Paleoclimate of the Last 10,000 Years, Glacier Bay National Park and Preserve: Progress Understanding Climate Change In Southeast Alaska

ANNUAL REPORT 2010

**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**

Prepared for the National Park Service, Glacier Bay National Park and Preserve

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Cover photo: Large interstadial log exposed in 2010 by erosion of the subglacial deposits of Geikie Glacier

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Executive Summary

Glacier Bay is the largest known repository of interstadial wood from the Holocene period in North America. This fact has provided the opportunity to obtain sections of this wood in the context of the glacial history and conduct tree-ring analyses that will ultimately provide data on paleoclimate during the glacial cycles that characterized the last 10,000 years, with ice possibly advancing in some areas as early as 13000 years ago. Tree-rings offer an exactly-dated chronology of changes in climate, ice volume and forest response, each of which is vital to understanding global change and placing contemporary changes into a long-term context. The interstadial forests that were overridden by the expanding terrestrial and tidewater glaciers in the Park were extensive and their preservation, although discontinuous and fragmented, is remarkable. In situ stumps, still rooted in growth position and logs held within glacial deposits remain in areas ranging from the intertidal zone to the highest reaches of the mountainous terrain. Finding the interstadial wood requires extensive ground searches conducted over many years time, and each may or may not produce useful samples because of the dynamics of the former glaciers and the intermittent and variable locations where erosion exposes the wood.

The emerging glacial history based on tree-ring dating is improving our knowledge of the environment during the last 10,000 years. In 2010, further details were added to the expansion of ice within the Glacier Bay watershed at approximately 4900, 3200, 2500, 1800, 1100 and 550 radiocarbon years BP. Our continuing investigations will place the contemporary retreat of glaciers in Glacier Bay into a long-term context by exactly dating times of advance and determining intervals of past forest growth when portions of the fjord system were ice-free. Some past ice losses within the fjord may have taken place over intervals comparable to the present catastrophic ice retreat which followed the maximum extent of ice during the Little Ice Age. Reconstructed intervals of terminus positions using calendar-dated trees killed by ice expansion also record some of the fastest rates of tidewater advance known. Our initial results suggest a more dynamic advance-and retreat-history than has been evident in previous work, yet the chronology is consistent with the work of Mann and Streveler (2008) on relative sea level changes in

Icy Strait. The glacial record is showing a reasonably strong correlation to other North American records of glacial cycles and global paleoclimatic trends. As such, we are currently working on evaluating hypotheses for the cause of these multiple periods of glacial advance and retreat across the Glacier Bay watershed.

Field work during 2010 focused on recovering samples of interstadial wood from areas where our previous work dated logs and stumps in the period of 1500 to 6000 calendar years ago, including Reid, Geikie and Hugh Miller Inlets. Stratigraphic sections in these areas were analyzed to define the glacial and periglacial processes and environments and historical behavior to correlate with the tree-ring record. In addition, additional cores of living trees on Beartrack Mountain were obtained to complete an elevation transect that will improve basic understanding of the current changing growth patterns in mountain hemlock forests, and thereby better apply ring-width records in climate reconstructions. Early in the summer, we conducted field tests of a hybrid crosscut saw with NPS staff and a USFS crosscut-saw expert to evaluate the saw's ability to cut sections of interstadial wood. Unfortunately, those tests revealed that this saw was unable to cut through ancient wood, results similar to other handsaws we had tested previously during this project.

Our laboratory analyses of the tree ring records focused on the periods of ~ 4K to 5 K years BP and the Little Ice Age, post ~1500 AD. Over 150 sections were processed and crossdating initiated. In addition, two papers were submitted finalizing previous year's work on the tree-ring and glacial records, one on the emerging history of glacial activity during the last ~3500 years BP in Geikie Inlet (Wiles et al. submitted), and the other on the decline of yellow cedar (Mennett et al. accepted; in revision). Collaborative work with D. Capps, J. Clague and B. Luckman resulted in a published paper describing tree-ring work at Brady Glacier (Capps et al. 2011) and another article in revision (Laxton et al. accepted; in revision) describing a GIS analysis of the radiocarbon database from Glacier Bay. The glacial history is linked intimately with native communities; our new dates on physical changes in the region will add detail to these well-documented legends. We are collaborating with Wayne Howell (NPS) and others on a paper for Alaska Journal of Anthropology tentatively titled "The Huna Tlingit response to terminal Little Ice Age landscape change in Icy Strait, Alaska".

Student projects in collaboration with park historians, community members and educators are examining the response of hemlock, spruce, pine and cedar forests to modern and past changes in climate (Appleton et al. 2010, Jarvis et al. 2010, Wiles et al. 2010). Assessing the relative health of these forests is important to managing and evaluating future changes in these carbon reservoirs that could affect future climate. Two undergraduate theses were completed, one examining the glacial geology and tree-ring record from Muir Inlet (Aughenbaugh 2010) and the other an analysis of cedar growth from Excursion Ridge and Pleasant Island (Mennett 2010). Student theses that are slated for completion in March 2011 include work on forest health (Jarvis, in progress) and a new project underway examining previously sampled material from Adam's Inlet (Appleton, in progress). We presented the current results of our research on the glacial and paleoclimatic records at national and international professional meetings and are preparing additional manuscripts for peer-reviewed journal publication.

Introduction

Glaciers and climate are intimately related, with the response of the glacial systems in the Park a reflection of the short- and long-term variability in the global and regional climate. The region of Glacier Bay is highly sensitive to short (decadal) and longer (millennial) term changes in climate, and the glaciers and ice sheets of the St. Elias-Fairweather Mountain Ranges have responded to that variability in the past and present (e.g. Arendt et al. 2002, 2008). The high mountains surrounding Glacier Bay feed the largest active glacier complex in the world outside of Greenland and Antarctica (Meier 1984; Meier et al 2007). With the exception of some lowlands at the southeastern and southwestern margins, Glacier Bay was covered by ice as recently as AD 1770 during the Little Ice Age (LIA) (Motyka et al. 2003). The historical loss of the LIA ice in Glacier Bay has had a significant effect on global sea-level rise (Larsen et al. 2004, 2007; Berthier et al. 2010); it is estimated to have contributed as much as 1 cm of the total sea level rise of 20 cm following the end of the LIA. The LIA deglaciation of the Glacier Bay watershed is one of the best documented in the world, with ice margins retreating distances as far as 120 km at some of the highest rates ever recorded. During this retreat, forests that were overridden previously by ice were uncovered and our research, including radiocarbon dating of these interstadial forests, reveal that in addition to the Little Ice Age expansion, ice apparently advanced into Glacier Bay multiple times, possibly as early as ~12,000 - 13,000 years ago (Lawson et al. 2007).

Placing these contemporary changes of the LIA and historic times into a long-term context is crucial to our understanding of how the climate system works and to demonstrating its full range of natural variability. As modern warming progresses, major changes in the cryosphere and biosphere are being observed especially in the higher latitudes (e.g. Hinzman et al. 2005, IPCC 2007), with similar effects likely in the subarctic Glacier Bay region. Modeling of the regional climate and potential future trends in it using Global Climate Models (GCMs) requires high-resolution data such as tree-ring records. Our ring-record of the Holocene period, a time characterized by much variability in temperature including sudden or abrupt, extreme magnitude changes, will be especially applicable to modeling future changes in climate within Glacier Bay and southeast Alaska. The potential long-term record of the last 10,000 years that we are working to develop will be unprecedented for the high latitude regions of Alaska and the North Pacific region. Most observational climate records here are less than 100 years long, spanning only the interval of possible anthropogenic influence, while other tree-ring records in this region are generally less than 1200 years in length.

