial glacial and glacial-marine environments is critical to determining the long term impacts that contemporary climate changes and anthropogenic activities may have on terrestrial and marine ecosystems in the Park. This understanding can only be acquired through long-term, repetitive and quantitative analyses of regional and global factors including climate, hydrology, oceanography and geophysical processes and their role in the physical processses of glacial and glacial-marine environments. We conduct repetitive hydrologic and oceanographic measurements inglaciers and fjords that reveal seasonal, annual and longer-term trends, as well as define rates of erosion, sedimentation and sediment flux. Climatic investigations include analyzing modern meteorological trends at 26 locations across Glacier Bay and measuring the isotopic composition (δO, δD) of precipitation, surface water and glacier ice to assess regional hydrologic trends. These data are improving our understanding of the regional variability in the hydrologic cycle and localized weather patterns, allowing us to examine how the current climate affects glacier activity and mass balance. Concurrently, the Park's longer-term Holocene glacial history and paleoclimate are being investigated using dendrochronological and radiocarbon dating of in-situ stumps, logs and soils. We have precisely located samples of over 100 interstadial stumps and buried logs that were overridden by ice moving down-fjords during several advances in the Holocene. Radiocarbon dating by Accelerated Mass Spectrometry (AMS) has provided a preliminary estimate of ice-marginal positions and probable rates of advance of tidewater glaciers during four advances over the last 12000 yrs BP. We are also attempting to develop a tree-ring chronology spanning the last 9,000 years on cross sections of these trees. If successful, this would be the only such dataset for a subarctic region in Alaska and the North Pacific region, and would provide data critical to calibrating Global Climate Models (GCM's) to predict future changes in climate. We will be intensifying our efforts to better understand the Little Ice Age climate and glacial history and the Tlingit legends of catastrophic glacial advance and flooding during that time.

Introduction

Glacier Bay National Park, located ~90 miles northwest of Juneau, Alaska (Figure 1), comprises 3.3 million acres, including 920 miles of coastline. 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. There are currently seven active tidewater glaciers and numerous terrestrial glaciers within the interior region of the Park. The outer coastal region west of the Fairweather Range is heavily glaciated as well.

The Glacier Bay watershed is delimited to the east and north by the Chilkat and Takinsha Ranges, to the northwest by the high crest of the Fairweather Range, and to the west by the peaks and ridges forming the eastern margin of the Brady Icefield. From this peripheral rim, a series of lower ridges extend radially inward toward the Bay, defining between them a complex of partially submerged and sometimes ice-occupied valleys that merge into two distinct fjord systems - the East Arm that includes Muir, Wachussett and Adams inlets, and the West Arm that includes Tarr and Johns Hopkins inlets. These in turn coalesce to form the main trunk of Glacier Bay (Figure 1).

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 is one of the best documented, with margins retreating distances 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 known-age 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.

Research Objectives

As part of our efforts to monitor and quantify the physical processes of modern and historic glacial phenomena in Glacier Bay, we are also looking to answer the following key questions:

- What effect have contemporary changes in climate had on the physical systems of the glaciers and fjords since the Little Ice Age maximum?
- 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 such as El Nino and the Pacific Decadal Oscillation?
- As a consequence of past changes in climate, how has the glacial system responded during each successive episode of glacial advance and retreat?
- What fjord and ice marginal processes control glacial advance and retreat?
- At what rate do glaciers erode mountains and fjords, and what becomes of the eroded sediments after they are released by the tidewater glaciers at their margins?
- How do terrestrial and tidewater glacial environments affect marine ecosystems?
- What role did past glacial activity have on human habitation in the Park; in particular, what can we learn about the sudden ice advance or catastrophic flooding captured in Tlingit legend?

