A Dendroclimatic Record of Paleoclimate of the Last 10,000 Years, Glacier Bay National Park and Preserve
2006 Progress 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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Introduction
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 climatic data, which are needed to demonstrate the full range of natural variability of the climate system on both short and long time scales. In addition, as global warming progresses, we expect to see some of the greatest effects in the higher latitudes. It is with this need in mind that we are conducting research on the paleoclimate of Glacier Bay, a climatically-sensitive area of the North Pacific region. Our research involves analysis of the climatically-driven glacial cycle during the Holocene, and linking this record to a unique 10,000-year chronology of high-latitude climatic events. The inferred climate record is derived from tree-rings of ancient wood from trees overridden and killed by successive ice advances, and cores from modern trees, which are together then compared with instrumented climatic data.

Background
Normally heavy snowfall in the high mountains surrounding Glacier Bay feeds one of the larger active glacier complexes in North America, a part of the fourth largest glaciated region in the world (Meier 1984), and recent changes in Glacier Bay alone have had a significant effect on global sea level (Arendt et al., 2002; Larsen et al 2005). With the exception of some lowlands at the southeastern and southwestern margins, the Glacier Bay watershed was covered by ice as recently as 250 years ago during the Little Ice Age (LIA). Retreat after the culmination of the LIA is one of the best documented in the world, with ice margins retreating distances as far as 90 km at some of the highest rates ever recorded. During this retreat, forests that were overridden by ice advance have been progressively uncovered. Today, these interstadial forests continue to be exposed by failure, erosion and degradation of slopes, migration, scour and erosion of streams, uplift of shoreline and intertidal areas, and the continuing retreat of terrestrial and tidewater glaciers. Radiocarbon dating of the interstadial forests reveal that in addition to the

advance during the Little Ice Age, glaciers advanced into Glacier Bay several or more times over the last 10,000 years (Lawson et al, 2007).

Although numerous global warming scenarios (IPCC 2001) indicate that Arctic and Subarctic regions are particularly sensitive to current and predicted climatic changes, our knowledge is severely hampered by the fact that measured climatic records are generally only ~100 years in length. Knowledge of climatic change over a much longer period may be gained from the unique, large repository of interstadial wood within Glacier Bay. Such repositories are unknown elsewhere in North America and extremely rare elsewhere in the world

The data contained within the wood of Glacier Bay can provide information on how climate has changed within the climatically-sensitive North Pacific region in response to global changes known to have occurred from ice core records in the North Atlantic region. The relationship of climate in these two arctic regions is not well known and how Pacific climate responds to global forcing is equally unknown. Thus, paleoclimate data from our analysis will provide critical, unknown parameters required to calibrate Global Climate Models (GCMs) and improve predictions of future changes in the Earth's climate.

Other work on modern and exhumed wood from areas in the western Gulf of Alaska have found that the tree-ring series of wood samples crossdate and correlate well with modern climatic records (Barclay et al. 1999, Wiles et al. 1999). However, these studies are limited in their expanse of time, spanning only ~1,000 years. In contrast, the interstadial forests of Glacier Bay provide the only known North American repository of wood that may continuously span the last 10,000 years.

Our continuing primary objective is to collect sections of the ancient trees overridden during the Holocene excursions across Glacier Bay before they are lost to erosion and decay. The recovery and processing of these samples is the primary resource in building a tree-ring record of the last 10,000 years. Presently we are engaged in showing conclusively that the ring-width data reflect paleoclimate by crossdating the Glacier Bay records with other tree-ring records from the Gulf of Alaska region, and that the sampling required to build this record is possible within the next several years.

2006 Objectives

Our paleoclimatic studies in 2006 specifically focused on sampling and developing tree-ring chronologies and analyzing this record for its climatic significance. Specific objectives include:

1) Obtain cores of trees living during the Little Ice Age (~ last 650 years) and develop a tree-ring chronology for the period
2) Compare Glacier Bay tree-ring chronologies of the last 1400 years with existing, calendar-dated chronologies from the Gulf of Alaska region to document their similarities or differences and thus the suitability of Glacier Bay trees and tree-ring records as robust paleoclimatic indicators.