In this Annual Report, we describe the results of our most recent work extracting tree-ring records from the interstadial wood and from living trees within the context of our research on the glacial and environmental history. The tree-ring record is providing calendar dates that are of significance to understanding the geomorphologic processes that affected ice dynamics and human habitation. To extract a paleoclimate signal from the ring series, we are using the meteorological records from along the Gulf of Alaska. In addition, the synergy between understanding past climate and modern or contemporary tree growth will be greatly aided by comparing the temporal and spatial trends in monitored climate of the last 10 years within Glacier Bay (Lawson et al. 2004, 2010; Finnegan et al 2007).

Brief History of Previous Work

Our research has revealed that interstadial wood from the recent LIA period through nearly 14,000 C14 calibrated years BP occurs within the Park. This wood is a huge repository of information on the paleoclimate and regional climate variability. On land, generally well-preserved wood is first exposed by erosion of glacial sediments, mainly tills and glaciofluvial deposits. Other interstadial wood is being exposed in the intertidal zone as the land rebounds following the loss of the LIA ice sheet. We continue to sample this wood as aggressively as possible within funding and logistical constraints because the exposed interstadial forest is transitory; it remains available for sampling for only a brief period of time, often as little as one to two years after exposure because the environments in which the wood is exposed are mainly actively eroding slopes, floodplains and alluvial fans, and the wood is either rapidly reburied or transported into the fjords. The uplift of the wood within intertidal areas exposes them to waves and nearshore currents as well the air and thus degradation. Examples of these environments are shown in the 2007 Annual Report (Lawson et al. 2007) available at the NPS Glacier Bay web site.

The first investigation of interstadial wood within glacial deposits began in 1994, and by 1996, we knew that the interstadial wood resource was extensive, wide-ranging in age and suitable for tree-ring analyses; a fact not previously recognized. At that time, sampling began in earnest and sections acquired each summer underwent basic laboratory processing and radiocarbon dating when possible. In the laboratory, each sample is slowly dried, stabilized with glue and then rough and fine sanded for an initial appraisal of its suitability for tree-ring work. Samples that are radiocarbon-dated define the range of representative ages and identify sections for crossdating to create ring records of specific time periods. Our detailed analysis of the tree-ring record was begun in 2002 when sufficient dated sections had been sampled so that a statistically relevant ring record could be created. The length of this study is largely a function of the searches required to locate interstadial wood; traverses on foot are required from the intertidal zone to high reaches of the mountainous slopes where wood may or may not be located.

Extensive sample processing and tree-ring analyses have now provided the first calendar-dated, tree-ring record for Glacier Bay, extending over the last 2000 years, the longest such calendar-dated chronology in the Gulf of Alaska region, and several groups of interstadial wood provide floating chronologies for periods of time around 3000 and 4000 C14 years BP. The calendar-dated ring record is based on a comparative analysis of tree-rings within living trees, some within areas not covered by ice during the LIA, with a long modern meteorological record from Sitka, Alaska. This comparison shows that ring-width varies with air temperature (Erlanger 2008). Climatic data now being collected at twenty-four sites across Glacier Bay (Lawson et al. 2010) will allow us to assess regional variability in air temperature and precipitation which can affect the tree ring records.

We are currently expanding the dated chronologies and hope to obtain sufficient sections to link them into a continuous record. Our data for the period of the past 1500 years correlates well with other calendar-dated chronologies within the Gulf of Alaska. As we continue to develop the chronologies, additional analyses, possibly including density, stable isotopic composition and radiocarbon content of each ring may be undertaken to provide further high-resolution information about seasonal and annual trends in paleoclimate. Additional details of the history of this study can be found in previous Annual Reports since 2004, all available at the NPS Glacier Bay web site.

The Uniqueness and Constraints of Glacier Bay
It is important to realize that a lengthy record covering multiple glacial cycles and periods of forest growth is extremely unique and invaluable toward developing a climatic record during the Holocene. No other repository is known from a heavily glaciated terrain like that of Glacier Bay. In most instances, subsequent glacial activity removes evidence of much, if not most of the record of previous glaciations, and thus in nearly all formerly glaciated regions of the world, a long-term record of ancient forests would be impossible to document or obtain enough samples for a tree-ring analysis. Glacier Bay goes against these principles and the more sampling we have done, it has become apparent that the Park has preserved within it an unprecedented record of the glacial history and the paleoclimate of the interstadial forests. Because all wood has to be first located by searching on foot, it takes a significant amount of time to obtain samples necessary for the analysis and hence the long-term nature of this research.

We have sampled interstadial wood at numerous sites across the Glacier Bay watershed. We have located wood in the West and East Arms, as well as the lower bay. Traverses in search of interstadial stumps and logs have often found wood in many valleys feeding the primary inlets and bays, sometimes in almost inaccessible higher-altitude steep slopes, as well as within the intertidal zone as tectonic and isostatic uplift exposes it. Logs and stumps that were sampled in the past rarely remain exposed due to the geomorphic processes that exposed them in the first place; they are either re-buried in alluvial fans, fluvial deposits and streambeds, or transported into the fjords. Decay of wood also takes its toll and only fragments may remain of wood exposed to the elements for several years.

Background on Dendrochronology and Methods
In this section, we outline some basic principles of dendrochronology and standard methods employed in our research. For those readers familiar with this, please skip to the next section on our 2010 work.

Tree-ring records from the interstadial trees are developed from sections cut from in situ stumps and logs in glacial sediments. We use standard geological methods to determine the nature of the deposits associated with the wood and to interpret their origins, particularly whether the death of the wood resulted from a glacial advance, which aids in producing information on the glacial and deglacial history of the bay. These methods include defining the glacial stratigraphy by sedimentological analysis of deposits (e.g. Benn and Evans 1998). Each core and section sample site is located precisely by GPS and photographed. Various parameters, such as dimensions, position of each sample section relative to the roots, tree species and overall condition, are recorded.

In the lab, cores of living trees and sections of interstadial wood are slowly dried, glued and sanded before counting and measuring the rings. Multiple samples of wood sections must be scrutinized to account for missing rings, as rings may be locally absent on a cross section due to various stresses in the environment. In addition, small samples (1-2 g) of the outermost five rings of wood sections may be radiocarbon-dated.

Ring-width chronologies from the interstadial sites are crossdated with chronologies from the living sites when they overlap in age, or are used as floating tree-ring series when they lie outside the range of the calendar-dated series (Figure 1). As we continue to obtain and analyze tree-ring records from new interstadial wood sections, we will link these floating series to develop a continuous tree-ring record. Thus, a current focus is to obtain the necessary sections for filling the entire series beyond the calendar-aged wood. Sections of trees living greater than one hundred years are essential to crossdating.