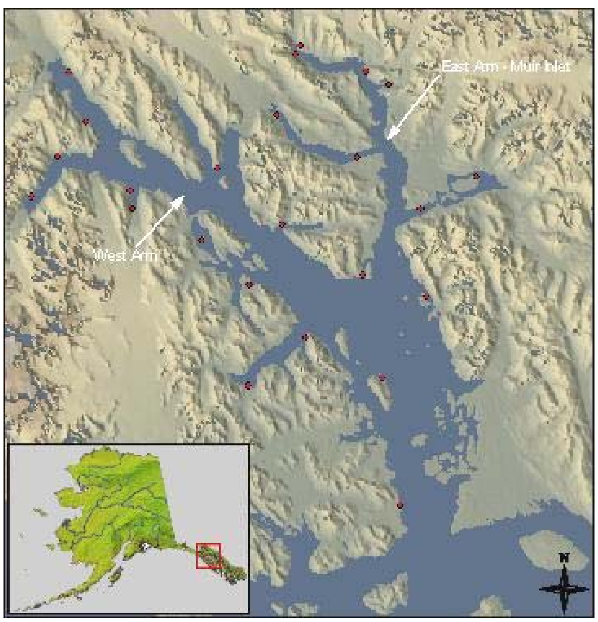

Figure 1. Shuttle Radar Topography Mapping Mission shaded relief (30 m resolution) of Glacier Bay National Park, southeast Alaska (see lower left inset). Red dots represent climate monitoring sites currently maintained by CRREL.

Climate Monitoring

The long-term monitoring of the present climate in Glacier Bay has been ongoing by CRREL and NPS since 1999. Understanding the modern glacial environment is essential for reconstructing the glacial history and dynamics throughout the Holocene, and allows an understanding of the impact that significant climate change will play on future biological marine and terrestrial communities and ecosystems. Weather patterns may be highly localized and are impacted by the glaciers themselves in addition to the regional influences of the mountainous topography. Glaciers respond accordingly based on their location in the park, amount of precipitation and respective source areas.

As of November 2003, there are 26 active climate sites and three snow water-equivalent gauges that are maintained by CRREL within the park (Figure 1). Each climate site includes a minimum of two rain gauges (one back up), a high resolution air temperature sensor and a bulk rainwater collector for laboratory anlysis of the stable isotope ratios of oxygen and hydrogen (Figure 2).

Each climate site is located to optimize data collection for regional comparisons, with most of them near sea level along each major fjord. In addition, we chose sites to minimize environmental and visual impact and respect wilderness resources. Expansion of the network to higher elevations and addition of wind sensors and radiation instruments is being planned to coincide with NPS monitoring activities.

Currently, climate stations are revisited during the spring and fall seasons to service instrumentation, download data, collect samples and repair weather or wildlife damage. In response to Park management concerns over visitation to sensitive areas such as Johns Hopkins Inlet during seal pupping, we began testing a GOES satellite transmission system in July 2003 (Figure 3). Using the GOES system, data are collected and stored on data loggers at regularly timed intervals (15 minutes) but are also transmitted for processing hourly. These stations allow near real-time retrieval of weather information and will greatly reduce man-hours and resources needed to maintain a consistent, yet accurate accumulation of climate data. The installation of additional GOES collection systems will reduce our impact on biologically sensitive areas at critical times of the year. We will be evaluating methods to make these data available to Park Rangers for rapid response during an emergency.

Figure 2. Typical rain and temperature gauge set up.

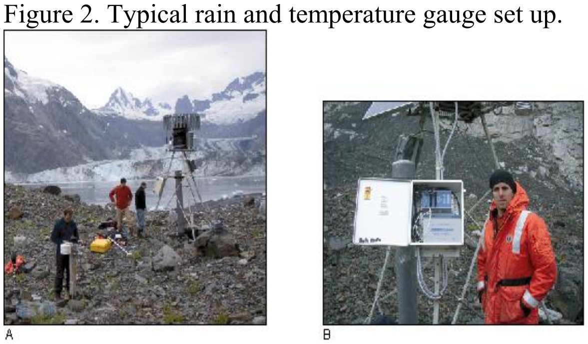

Figure 3. GOES test site in Johns Hopkins inlet. A GOES satellite transmission system transmits hourly data on precipitation and temperature, while also storing these data as a backup on Campbell data logger.

Temperature and precipitation records from across the Park show distinct seasonal and annual changes (Figure 4). Trends in both parameters are consistent with historical and anecdotal records that indicate the region is climatically sensitive and is highly variable in rainfall amounts between the East and West Arms. Monthly averages of air temperatures span about 3.5 ˚C between the warmest and coldest sites near sea level. Over the last three winters, temperatures were an average of more than 1 ˚C colder in the West Arm than the East Arm. We found extreme gradients of increasing rainfall from the mouth of Muir Inlet to Muir Glacier, from the mouth of Hugh Miller Inlet to the head of Johns Hopkins Inlet, and from near the Carroll Glacier margin through the mouth of Wachusett Inlet to the head of Adams Inlet. May to November totals show a precipitation gradient increasing northward from the lower Bay to the head of Muir Inlet, while decreasing northwestward into the West Arm. Winter monthly temperatures also vary regionally, with average temperatures typically decreasing northward while remaining milder within the lower Bay.

