C12A-0873 1330h POSTER

Recent climate trends, Glacier Bay, Alaska

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Glaciers and ice caps respond to changes in regional climate at decadal scales and can thus serve as indicators of regional climate change. Many of the tidewater and terrestrial glaciers in Glacier Bay, Alaska have been in a state of rapid retreat since the late 1700s, with highly disparate rates of recession occurring in the western versus eastern arms, yet the combination of environmental and glaciological factors that must exist to catalyze these rapid changes is not clearly understood. The Cold Regions Research and Engineering Laboratory (CRREL) initiated the first systematic analyses of weather and precipitation patterns across Glacier Bay National Park in 2000 by establishing 26 meteorological stations with the long-term objective of better understanding regional and global factors, that control terrestrial and marine physical systems. Initial temperature and precipitation trends show rapid seasonal and annual shifts. This is consistent with apparent paleotrends in climate and glacier advance and recession over the last 9K years, as well as the historical record that indicate the area is climatically sensitive. Comparisons of summer and winter precipitation totals show a precipitation gradient increasing northward from the lower bay to the head of Muir Inlet (east arm), and decreasing northwestward in the West Arm. Monthly averages of air temperatures span about 3.5 C between the warmest and coldest sites near sea level. Winter temperatures averaged more than 1 C colder in the West Arm than the East. We also found large gradients of increasing rainfall from north to south in the east arm, from north to south in the Western arm. Average temperatures in October decreased westward in the northern half of the Park and were milder at sites within the larger southern Bay. Continuing a long-term climate-monitoring program in Glacier Bay will assist with quantifying climate trends in the context of glacial movement, helping to determine the overall sensitivity of the regional glacial system to regional climate signals.

C12A-0874 1330h POSTER

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

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Understanding tidewater and terrestrial glacier processes is critical when determining the impacts that contemporary climate and anthropogenic influences play in long-term glacier response. This understanding can only be acquired through a myriad of long-term glaciological and environmental measurements aimed to quantify glacial system response. The primary focus of our long-term investigations in Glacier Bay, Southeast Alaska is to better understand regional and global factors, such as climate, hydrology, oceanography and geophysical processes that control terrestrial and marine based physical systems. Our recent climatic investigations include analyzing modern climate trends at 26 locations across Glacier Bay and measuring the isotopic composition (oxygen and hydrogen) of precipitation, surface water, and glacier ice to assess regional hydrologic trends. Stable isotopes from samples of glacier ice, precipitation, and meteoric waters, have provided a regional assessment of the hydrologic cycle and weather patterns, allowing us to examine how current climate affects glacier activity and mass balance, and to assess the effect of precipitation on subglacial processes. 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 100 interstadial stumps believed to be overridden as ice moved down-fjord during glacial periods, as well as over 100 paleo-wood samples found in adjacent moraine, outwash, and lacustrine sediment deposits. Conventional radiocarbon dating by Accelerated Mass Spectrometry (AMS) has provided an estimate of ice-marginal positions throughout the Holocene. Using these data, we are also attempting to develop a tree-ring chronology of the last 9,000 years. If we succeed, this would be a unique dendrochronological record for a subarctic region in North America.

C12A-0875 1330h POSTER

Spatial Variation of Ionic and Isotopic Records From Snow Pits and Shallow Ice Cores in Central and Southeast Asia

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The alpine glaciated regions of the Belukha massif on the Altai, the massif of Pobeda-Khan Tengry in central Tien Shan, and the Bomi massif in Southeast Tibet were studied during annual summer field sessions since 1998. Analysis of soluble ion concentrations and äO18 signals in snow pits and shallow ice cores from glacier accumulation areas occurred to provide spatial coverage of documenting the climate change for the vast Asian continent, to identify the physical links controlling the glacio-chemical climate signals and to determine the appropriative deep ice core drilling sites. The geochemical records from central Asian sites show elevated levels of major ions corresponding to their terrestrial origin, continental location and greater influx of both primary and secondary aerosols compared to the Southeast Asia. Seasonal variability in the ice core obtained from the three glacier massifs was detected in the soluble ion concentrations of the vertical profiles throughout the firn pits and shallow ice cores to depths of 20 m. representing the time series for the past five years. äO18 analysis from the Asian sites shows pronounced peaks and are interpreted to represent annual accumulation layers. The signal variation is well-preserved at all locations and associates with seasonal changes in precipitation, air temperatures and sources of moisture. Analysis of the ä18O signals from the 14 m core obtained at southeast Tibet shows the considerable variability with the range of $14.19^{o}/_{oo}$, and mean value of $-16.19^{o}/_{oo}$. These isotope and geochemistry records will aid in understanding inter-hemispheric dynamics and global teleconnection of climate, and can provide information important to the forecasting of global climate change linking regional responses with broad atmospheric circulation patterns from the North Atlantic to Pacific and Indian Oceans. In addition, these snow/firn records can be directly associated with the internal circulation system in Central Asia. The developed research proved the feasibility and benefit of a deep ice coring from the Altai glaciers. Since that, the 175 m. deep core was obtained in the Belukha Plateau during the summer of 2003 to expand the high-resolution climatic records in Central Asia.