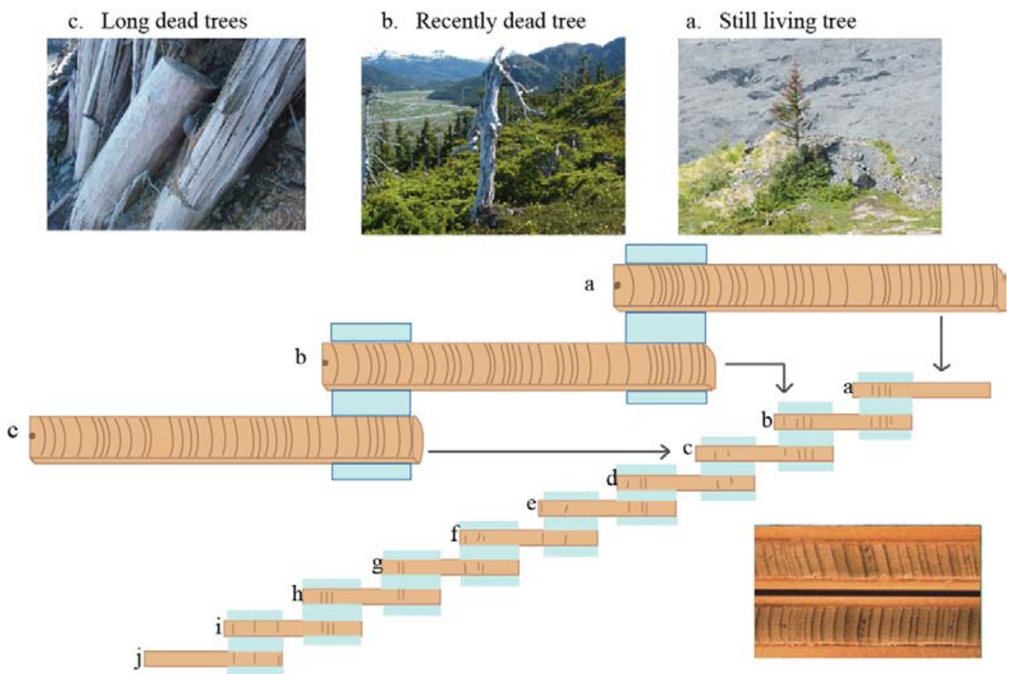

Figure 1. *Diagram showing the tree-ring crossdating technique. The age of the wood increases from right to left. We are now establishing calendar-dated tree-ring records from living trees in Glacier Bay and matching them with floating ring-width series from interstadial wood, extending the calendar-dated series back several millennia.*

For each ring-width chronology, we must collect a sufficient number of wood sections of a particular range in age to produce a continuous and reproducible tree-ring record. We estimate that based on measuring two to three radii from each cross section and needing approximately twenty radii for a reliable, well-replicated dendroclimatic signal that we will need a minimum of ten cross-sections covering each range in age throughout the entire tree-ring series. Twenty sections or more per age-range are preferred statistically and provide a more robust record of climate variability.

Living ring-width series are correlated (calibrated; Fritts 1976) with the instrumental data from meteorological records of nearby sites, which include Juneau, Haines, Yakutat and particularly Sitka. In addition, we crossdate our living tree-ring and interstadial records with those from other regions in the Gulf of Alaska. For example, the 1500 year long tree-ring record from Columbia Bay in Prince William Sound correlates well with tree-ring series from Geikie Inlet, Berg Bay, Adams Inlet and North Fingers Bay (Wilson et al. 2007, Erlanger 2008).

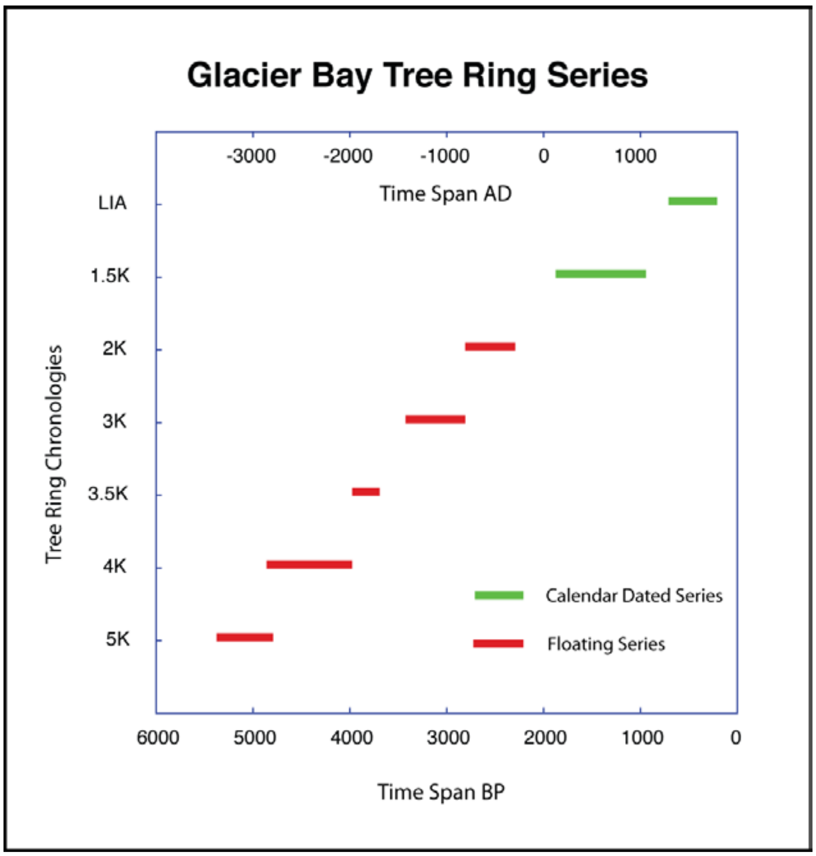

Figure 2. *Master diagram showing the approximate ages of wood that have been incorporated into tree-ring analyses at Glacier Bay. Calendar-dated series (green) are linked to living tree-ring series, whereas the "floating" series are floating with respect to radiocarbon ages. The current goal is to build a continuous ring-width chronology for Glacier Bay over the last six millennia. We are hoping to obtain sufficient samples during the next couple of field seasons to close gaps between the various series and link the chronologies into a 5000 year time series.*

Work Accomplished During 2010

We have made significant progress toward our continuing primary objectives to collect sections of ancient trees overridden by the glaciers during the Holocene excursions across

Glacier Bay before they are lost to erosion and decay and to analyze the interstadial ring-width records for their paleoclimatic information related to the glacial cycles of the Holocene period. We significantly increased the number of sections analyzed as well as the number of series of data within fixed and floating chronologies in 2010 (Figure 2). The analysis of the 4000-year series was expanded this year, as well as adding detail to the LIA, 1.5 and 3 K year data sets. In addition, sedimentologic analyses of glacial and periglacial deposits has expanded our knowledge of the relationships among the various age-groups of interstadial wood and further defined the positions of ice margins with time. An updated list of sections acquired in 2010 has been submitted to R. Yerxa (NPS).

Late Holocene Environmental Changes and 18th Century Tlingit Migration

Sarah Appleton (Appleton et al. 2010) examined the modern tree-ring records from Beartrack Mountain and Excursion Ridge with respect to the LIA ring-record of the lower bay region for paleoclimatic information related to Tlingit oral history of the last 500 years (Figure 3). Tree-ring dating of the Little Ice Age expansion in Glacier Bay documents the AD 1730's advance of ice over the ancestral home of the four matrilineal clans who comprise the Huna Tlingit. One of those clans, the Chookaneidi, recount a time of privation when food was scarce during their multiple moves in search of a new home not exposed to the cold winds coming off the glacier. They eventually settled behind a cliff near the mouth of Port Frederick in a place they named Xuniyaa, "Shelter from the North Wind", now conflated to the village name of Hoonah. At Xuniyaa, they found a place to survive, encountering deer in a nearby meadow. Through the powers of a shaman, a large halibut was caught in a pond and a rocky reef was raised up from the water to provide shellfish.

During the time of privation, the Huna Tlingit also tell of experiencing Wooch it taakw, or "Winter following Winter", a period without a summer. Tree-ring records show an abrupt decrease in ring-width and late wood density in AD 1754 continuing into 1755. The temporal and spatial signature of this 1750's event suggests volcanic forcing in the region. The source of the 1754 volcanic event is unknown, but may have been related to a major eruption of Ksudach on the Kamchatka Peninsula, Russia, that dates to about this time. The cooling in 1754 and 1755, along with the concurrent glacial expansion, surely would have affected salmon migration in addition to impacting other food sources for the native people of the region. The tree-ring dates provide an absolute chronology for the oral legends of the eviction of the Huna Tlingit from their homeland.