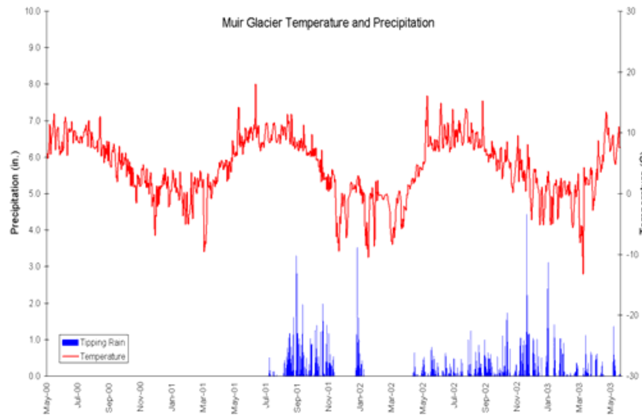

Figure 4. Example of the temperature and precipitation records at the Muir Glacier climate site. Intense rainfall events and sharp changes in temperature are common.

Stable Isotopes and Hydrology

Since 1995, we have collected precipitation, snow and glacier ice samples annually for analysis of their oxygen (δO) and hydrogen (δD) stable isotope contents. Trends present in the preliminary data lead us to believe that the storm sources are diverse, but there is a regional effect within the park related to primary storm tracks. Studies in other regions of the world have shown that the natural spatial distributions of the δO and δD isotopic compositions of precipitation are influenced by source, temperature, altitude, distance inland along different storm tracks and latitude. Our data show a consistent trend compared to the Global Meteoric Water Line (Figure 5), which represents the average relationship between δO 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 2 to 3 ‰ across the Park. Within the East Arm, the oxygen isotope ratio of precipitation shows seasonal variations ranging from –12.5‰ to -14‰, whereas in the West Arm they range from –12.5‰ to –15.5‰ (Figures 5, 6).

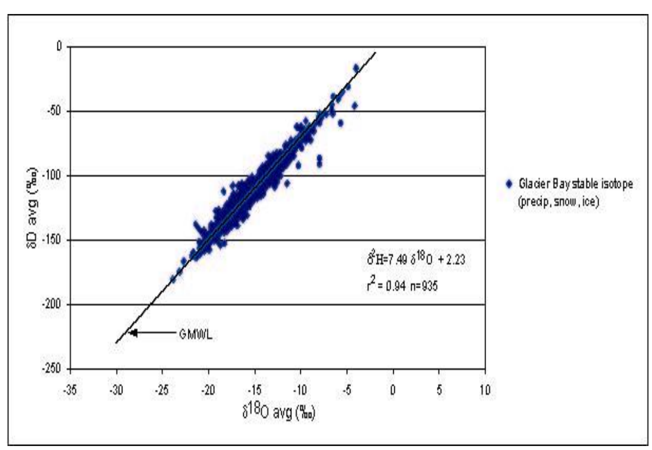

Figure 5. Relationship between δ18O and δD values for all precipitation, snow and ice samples (1997-2003). Samples are shown in comparison to the Global Meteoric Water Line (GMWL) where δD =8 δ18O + 10. The data show a reasonable fit.

The isotopic values vary significantly with location (Figure 6). Along north-south transects from the mouth of Glacier Bay to the head of Muir and Tarr Inlets respectively, the δO values for cumulative samples of precipitation decrease, becoming more negative with distance. Annual precipitation totals in contrast 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.