C12A-0876 1330h POSTER

A Reanalyis of the Contribution of Meteoric Ice, Flooding and Snow Ice Formation to the Mass Balance of Antarctic Sea Ice

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Sea ice core data from five autumn to early spring cruises in the Ross, Amundsen, and Bellingshausen Seas from 1993 to 1998 are reanalyzed to determine the role of meteoric ice, flooding and snow ice formation in the mass balance of Antarctic Sea Ice. Previous analysis of crystal texture and oxygen isotope data have determined that 15% to 38% of the total ice thickness has a meteoric ice component. This suggests a substantial component of the sea ice mass balance in the Southern Ocean during the growth season is due to flooding and snow ice formation. We show that although determining the meteoric component is relatively straightforward, attributing a mechanism of formation to this ice is more difficult. A number of post-genetic changes can occur that may significantly alter the isotopic signature of the ice, making definitive attribution of genesis difficult. Here, the oxygen isotope and crystal structure data is reanalyzed, and using a variety of models of ice growth and compositional evolution, we suggest that the true contribution of flooding and refreezing to the mass balance may be significantly lower, at 6% to 18% of the total ice thickness. However, we show that such estimates are highly dependent on the thermophysical behavior of the vertical exchange of brine in the ice, about which little is known quantitatively. The uncertainty in these estimates suggest that our understanding of the mass balance of Antarctic sea ice and its snow cover remains incomplete and awaits a better understanding of the ice permeability evolution and other small scale sea ice processes. Lastly, recent evidence from flooding experiments on Arctic sea ice is presented that demonstrate the importance of the vertical exchange of brine in determining the compositional properties of the ice.

C12B MCC: 3004 Monday 1340h

Fracture Processes in Glacier Ice II

(joint with OS)

Presiding: **H A Fricker,** Scripps Institution of Oceanography**; C Hulbe,** Portland State University

C

C12B-01 1340h INVITED

What lies beneath? The question of sub-surface crevasses

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The process of fracture is a major control on the form of the Antarctic ice sheet, both through the process of iceberg calving and through the isolation of streaming flow by the formation of crevassed shear margins. Furthermore, the presence of crevasses is a valuable diagnostic of stress within the ice sheet. Their persistent visibility after burial provides our primary tool for mapping changes in ice stream activity. However, the processes of fracture initiation and growth are poorly understood. Hitherto it has been a fundamental assumption that crevasses always initiate at the surface and propagate to some limiting depth. We revisit the linear elastic fracture mechanics (LEFM) description of the initiation and critical-growth of near-surface crevasses to examine this assumption. We assume growth of an isolated crevasse from a small "starter crack", driven by tensile stress resulting from glacial deformation and opposed by weight-induced lithostatic stress. The LEFM approach allows us to estimate the minimum length of "starter crack" required for growth to occur. In this formulation the dynamic tensile stress varies substantially with depth, such that the tensile strain rate remains constant. We show that under these conditions crevasse initiation may be from centimetre-scale starter cracks located either at the surface or at depths of 10-30 m. At present, the formulation of a reliable predictive model is limited by an incomplete knowledge of the mechanical properties of firn and a lack of material evidence to support the existence of "starter cracks". Ground penetrating radar data acquired on Rutford Ice Stream, Antarctica show crevasses at depths of several metres beneath the ice surface that do not appear to have been bridged in the normal way, and which must have been formed either at depth, or at the surface in areas where no surface crevassing is currently visible. The theoretical treatment together with apparent observations of sub-surface crevassing calls for a reinvestigation of the processes of fracture to re-establish the validity of assuming that the depth of a crevasse is a reliable indication of its age.