Non-Stationarity in Mountain Hemlock Growth and Dendroclimatic Reconstruction

Mountain hemlock at treeline sites have been widely employed in reconstructions of Pacific Decadal Variability (PDV) due to their high sensitivity to temperature. In Glacier Bay, our analyses of treeline sites on Excursion Ridge and Beartrack Mountain provide the temperature correlation from which we interpret the older sites across the park, many of which are at lower elevation than these calibration sites. Stephanie Jarvis (Jarvis et al., 2010) examined the climate response at our sites and compared them to other near-coastal sites along the Gulf of Alaska with respect to elevation. While most high-elevation treeline sites appear to be faithfully tracking contemporary warming, many low-elevation sites show a marked decrease in ring-width after about 1950 (Figure 3). This decrease in tree growth is reminiscent of the well-studied Alaska yellow cedar decline attributed to a decrease in insulating snowpack and a resulting increase in their susceptibility to frost damage. The cedars are in the midst of a century-long decline, coinciding with the end of the Little Ice Age, circa A.D. 1880 (Mennett et al. 2011).

To determine if mountain hemlock at low elevations could be susceptible to cedar-like decline, monthly temperature and precipitation records from Sitka, Alaska, that begin in 1828 and includes data from the LIA through contemporary warming, were compared. The Sitka Magnetic Observatory record is the longest continuous recorded climate record in North America, starting in 1828 and ending in 1990, and includes air temperature, precipitation and other observations.

Temperature correlations throughout the record show no significant change in response; tree growth favors warm temperatures in most months. Comparisons with precipitation records, however, suggest a shift in response at both low and high elevation sites; trees that were negatively correlated with precipitation during the Little Ice Age began in the mid 1900s to favor increased spring precipitation (snowfall) that may serve as protection against damaging spring frosts. These observations are consistent with the loss of snowpack, possibly due to earlier melt-out or decreased snowfall over the last few decades. Low elevation sites first experience loss of snow cover and thus are more vulnerable, as in the case of the yellow cedar. Unlike the yellow cedar (Mennett et al. 2011) however, mountain hemlock are responding to these changing conditions with an upward treeline migration, indicating that this "decline" at low elevation sites could be an ongoing adjustment of the species.

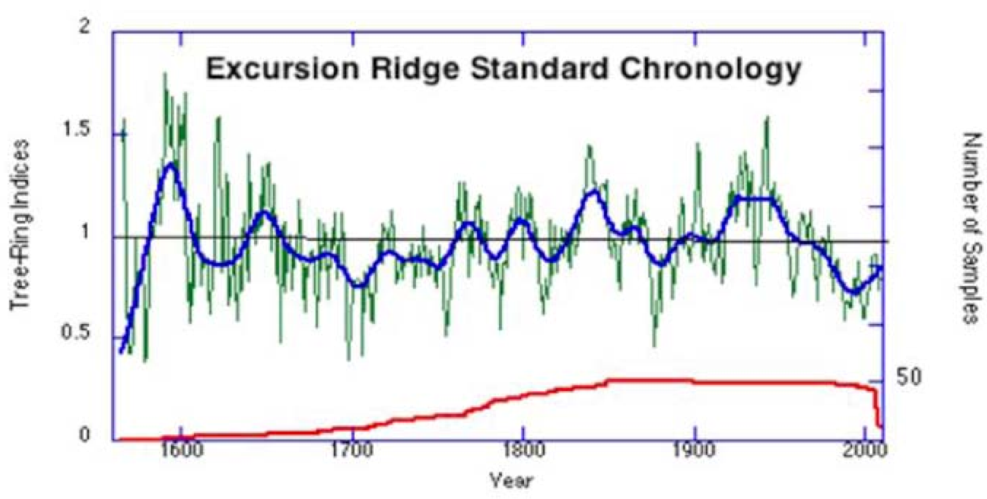

***Figure 3**. Ring-width series from yellow cedar on Excursion Ridge. Note the decline in growth during the latter half of the 1900s and the apparent recovery over the last 10 years.*

Dendroclimatic Results from Treeline Sites

We continued our efforts to core mountain hemlock trees at high elevation sites, with a detailed analysis focused in 2010 on the trees on Beartrack Mountain. These tree-ring width chronologies are strongly correlated with temperature data from Juneau and other coastal sites along the Gulf of Alaska (Sitka). Therefore, we consider the value of these series as records for interpreting temperature variability in the past from the interstadial ring records. For example, both the Beartrack and Excursion series (Figure 4a, b) show a

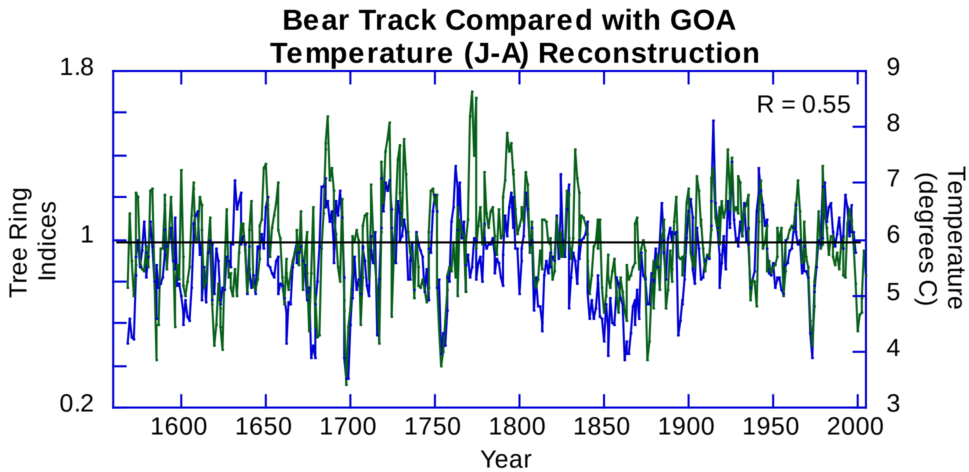

Figure 4a. *The Beartrack ring-width chronology (green) compared with a regional (Gulf of Alaska (GOA) temperature (January through August) reconstruction based on other tree-ring series from along the Gulf (blue).*

strong, rapid cooling during the early 1750s. Such a cooling is reported in Tlingit and other native legends (W. Howell, personal communication), possibly referring to the two years of cold in these series at 1754 – 1755 (Figure 4a, b).

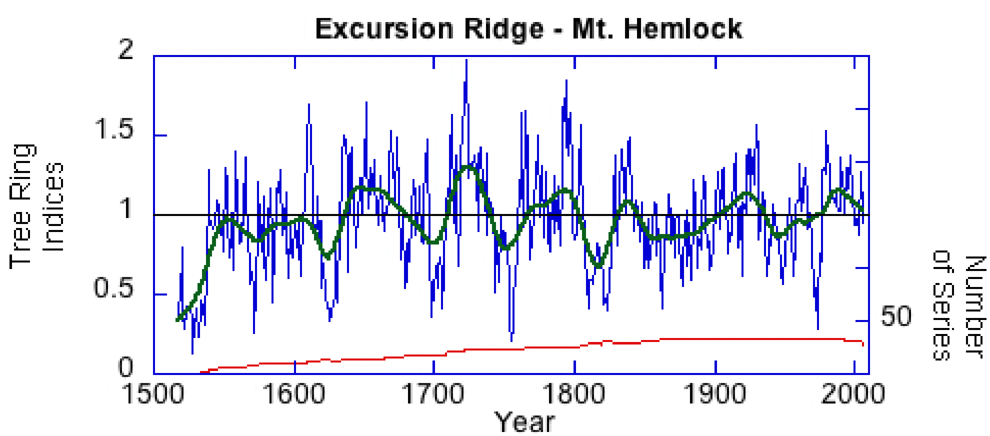

Figure 4b. *Mountain hemlock chronology from Excursion Ridge. This record of temperature exhibits multiple periods of cold weather at a decadal interval throughout the Little Ice Age.*

Little Ice Age History of Lower Glacier Bay

Tree-ring dates from the eastern shore of lower Glacier Bay indicate the glacier covered the area between AD1720-1735. To do so, the ice would have advanced ~10 km over this 15-year period. This is an average rate of over 600 meters per year. This may be the fastest ice expansion ever inferred or measured, but it is consistent with Tlingit oral narratives. Such a high rate of flow is generally experienced only during a surge of a glacier terminus, but the apparent duration of the advance is not consistent with a surge mechanism which generally lasts several years or less. The radiocarbon-dated chronology as presented by Connor et al. (2009) is consistent with our calendar-dated chronology.