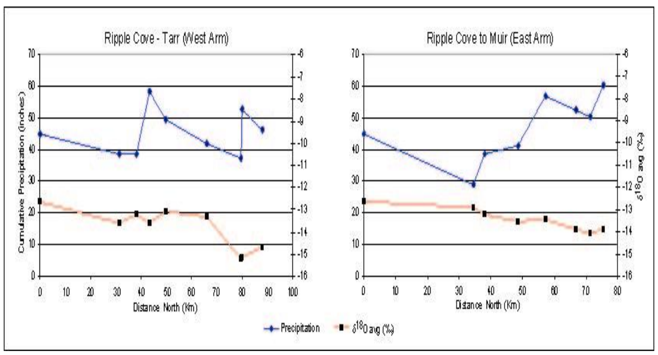

Figure 6. Spatial distribution of δO and annual precipitation amounts measured at CRREL climate monitoring sites in 2001 along South to North transects in the West and East Arms (Figure 1). Precipitation increases from the mouth of Glacier Bay to the head of Muir Inlet and less so to the head of Tarr Inlet. The isotopic values become increasing lighter with distance up each inlet. More recent data suggest that this relationship may vary annually or over a longer term for as yet unknown reasons.

We also see isotopic differences and trends within glacial ice (Figure 7), with the values for glaciers in the East and West Arms differing significantly from one another.

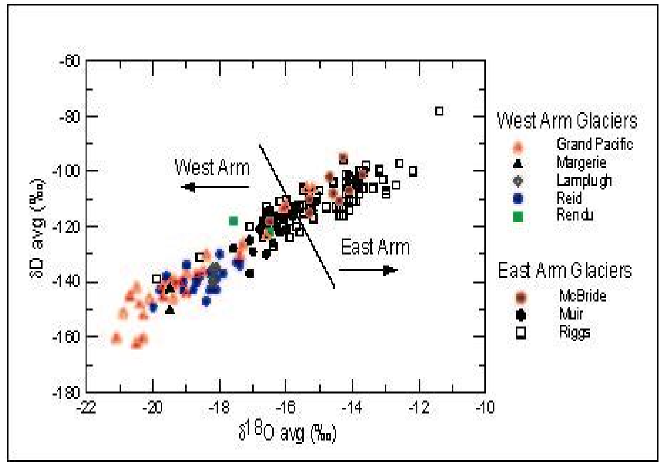

Figure 7. Relationship between δO and δD stable isotope ratios for glacier ice across Glacier Bay. Groupings of isotopic values indicate that there is a regional difference in meteoric waters which form glaciers in the East Arm and the West Arm that may be related to both the elevation and the primary sources of precipitation of their respective accumulation areas.

These differences 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 1200 to 1900 meters (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 2500 to 4500 meters (ELA ~ 1000 – 1100 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.

Radiocarbon Dating and Paleoclimate

As part of our continuing studies of modern and ancient tidewater and terrestrial glaciers and climate dynamics, we have been examining apparent differences and asynchronous movement of glacial ice between the East and West Arms of Glacier Bay during the Holocene. Within much of the Park, a significant number of overridden trees and logs from each cycle of glacier advance and retreat are preserved as either in-situ stumps (in growth positions), or as logs and wood fragments in glacial deposits exposed within subglacial and proglacial sediments (Figure 8). The ancient forests appear similar in composition to those in Bartlett Cove today, with mostly Sitka Spruce and Western Hemlock species predominating. Although incomplete, the length of the radiocarbon record is considerable, extending approximately 11,000 yrs BP, and may ultimately provide an unprecedented record of the climate during interstadial periods (Figure 9). We are currently analyzing the tree ring chronologies in cross sections of modern and ancient wood from across the Park to determine how sensitive the trees are to changes in precipitation and temperature and thus indicative of paleoclimate during periods of glacial advance and retreat.

Figure 8. Large, in situ stump in growth position. Note the bend in the upper part of the trunk which resulted from glacier ice overriding it..

Unfortunately there is urgency to the sampling of ancient forests. As each log or stump becomes exposed, it begins to deteriorate at an alarming rate. Within several or less years, much of the oldest wood breaks down, rotting and loosing its stability. This in turn affects our ability to sample and analyze the tree ring record. We are planning a more extensive search for wood in the near future; our sampling in 2003 was limited to only a handful of date samples and no tree sections.