3) Obtain sections of interstadial wood that grew for various intervals through the past 3000 years to supplement existing radiocarbon-dated sections for which ring-width chronologies could be developed.
4) Develop tree-ring chronologies for selected groups of previously-sampled, radiocarbon-dated cross sections and produce floating ring-width series for periods of time beyond 1400 years BP.

Dendrochronology

Dendroclimatic studies involve the statistical comparison of tree growth (such as measured ring widths) to important climatic factors such as regional temperatures; this is most often accomplished with instrumented climate records (Fritts 2001). We must show that modern trees have tree-ring widths that statistically vary with climate, thus providing the basis for future analyses of paleoclimate in the 10,000-year chronology we plan to establish. Climate data now being collected at sites across Glacier Bay (Lawson et al 2006 a, b) will provide data on how climate varies regionally across the Park, and allow us to determine whether historical records from climate stations outside Glacier Bay reflect the climate within the bay.

Radiocarbon dates from the exhumed interstadial wood are at their youngest 250 to 500 years old, which puts the older wood outside the range (~100 years) of instrumented climatic data for southeast Alaska. In order to know the exact year of growth on each of these older specimens, we need to connect them to the present day calendar-dated tree-ring record, which can be done with the oldest still-living trees that we have begun to sample at four locations within the Park (Figure 1). These older living trees grew through

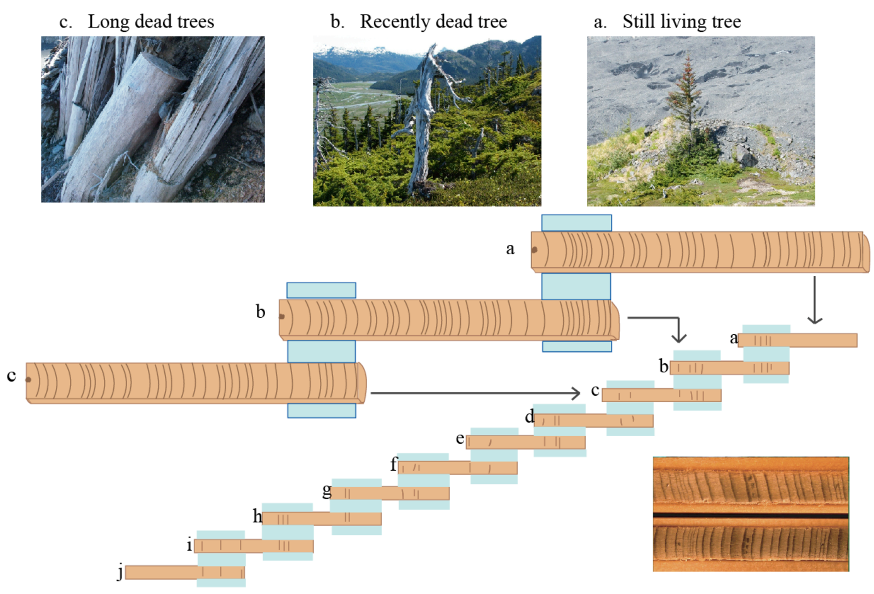

Figure 1. Diagram showing the tree-ring crossdating technique. The age of the wood increases to the left. We are now establishing calendar-dated tree-ring records from living trees in Glacier Bay and matching them with *floating* ring-width series from interstadial wood, extending the calendar-dated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

the duration of the Little Ice Age and have ages in some cases exceeding 650 years.

Once we have established that tree ring properties reflect climate in response to changes in precipitation and air temperature, and have linked the interstadial wood by calendar dates to living trees (Figure 1), we can develop the periods of record represented by the radiocarbon-dated sections of interstadial wood. These ancient trees have dates spanning the last 10,000 years, but each section may only cover several hundred years or less when they were growing prior to being killed as the glaciers advanced across the forests.