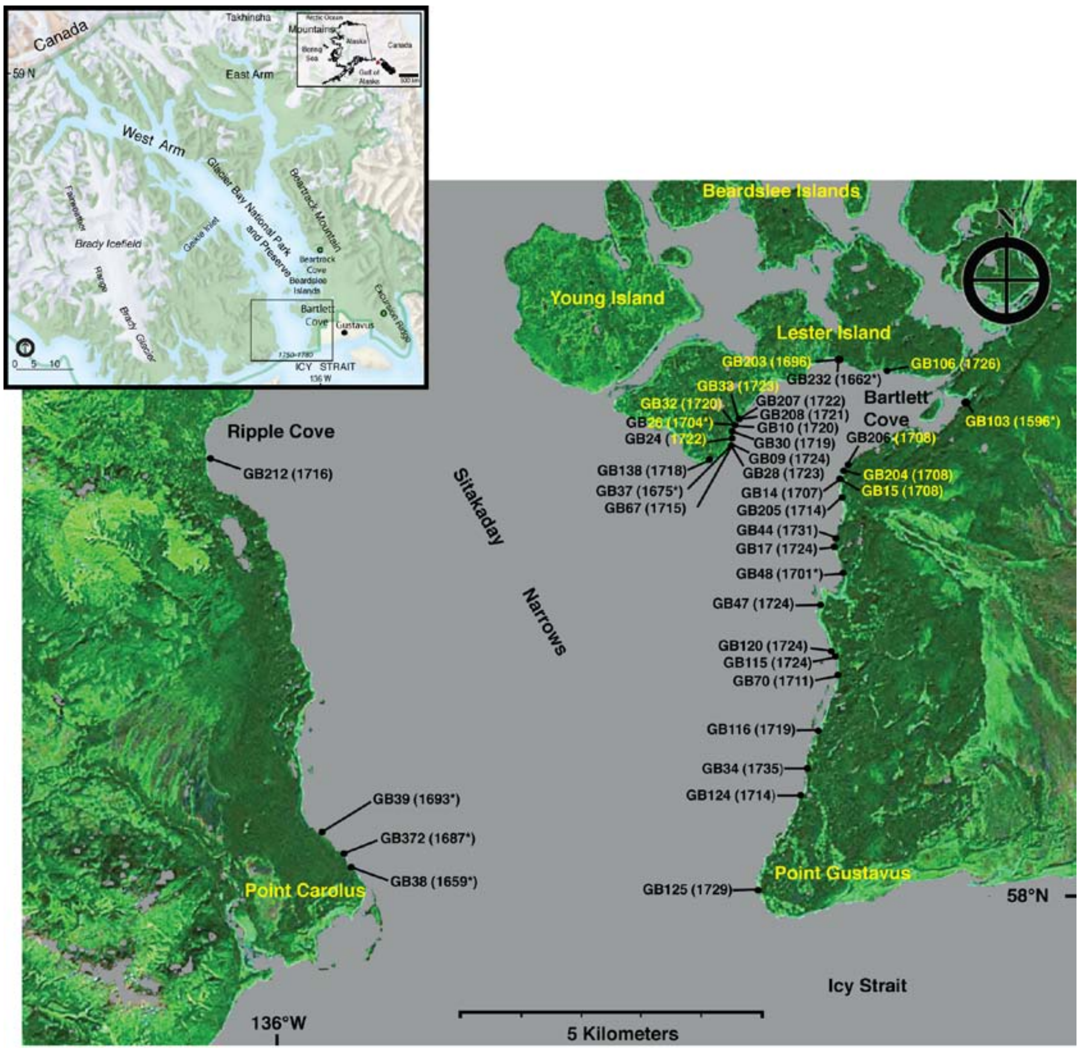

Figure 5. *Updated map showing the lower Bay and locations of tree-ring dated logs in the intertidal zone from the Little Ice Age period. The numbers in parentheses are the calendar dates on the outer rings of logs dated using dendrochronology. The asterisks after the date indicate the log was abraded and lacks the outermost growth ring indicating the year of death.*

Floating Chronology for the 4 K to 5 K years BP

Considerable effort was made in 2010 to develop the tree-ring record for the important time period of approximately 4000 to 5000 radiocarbon years BP. This is a new floating chronology that is during a period recognized as one of significant change in climate from multiple sites across the globe. The ring-record (Figure 2) is comprised of section data from multiple sites across the middle of the Glacier Bay watershed, including several new sites sampled in 2010 in the Hugh Miller and Queen Inlet areas (Figure 6). Many of these sections were recovered from logs on alluvial fans in the Charpentier Inlet area that were eroded and deposited on fan surfaces during an unusual precipitation event in November 2005 when over 24 inches of rain fell in a 24-hour period. It is significant that we have been able to crossdate sections from multiple locations suggesting the similarity in climatic response during this time. Over 70 sections are now included in the ring record for this period of time (Figure 7). We are continuing to expand the age-range of this chronology with the aim of linking it to the floating chronology from the 3K period (Figure 2), and subsequently analyzing the possible paleoclimatic temperature signals which appear to be present within the record.

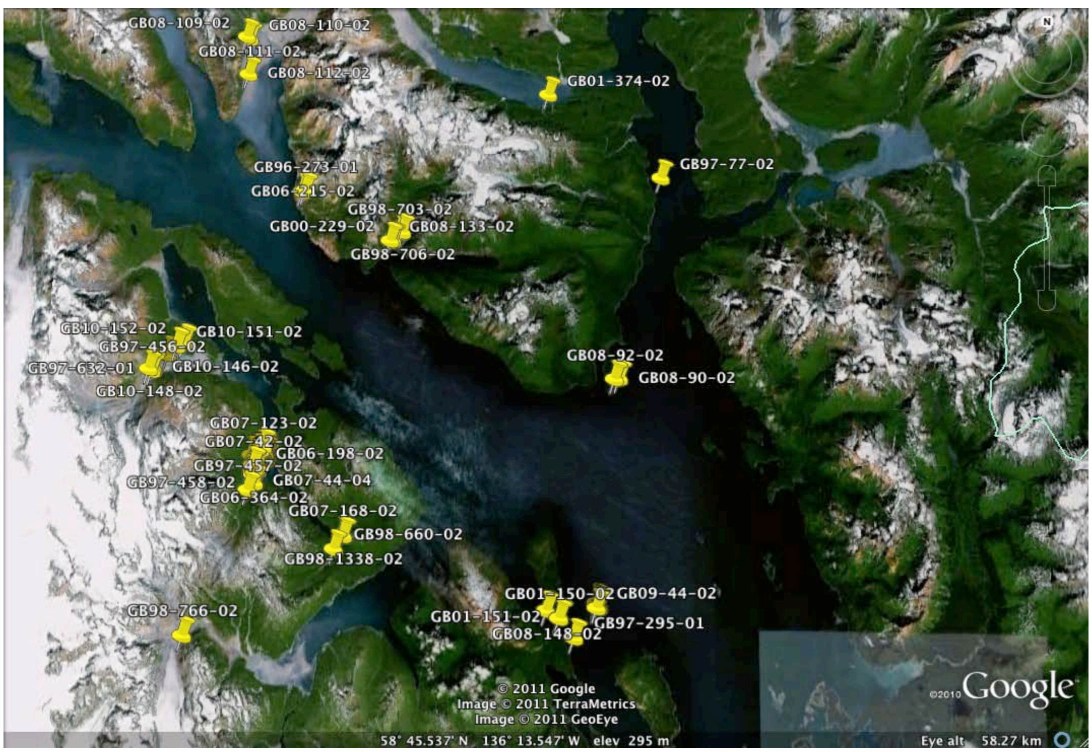

Figure 6. *Locations of samples with radiocarbon ages in the 4 k to 5.5 K BP range. Crossdating is underway for sections from these locations.*