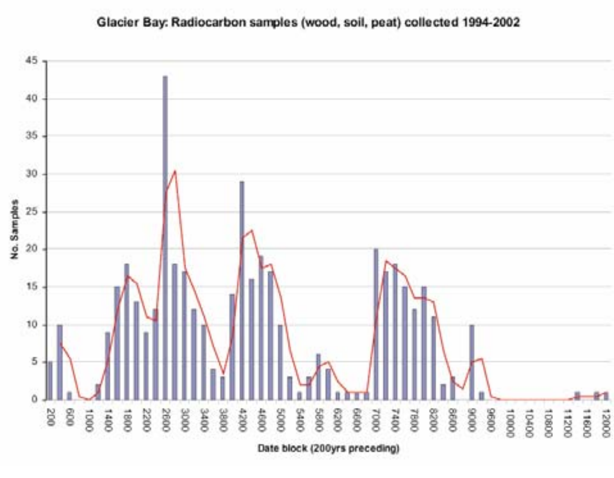

Figure 9. Range of radiocarbon ages for samples of peat, wood and soil organics

Glacial Advance, Retreat and Rates

The response of glaciers to global or regional changes in climate is a critical component to predicting future atmospheric and oceanic changes. Evidence of past glacier response is however often destroyed by the more recent advance in ice as glaciers can react to relatively small, but sometimes rapid climatic changes. But unique to Glacier Bay, much of this evidence is preserved within and beneath glacial and glacial-marine sediments.

The dating of wood in the glacial deposits and the dates from in situ stumps suggest that there were three and possibly four distinct periods of ice advance that reached the lower part of Glacier Bay. Our results, which must be considered preliminary because of insufficient dates across the region, suggest that glaciers advanced at different times and rates from the East and West Arms. This asynchronous behavior is interesting and probably related to the variability in climate across the Park as clearly shown by our data from the climate stations. We continue to search for and acquire datable materials and analyze the glacial deposits and landforms to further the picture of the glacial history. Our process studies at the Park's active glaciers also provide knowledge necessary to correctly interpret these data which are limited in extent and quantity.

Using the radiocarbon dates from numerous "in-situ" interstadial tree stumps, it is also possible to calculate the approximate rate of tidewater terminus advance during the Holocene. The radiocarbon dates of trees that remain in growth position can record the timing of ice encroachment and subsequently the death of the tree. In a number of locales, stump groupings clearly represent the timing of complete forest destruction following inundation under glacial outwash sediments and eventual overriding by the ice margin. By using a series of sites along the length of each fjord, we can calculate the average rates of terminus advance through them.

We used radiocarbon samples for this analysis from stumps that are in growth position and on which the outermost wood is recognized by the presence of bark and the outer cambium layer. In certain cases where there is a lack of in-situ stumps, date samples from large logs and stumps that were interpreted to be near their origin were use. The outermost 10 growth rings were precisely dated by Beta Analytic using the Accelerated Mass Spectrometry (AMS) technique. The precise geographic location of each sample is recorded using a Global Positioning Systems (GPS).

For this rate analysis, we assumed that the radiocarbon dates represent the date when the tree was killed by glacier ice flowing down the adjacent fjord and thus at any given point in time, the position of the tidewater ice margin. Distances along the fjord centerline are used to calculate the average rate of ice advance. While this approach does not identify the controls on the rate of ice advance, it does provide a first order approximation of the magnitude and range in the advance rate of tidewater ice margins.

Observations of modern tidewater glaciers suggest that their advance is relatively slow (several tens of meters or less per year) compared to the often rapid and sometimes catastrophic retreat (e.g. tidewater glaciers in Glacier Bay have retreated ~90km in 300 years, or 300 m/yr). By contrast, our calculations indicate that the advance rate of tidewater termini during different times in the Holocene were highly variable, with rates ranging from tens to over a hundred meters per year. Our preliminary results show that from approximately 8 to 6.8 K yr BP, average rates for Muir Inlet ranged from 9.6m/yr to 63m/yr. In the West Arm and the Lower Bay during the period from 4.8k to 3.3 K yr BP, advance rates reached as high as 72m/yr.

Fjord Oceanography

Long-term studies of water quality parameters in actively glaciated fjords can provide critical understanding of the dynamics of glacier and fjord interactions, and provide information on the physical processes that ultimately affect the fjord marine communities and ecosystem.