Thus we must acquire multiple groups of wood sections to cover the entire ten thousand year period, and we must also collect a sufficient number of wood sections of a particular age range to produce a continuous and reproducible tree–ring record for each of the much smaller time spans during which each group of ancient trees lived. Ideally, we attempt to obtain approximately 20 useable sections of each age group to insure statistically representative records. To obtain 20 useable sections for the tree-ring analysis may in fact require us to sample more than this number; problems such as missing rings, condition of the wood once dried and other factors may result in a wood section being unsuitable for the analysis. Age groups of tree-ring records are then linked by overlapping ages (rings) to produce the continuous tree-ring record (Figure 1)

Methodology

Tree-ring analyses are conducted in laboratories at The College of Wooster, Dartmouth College and CRREL under the direction of the principle investigators. We use standard dendrochronological techniques to prepare and analyze the cores and cross sections (Stokes and Smiley, 1968, Cook and Kairukstis, 1990). Ring-widths are measured to the nearest 0.001 mm using a stereo microscope and crossdating is performed using the computer program COFECHA (Holmes, 1983, Grissino-Mayer, 2003) and visual examination.

The resulting ring-width series from living trees are compared (calibrated; Fritts, 1976) with the instrumental data from meteorological records from nearby sites, which include Juneau, Sitka, Haines and Yakutat. We then compare the series to an existing network of tree-ring series available from the Gulf of Alaska region that span the living tree age ranges and extend back beyond modern trees to over 1000 years ago (Barclay et al 1999; Wiles et al 1999).

Ring-width chronologies from the interstadial sites are added to chronologies from the living sites when they overlap in age, or 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 sample sections for filling in the series beyond the calendar-aged wood. We are especially encouraged because the extensive set of living tree-ring records and interstadial records from other regions along the Gulf of Alaska match well with the tree –ring records from Glacier Bay. For example, a 1500 year long tree-ring record from Columbia Bay in Prince William Sound correlates well with tree-ring series from Geikie Inlet and other sites that have known caches of logs in the age range of 1200 yr. BP.

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 and thus aid in producing information on the glacial history of the bay. These methods include defining the glacial stratigraphy by sedimentological analysis of deposits (e.g. Benn and Evans 1998), and by dating organic material in soils, peat horizons and small pieces of wood within these sediments using radiocarbon methods (e.g. Bowman 1990). Each core and section sample site is located precisely by GPS, photographed and various parameters, such as dimensions, position of each sample section relative to the roots, tree species and overall condition, are recorded about the wood source in field books

In the lab, the core and wood sections are slowly dried prior to processing. Cores and sections are then glued and sanded for counting and measuring the rings within each sample. We must carefully scrutinize multiple wood sections to insure reproducibility of the records and account for missing rings, as rings may be lost due to various stresses in the environment, as well as to account for sub-regional differences that may be present in the climate that can locally affect growth patterns. In addition, small samples (several grams) of the outermost five rings of interstadial wood sections are radiocarbon-dated using the high-resolution Accelerator Mass Spectrometry (AMS) technique (e.g. Gove 1999); we use the AMS method to limit the possible error in gaging the age range of groups of interstadial stumps and logs.

2006 Accomplishments
We continued to examine the relationship between modern measurements of climate and tree-ring width, and to link these modern (last 100 – 200 years) tree-ring records to those of the first millennia for which we acquired additional sections of interstadial trees. We initiated the processing of interstadial wood obtained this past summer in preparation for ring-width analyses. In addition, we were able to begin crossdating of the samples processed from 2005 with tree-ring records from the Gulf of Alaska region. Field work took place from 21 to 28 June, 26 July to 2 August, 20 to 24 August and 14 – 15 September.

We collected 40, 5-mm diameter increment cores from 27 living trees in 2006 at locations where our previous work had shown them to potentially provide a continuous tree-ring series spanning the last 650 or more years. Living trees of this age occur west of the mouth of Glacier Bay along Icy Strait, in the Dundas Bay region, along the ridge of the Beartrack Mountains and north to Mount Wright, and on Excursion Ridge east of Bartlett Cove. Our sampling focuses on the two major tree species in the Park, Sitka spruce (*Picea sitchensis* (Bong.) Carr.) and Western Hemlock (*Tsuga heterophylla* (Raf.) Sarg.). The new cores obtained at Beartrack were primarily from Western Hemlock, whereas the Dundas Bay cores were from both Hemlock and Sitka Spruce. The cores of living trees are critical to filling gaps in linking our ancient wood data to that of the present, thus making the annual and seasonal reconstructions of climate from the longer chronology. Core samples of the older trees in Beartrack and Dundas Bay will allow us to explore the statistical relationships between tree growth and climate in the period of roughly 100 years for which we have modern climatic data.