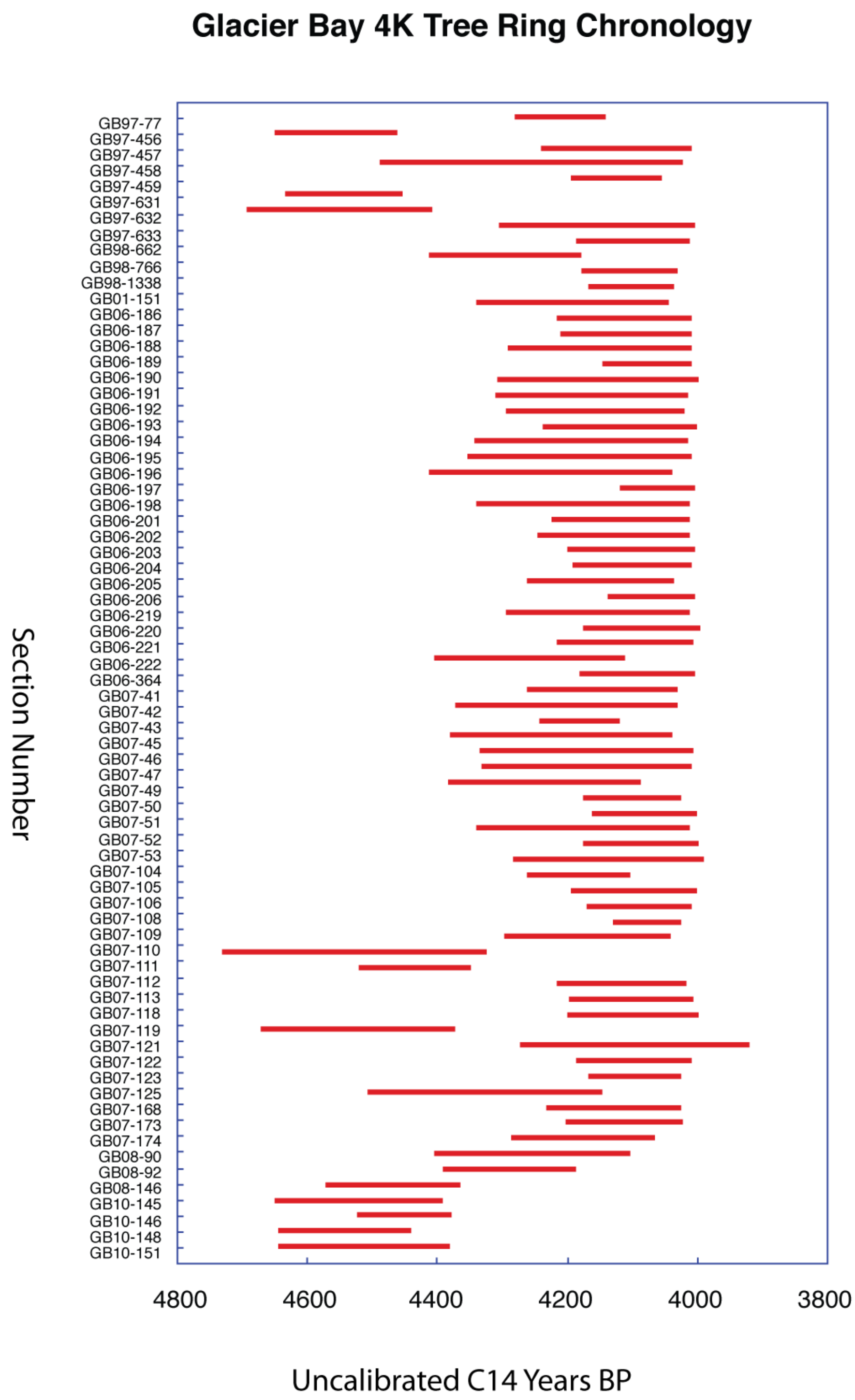

Figure 7. *Current ring-width chronology for the radiocarbon-dated floating chronology of the period from ~4000 to 5000 years BP that is currently being developed.*

Reconstructing Late Holocene Glacial Movement in Muir Inlet

Kelly Aughenbaugh completed her undergraduate thesis on glacial activity within upper Muir Inlet during the late Holocene. Her findings were based on tree-ring and radiocarbon dating of wood at several sites on the eastern side of the inlet. Determining the glacial history of Muir Inlet builds on data collected from researchers previously working in the region. Her work was based on the analysis of 35 ring-width series from 14 sections, six of which were radiocarbon-dated. The analyses show that the trees were living for a 439-year time span (Figure 8) during which Muir Inlet was ice-free. The use of the floating ring-width series and radiocarbon ages allowed for wiggle matching which indicated that the advance of the Muir Glacier in the upper reaches of the fjord began about 2370 calendar years BP. The data also suggest that the ice advanced at an average rate of 20 meters per year over a 369 year span, based upon the death dates calculated using tree-ring data and the locations of the dated logs along Muir Inlet.

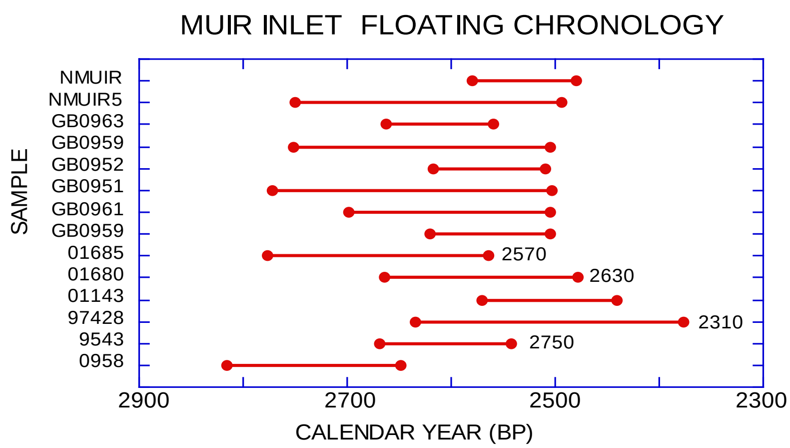

Figure 8. *Floating ring-width series from upper Muir Inlet. Some of the individual (red) ring-width series have radiocarbon ages on the wood (black numbers).*

Glacial Cycles and Climatic Instability

The complex regional response of glaciers during the Holocene is becoming more evident as ice continues its retreat since the end of the Little Ice Age (LIA) and subglacial deposits and landforms are exposed (Figure 9). The datable sedimentary glacial sequences coupled with in situ (rooted) tree stumps from within the Glacier Bay watershed provide a unique and unparalleled picture of the history of glaciated fjords and valleys in southeast Alaska. Periodic glacial advance and retreat apparently took place at ~1000 to 1200 year intervals beginning prior to 9000 calendar years BP. Advance associated with the extreme cold period known as the Younger Dryas (~11,500 – 12,500 BP) apparently terminated at some distance up-valley and beneath the active glaciers of the bay region. A radiocarbon date obtained on wood samples during 2010 suggests deposits from this time period may now be exposed along the eastern lateral edge of Reid Glacier, a significant finding if verified by correlative dates in the subglacial till.