As part of our continuing studies of modern tidewater glaciers, we have been monitoring the proglacial water quality parameters along the profiles of fjords since 1994. We have established a grid of locations within each inlet at which we relocate using precise GPS positioning and repeat CTD casts to understand how tidewater and terrestrial glaciers influence or control the physical oceanography of the Park's fjords and inlets. We try to capture how the various parameters change seasonally as well as annually including temperature, salinity, turbidity, sedimentation patterns, and freshwater plume dimension and location. In Muir Inlet, we have been monitoring changes in these parameters during Muir Glacier's transition from tidewater to a terrestrial margin, a transition not previously examined by other researchers. Analyses of the fjord oceanography is then analyzed with respect to the subglacial hydrology obtained my measuring water and sediment discharge from subglacial streams that drain from each glacier margin. In addition we collect samples of each glacier's debris-laden ice to determine the net transport of sediment that occurs by each glacier; this too becomes a part of the net flux of materials into each inlet.

We collect oceanographic data from the MV Nunatak using a Sea-Bird SBE 25 Sealogger profiler equipped with sensors to measure conductivity-temperature-depth (CTD) plus additional sensors that measure oxygen content and pH/eH. By sampling at multiple locations in a grid we are able to look at the three dimensional variability in the various water quality parameters and their relationship to the bottom topography which we map using a fathometer (Figure 10). The latter data allow us to calculate rates of erosion and sedimentation adjacent to the ice margin as well as down-fjord. Our measurements of sediment and water discharge from the glaciers themselves allow us to calculate the flux of both into the fjords.

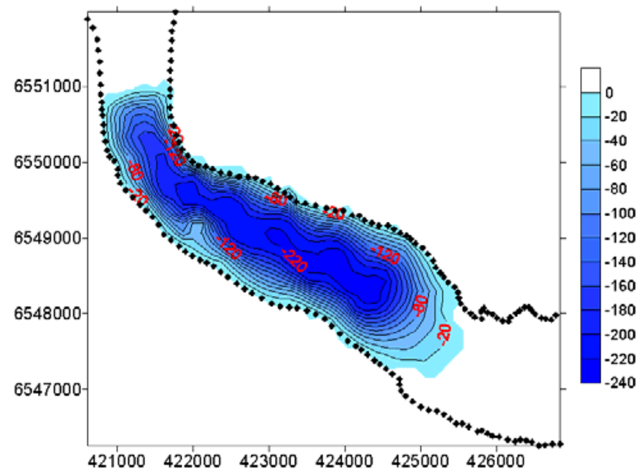

Figure 10. Upper Muir Inlet fjord bathymetry in July 1999.

Suspended sediment concentrations generally decrease with distance away from the ice, and also vary seasonally as meltwater runoff and subglacial discharge are reduced during winter months. In the spring and summer, overflow plumes of sediment-laden fresh water extend for several kilometers or more from tidewater margins. Similar behavior characterizes fjords with glacial streams draining nearby terrestrial glaciers. During periods of high sedimentation, plumes of sediment gradually settle to the bottom of the inlet and extend towards the mouth of each inlet and Glacier Bay (Figure 11).

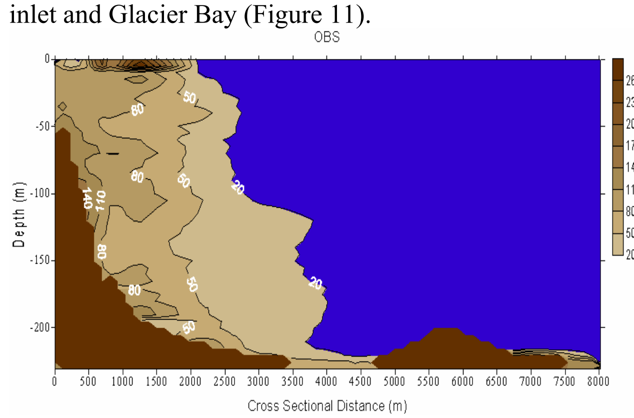

Figure 11. Example of mid-summer sediment concentration measured in FTU and shown with depth and distance from the margin of Muir Glacier.

As expected, salinity profiles show the freshwater plume is largest during the warm summer months and less prominent during the colder months, reflecting the decreased melting and runoff during the cold season. Salinity ranges from near 0 ppt directly within the meltwater plume at the ice face, but exceeds 31 ppt below about 50 m (Figure 12). The greatest mixing occurs in the upper 50 m, where the freshwater plume interacts with the denser underlying saline waters of the fjord. Salinity below 50 m ranges between 30 and 32 ppt within several km of the ice face.