We continued the laboratory processing and analysis of tree cores from the Dundas Bay and Bartlett Cove areas in the Tree-Ring Lab at Dartmouth College, and initiated the processing and analysis of the new cores obtained in 2006 from the Beartrack Mountains at the Tree-Ring Lab of The College of Wooster. Processing has shown that some cores of the older trees in Dundas Bay are unusable due primarily to gaps in the record and additional core sampling in Dundas Bay is planned for 2007.

From our initial results of the Beartrack core analyses, we have produced a preliminary ring-width series (Figure 2). This ring-width series was then compared (calibrated) with the instrumental data from along the Gulf of Alaska (GOA) using a regional five station monthly temperature series. We then compared the Beartrack series to a temperature reconstructions based on a network of tree-ring series available from the GOA (Wilson et al., 2007) (Figure 2). This comparison shows that the climate signal is a regional temperature signal and is therefore not only representative of the Glacier Bay region, but can be considered as a thermal record of climate for a large area of the Northeast Pacific coastal sector. Further analyses are on-going to develop the relationships with temperature and precipitation, while extending the calendar-dated tree ring chronology back beyond 1500 years ago.

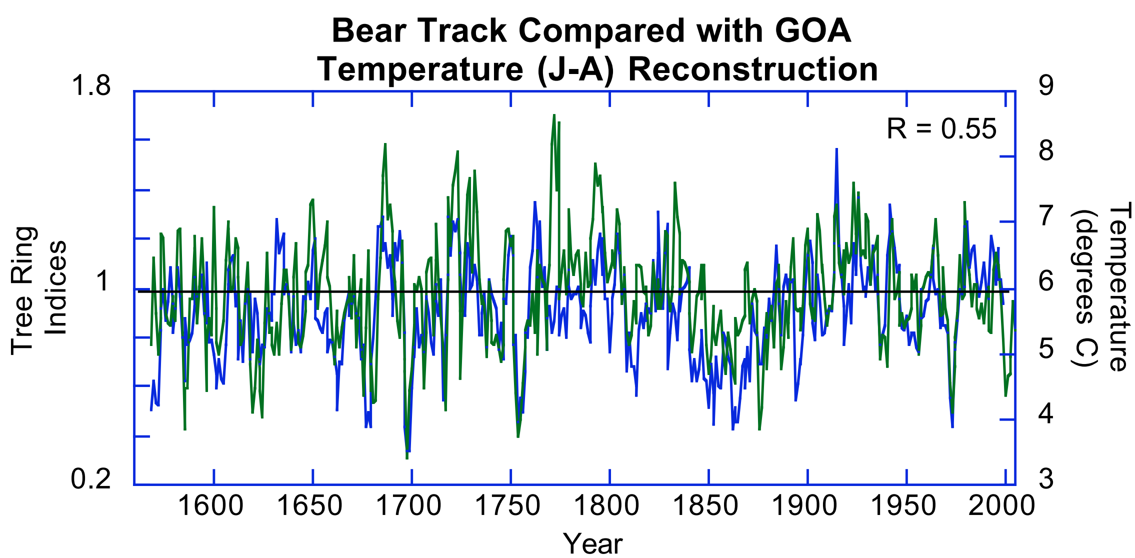

Figure 2. Ring-width series from Beartrack Mountain (green) compared with a tree-ring based average January through August temperature reconstruction (blue; Wilson et al., 2007). Over the 430 year interval, the correlation of the series is 0.55 showing a strong regional climate signal that is shared by many series along the Gulf of Alaska.