Figure 9. *Recently exposed log protruding from a subglacial diamicton (till) near the Geikie Glacier terminus (right and below person). These types of sequences provide the geologic data to define the timing and location of advancing glacier margins in the past.*

The mature forests that grew between each successive advance and which were subsequently overridden, record the ice margin positions over time. They also document where and when areas of the bay were ice free. Our current data from multiple locations, including Geikie Inlet (Figure 10) and the well documented advance and retreat during the Little Ice Age (Figure 5), are examples of the detail we are developing to examine the glacial succession during the Holocene. The ice appears to have advanced into the fjords at rates of ~30 to 100 meters per year (Lawson et al. 2007), but appears to have reacted in some cases as it did at the end of the LIA, receding rapidly to the upper parts of the fjords between several of the advances. Based on the observed response during LIA ice retreat, re-vegetation of the fjords probably required at least 100 years (Chapin et al. 1994). Ring counts reveal trees grew for periods of several hundred or more years before being killed by each successive ice advance; these document the extended nature of the ice-free periods. With each period of advance, the ice appears to have extended further down-fjord before receding; the furthest extent was the LIA ice margin position in Icy Strait at the mouth of Glacier Bay.

The extent of the ice across Glacier Bay, as we are currently able to define it, appears to correlate well with the increasing magnitude of relative sea level recorded in Icy Strait (Mann and Streveler 2008). Although the possible drivers for millennial-scale glacial cycles remain debatable, wiggle-tracing with proxy data for solar activity and solar flux of Bond and others suggests that advance and retreat may have responded to highs and lows in solar flux. We continue to analyze the records of glacial activity and interstadial tree-ring records with the goal of defining the glacial history more precisely while developing evidence that will allow us to examine this hypothesis quantitatively.

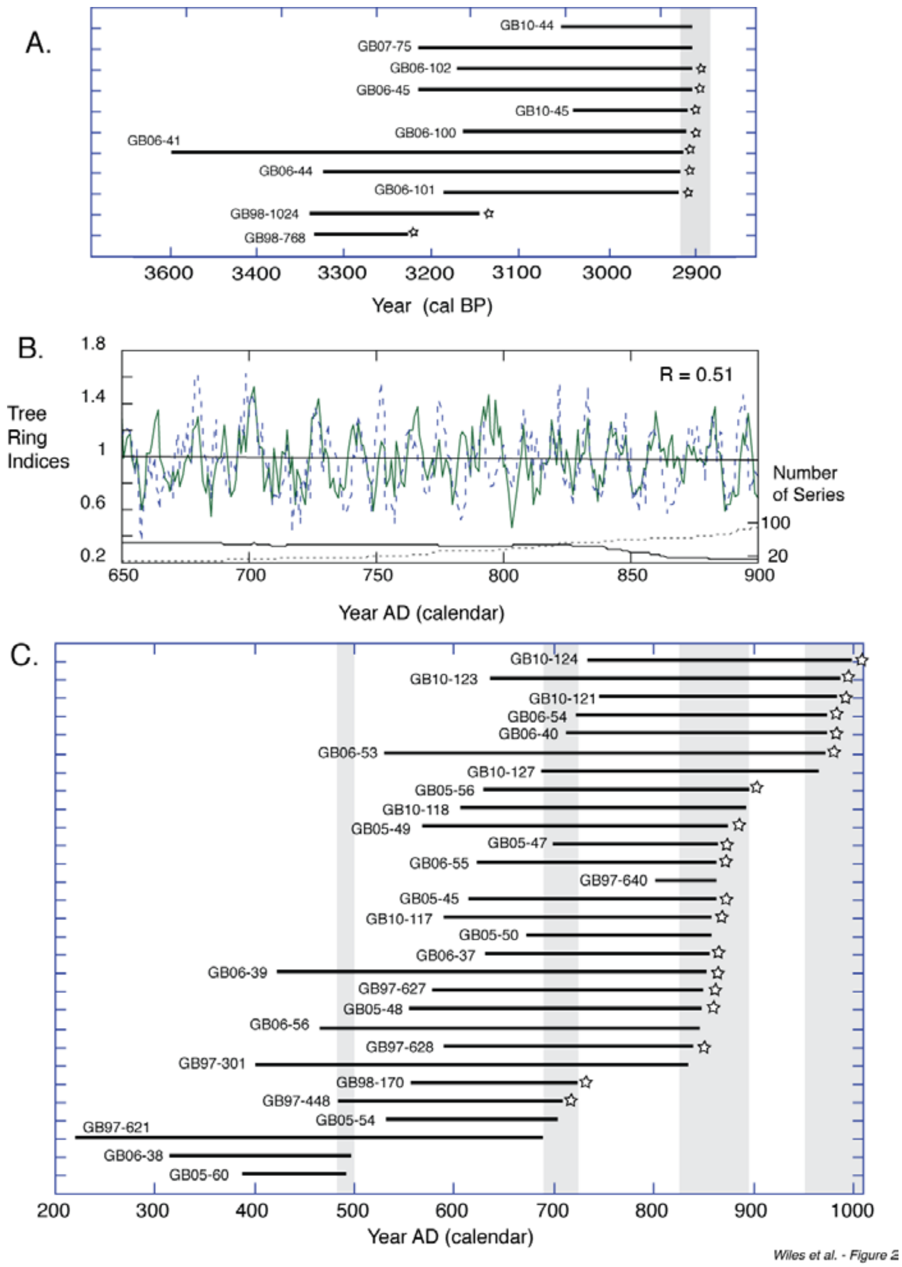

Figure10. *Tree ring data from the Geikie Inlet valley and fjord. Our analyses suggest two pre-LIA ice advances at ~ 3 K year BP and ~ 850 AD, with extended ice-free periods of over 500 years in this region where ice is fed by the Brady Icefield (Wiles et al. submitted).*

Future Work

We plan to continue processing the existing sections of wood sampled in previous years, while conducting field studies to obtain additional sections of interstadial wood that are required to complete the ring-series record from present to 10,000 years BP. We will target certain areas of known reserves of wood within the age ranges for which additional sections are needed to complete the series, as well as conduct searches in other areas to attempt to locate wood that will provide ring data between the floating chronologies in the 5 K year to present time period. In particular, additional samples are needed in the 3.8 to 3.0 K year, 4.8 to 6.0 K year and 1.8 to 2.4 K year periods. As the 5 K year series is finalized, we will conduct the ring-width analyses of wood within the 10K to 5K year BP range. Simultaneously, statistical analyses and paleotemperature reconstructions of the 5000-year record will be done and results published in professional journals. We will finalize the cataloging, marking and imaging of the sections for archiving to the NPS database.

Significance and Products

Global climate is changing and humans may have a significant role in affecting those changes. Our knowledge of how the climate system works is hampered by a lack of long-term, high-resolution records, which are needed to demonstrate the full range of natural variability of the climate system, especially on annual to century time scales. As contemporary warming progresses, major changes in the cryosphere and biosphere are being observed especially in the higher latitudes (ACIA 2004). It is with this need in mind that we are conducting the research on the paleoclimate of Glacier Bay, a climatically-sensitive region of the North Pacific.