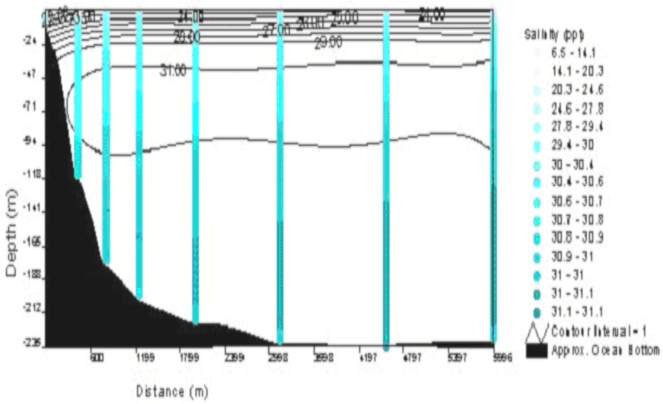

Figure 12. Example of mid-summer salinity variations along a transect that trends down-fjord from the margin of Muir Glacier.

Temperature profiles show a generally consistent pattern of lateral temperature stratification within the cooler, freshwater surface plume; when discharged from the glacier, it is typically 1 to 3 degrees depending on the season (Figure 13) with a very sharp gradient with the warmer waters beneath it. Fjord water temperatures in the spring and summer range from near 8°C on the surface to about 4°C at depth. In the fall and early winter, the temperature difference is only about 1°C. Freshwater discharge in winter freezes to form frazil and pan ice that may coalesce and freeze into a sheet covering the breadth of the inlet.

Diurnal tidal cycles and tidal ranges play a role in defining geometries and lateral connectivity of plumes. Dissolved oxygen gradients are apparent in nearly all samples, as highly oxygenated waters enter from the glacier area. The plumes of high oxygenation may be affected by tidal cycles. In the summer during ebb tides, the plumes of dissolved oxygen are often laterally continuous, extending some distances down the fjord from the ice margin, whereas flood tides can dam oxygenated water adjacent to the ice face. Tidal fluctuations (range and duration) also affect the dispersal of the freshwater plume in often complex ways.

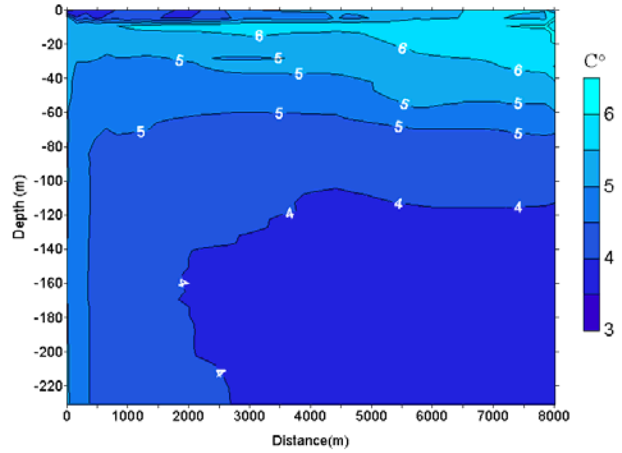

Figure 13. Muir Inlet temperature profile in mid-summer, with glacier discharge entering the fjord on the left side of the diagram.

Continuing Work

Future efforts will focus on defining the trends in paleoclimate and paleo-temperatures through dendroclimatic analysis of modern and ancient forest samples. As a proxy for paleotemperature, we are looking into analysis of the stable isotopes of modern and ancient tree rings. We will continue additional field sampling to fill in apparent data gaps in ages, as well as to expand coverage to areas not yet sampled but critical to defining the glacial and climatic history of the Park. We are planning to intensify our efforts to understand the climate and glacial history during the Little Ice Age so that we can apply this knowledge to interpreting Tlingit legends and locations where native habitation were possible. Climate monitoring will continue, with equipment upgrades to near real time status once initial assessment of existing test sites and equipment have been made. Our continuing investigations of tidewater and terrestrial glacier environments and processes will enable us to better interpret the glacial record and better understand the role of glaciers in the marine ecosystems of the fjords and inlets in the Park.

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