We obtained 67 cross-sections from recently exposed in situ interstadial stumps and logs across Glacier Bay, focusing our efforts on areas that we believed would fill gaps in the longer chronology. We focused part of our wood searches in the Geikie River drainage

(Figure 3) where radiocarbon dating had previously shown the ancient trees were growing during the critical time period of ~1800 to 1100 years BP, as well as back to 3000 years BP. This wood is especially important for showing that the paleoclimatic data of Glacier Bay records a regional or global signal in climate; this is being accomplished by comparing the tree-ring chronology with that of Columbia Bay in the Gulf. Locations we searched for interstadial wood of the period of 1500 to 4500 yrs BP included Wachusett Inlet fans and stream beds, upper Muir Inlet streambeds, the stream valley at the entrance to Tidal Inlet, Charpentier Inlet fans and Scidmore Glacier streambed and fan. Although we had previously found interstadial wood in the Tidal and Scidmore valleys, no such wood was located during our searches this year.

Both age groups of sections from upper Geikie Inlet are critical to linking modern and ancient tree-ring records. The interstadial cross sections have been processed at CRREL and we are currently analyzing sections of ~ 1500 yr BP interval. These data will be used to determine whether they crossdate with the tree-ring record from Columbia Bay in the central Gulf of Alaska region. The preliminary result of this analysis suggests that a common climatic signal exists between the two areas. Further sampling and analysis of this overlapping period will presumably show this common signal to be strong and reproducible, a key to extending the paleoclimatic record beyond 1500 years.

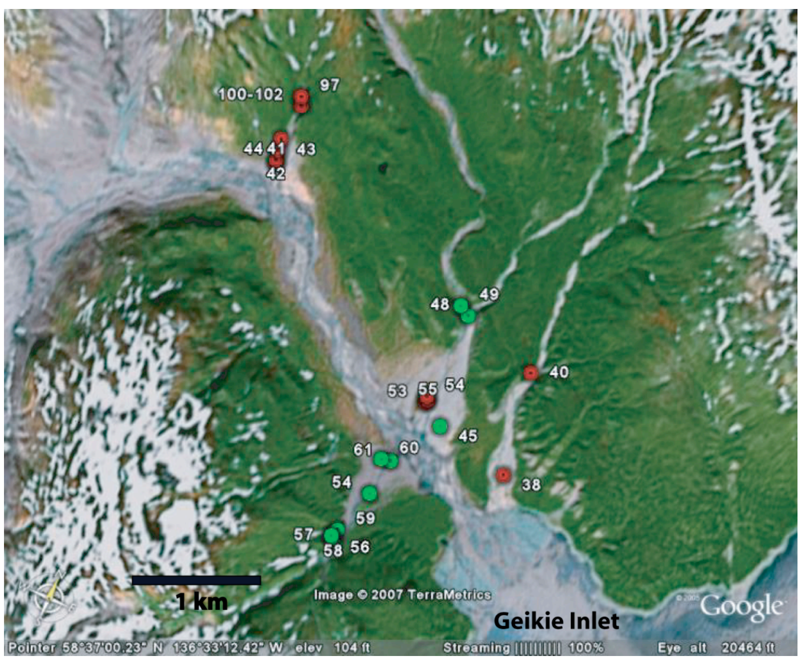

Figure 3. Sample sites from 2005 (green) and 2006 (red) from the head of Geikie Inlet. These interstadial logs have now been incorporated into the long (1500 year) regional tree-ring series or have been crossdated with the 3000 yr. BP or a 1800 yr. BP floating ring-width series that will be matched and calendar-dated with the regional series as the gaps in the record are filled.

Continuing Work

We will focus our efforts in 2007 on obtaining additional sections of interstadial wood from the period of 1500 to 10,000 years ago. Our objective will be to locate and sample wood with radiocarbon ages that fill crucial gaps in our existing sample collection so that we can develop a complete tree-ring chronology for the Holocene. We will also seek to obtain additional cores from the oldest living trees in Dundas Bay to complete the living tree-ring record there, and analyze the important relationships between ring widths and a recently discovered, long historical climate record of air temperature and precipitation from nearby Sitka. We will continue laboratory analyses to develop the tree-ring records for the interstadial wood and begin the interpretation of the paleoclimatic record of temperature and precipitation for the time periods represented by the various age groups. One overarching goal in 2007 will be to search for wood that will complete the record of the last three millennia and allow us to verify what our limited sampling has shown to date – a strong crossdating with the western Gulf tree-ring records and thus a clear link to ancient changes in climate.

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