Our research involves analysis of the climatically-driven glacial fluctuations during the Holocene, and linking this record to a unique, potentially 10,000-year long tree-ring chronology of high-latitude climatic information derived from ancient wood of trees overridden by successive ice advances. The record of glacial activity in the Park is also unique; other parts of the Gulf of Alaska as well as neighboring British Columbia have few well-defined records of glacial activity beyond 3000 years ago. Yet here, our initial data suggest that multiple cycles of glacial advance and recession, possibly seven or more, can be documented since the end of the Late Glacial Maximum (LGM) about 14,000 years ago. Of primary significance is thus the development and analysis of a millennia-scale tree-ring record for Glacier Bay National Park and Preserve and defining its relationship to global and regional changes in climate and the periods of glacial advance and retreat that resulted. The combined records of climate and glacial activity are a unique and important contribution to understanding the forces shaping the terrain in concert with tectonic activity.

Based on our initial and ongoing analyses, this chronology of paleoclimate has the potential of being one of the longest tree-ring records in the world from which paleotemperature records may be extracted. The temperature proxy record already suggests that an interval during the First Millennium AD may have been as cold as the better studied Little Ice Age. Knowledge of the paleotemperature trends during the advance and retreat cycles of the glacial systems will allow us to examine how they relate to the decadal and millennial scale variability in climate and the factors causing those changes. Ultimately it will be a major contribution to larger-scale efforts to reconstruct climate variability for the Northern Hemisphere (D’Arrigo et al. 2005; Mann and Jones 2003; Moberg et al. 2005). The paleo-records of climate and glacier response will be the only paleoclimatic data spanning the periods of abrupt (decadal) climatic changes of the early Holocene, a scenario that recent research indicates could cause extreme societal and environmental disruptions were such events to happen today. We are currently working with R. D'Arrigo and colleagues to compare southern Alaskan tree-ring records with those of southern South America (Chile and Argentina) to examine pan-Pacific climate synchroneity and differences for the past two millennia. This work builds on initial comparisons by Villalba et al. (2010).

We will continue to present the initial and ultimately final results of our research at national and international meetings on climate change, past and present. We will also publish our research results within prestigious professional journals as they are obtained, and provide the Park with Annual Summaries of our research activities and results. In addition, our data will continue to be archived on the Glacier Bay network server and be contributed to the International Tree-Ring Data Bank, maintained by NOAA in Boulder.

Collaborators and Synergistic Activities

We have collaborated with other researchers working in Glacier Bay. Using our Beartrack and Excursion Ridge ring-width chronologies, Brian Luckman (University of Western Ontario), Danny Capps and John Clague (both at Simon Fraser University) were successful in tree-ring dating the killing of a forest at Brady Glacier. Rosanne D'Arrigo (Lamont-Doherty Earth Observatory, Tree Ring Lab) and Rob Wilson (University of Edinburgh) are serving as advisors on the project and will be involved with us in modeling the dendroclimatic record. A new collaboration with Dr. David Frank of WSL-Switzerland is adding a new aspect to the tree-ring work. This lab is one of the premier groups that generate and analyze latewood density series. We are currently collaborating on a manuscript with Wayne Howell, Greg Streveler, Dan Mann, Mary Beth Moss and Aron Crowell on the Huna Tlingit response to the advance of the Glacier Bay glacier during the Little Ice Age.

We also provided wood sampled from the lower bay area for dating and inclusion in the LIA glacial and Tlingit history analyses of Streveler, Connor, Howell and Montieth. Chris Fastie (Middlebury) and Roman Motyka (UAF) have generously shared their ring-width data from sites within Glacier Bay and Icy Strait which we will compare with our results. We were successful in proposing research to NSF in 2009 and have a second proposal in the works with R. D'Arrigo (Lamont) to fund the continuing field and laboratory work. During the summer of 2010, we hosted an Earth Science teacher from Mount Vernon High School, D. Prinkey participated in field work and enriched her course in Earth Sciences as a result.

We also worked with many volunteers from the seasonal and permanent staff of the Park this past summer, some traveling into the field with us to be engaged in our field work, thereby providing a better understanding of our research and its significance; hopefully providing a background useful to their work. We are extremely grateful of course for the assistance they provided! In addition to the undergraduate students doing their theses, we continued to involve high school, graduate and undergraduate college students in our field work this past summer.

Completed and Current Theses

Lyon, E., 2007, “Progress towards the development of a multi-millennial tree-ring chronology, Glacier Bay National Park and Preserve, Alaska”, unpublished thesis, Department of Geology, The College of Wooster.

Malcomb, N., 2007, “Using tree-ring time series from the Gulf of Alaska to model mass balance from the Northeast Pacific Rim”, unpublished thesis, Department of Geology, The College of Wooster.

Trutko, A., 2008, “Development and climatic analysis of the Bear Track and Excursion Ridge Ring Width Series, Glacier Bay National Park and Preserve, Alaska”, unpublished thesis, Department of Geology, The College of Wooster.

Erlanger, E., 2008, “Reconstructing Sitka, Alaska temperature change for the last 450 years using tree rings”, Unpublished thesis, Department of Geology, Union College.

Plourde, A., 2008, “Using North Pacific tree ring chronologies to reconstruct Laurentian Great Lakes levels over the past several hundred years”, Unpublished thesis, Department of Geology, Colorado College.

Laxton, S., 2009, “Manifestation of the ~5 ka rapid climate change event in Glacier Bay, Alaska: interpreting a dendro-glaciologic record”, PhD Thesis, Department of Geology, University of Cincinnati, Ohio.

Fetters, C., 2009, “Tree-Ring dated Little Ice Age history and Tlingit legends during the Early 18th Century in Glacier Bay, Glacier Bay National Park and Preserve, Alaska”: Undergraduate thesis, The College of Wooster.

Krivicich, M., 2009, “Developing the glacial history of Middle/Lower Glacier Bay, Alaska, through the tree-ring dating of subfossil wood, Glacier Bay National Park and Preserve”: Undergraduate thesis, The College of Wooster.

Aughenbaugh, K., 2010, “Reconstructing Late Holocene glacial movement in Muir Inlet, Glacier Bay, Alaska”, Undergraduate thesis, The College of Wooster.

Mennett, C., 2010, “Decline in Alaskan Yellow-Cedar: Tree-Ring Investigations”. Undergraduate thesis, The College of Wooster.:

Jarvis, S., in progress, “Non-stationarity in climatic response of coastal tree species along the Gulf of Alaska”: Undergraduate thesis, The College of Wooster.

Appleton, S., in progress, “Glacial chronology from Adams Inlet, Glacier Bay National Park and Preserve, Alaska “(tentative title): Undergraduate thesis, The College of Wooster.

Acknowledgements

This project has been funded in part by the US Army Cold Regions Research and Engineering Lab, National Science Foundation (Grant ATM-0902806), The College of Wooster, Rockefeller Center for Public Policy and the Social Sciences, Institute of Arctic Studies at Dartmouth College, Keck Geology Consortium, National Geographic Society and various grants to students for field travel and laboratory assistance. 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 enthusiastic encouragement. We particularly would like to thank Cherry Payne, former Superintendent, Craig Smith, former Chief Resource Management, and Lewis Sharman, Ecologist, for their permission and encouragement to conduct the research, and providing the continuing support of their staff, vessels, housing, office space and other facilities that make the work possible. We thank Justin Smith, Captain of the *RV Capelin* for the safe transport in the field, his assistance and the many stimulating discussions of our research. Finally, we are thankful and greatly appreciate the field assistance of numerous students and volunteers over the years who have assisted us under arduous conditions and performed often strenuous work to acquire the wood samples and glaciologic data necessary for this research; the 2010 students included Matt Bigl (Middlebury), Kyle Lawson (Dartmouth), Brady Lawson (UMaine), Stephanie Jarvis (Wooster) and Cooper Lawson (Oxbow HS), and high school teacher Deb Prinkey.

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