C12B-02 1400h INVITED

Borehole Observations of Cracks in a Polythermal Glacier

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We drilled 53 boreholes in the ablation zone of Storglaciaren, a polythermal glacier in northern Sweden, to characterize the englacial hydraulic system. Eighty percent of the holes connected to an englacial system, as indicated by a drop in water level within the borehole during drilling and subsequent diurnal fluctuations in water level, suggesting input from surface melt. Our expectation was that these connections would be Rothlisberger-type conduits with elliptical cross-sections. To our surprise all englacial connections but one were made to cracks in the ice. The one exception was a Rothlisberger-type conduit intercepted by a borehole drilled 11 m away from a moulin. Video images from a camera lowered into the boreholes revealed that the cracks varied in width from about 1 cm to several cm. However, we believe the warm drill water escaping from the borehole into the cracks during the initial connection melt-enlarged the openings. The plunge of the cracks is quite steep, typically near vertical, but the lateral extent is unknown. Cracks were observed at depths between 20 and 158 m below the glacier surface, with a few relatively close to the glacier bed. The location of each crack was associated with a band of clear ice, suggesting some refreezing during its lifetime. The clear ice also made observations difficult at times. Orientation of the shallow cracks (less than 50 m depth) was parallel to the observed surface crevasses, while deep cracks were generally oriented perpendicular. Most cracks exhibited some natural water movement, speeds of 0.1- 1 cm/s (laminar). Water pressures were generally close to the total overburden pressure of the ice, but were less than the local overburden estimated relative to crack depth. These results suggest that alpine glaciers are highly fractured with cracks existing at all depths. Whether the cracks are formed in situ or are advected from surface areas higher on the glacier is unclear. The cracks are the main conveyor of englacial water suggesting that models of flow through a network of fractures may be more appropriate for glaciers than the classic Rothlisberger approach.

C12B-03 1420h

Englacial Crevasses: Observations and Theory.

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Recent observations on the Bench Glacier and other temperate glaciers in the coastal mountains of Southeast Alaska have shown the existence and importance of crevasses that crack over the full glacier depth. Direct video and hydrologic observations show these pervasive crevasses to be rapidly evolving and laterally and vertically extensive. Hydrologic monitoring demonstrates that the crevasses are connected to the surface, basal, and englacial hydraulic systems, and form part of the seasonal development of the englacial water system. We present data, including englacial video, of evolving crevasses at depths from 100 to 200m. The data demonstrate the existence and extent of crevassing well below the region of surface crevassing and into the region of fully compressive stresses (non-deviatoric). Preliminary theoretical work is presented discussing the role of water weight driven crevasse propagation. The theory addresses the propagation speeds of crevasses. It is concluded that crevasse propagation may be controlled by the available volume flux of water in the hydraulic system, not by classic crack propagation considerations. Some of the effects of modeling crevassing in 3 dimensions, as opposed to 2 dimensions, is discussed, where it is concluded that 3 dimensional crevassing should allow crevasses which greatly facilitate the creation of a connected and through draining glacial hydraulic system.

C12B-04 1435h

The role of hydrologically-driven ice fracture in drainage system evolution on an Arctic glacier

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Observations from Ellesmere Island suggest that a connection between surface and subglacial drainage on a predominantly cold glacier is made abruptly in spring by hydrologically-driven propagation of fractures from the ice surface to the glacier bed. Where ice is 150 m thick, water ponded to a depth of 6.9 m within a supraglacial stream system before a permanent connection to the bed was established. Multiple premonitory drainage events preceded the final drainage of the ponded water, implying that fracturing is necessary, but insufficient, to establish a permanent link between the surface and subglacial drainage systems. Refreezing of water that penetrates the first fractures to form may reseal the connection, while flow resistance within the subglacial system may delay the onset of continuous through-flow. A large volume of ponded water seems to be required to enlarge fractures sufficiently by melting to maintain continuous drainage, while feedbacks between subglacial hydrology and ice dynamics may assist in maintaining the connection and initiating subglacial outflow.

URL: http://arctic.eas.ualberta.ca/sarah/resume.html#publicns

C12B-05 1450h INVITED

Fracture Mechanics of Ice Shelves

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The importance of large-scale fracture processes has recently been emphasized by the break-up of ice shelves on the Antarctic Peninsula and underlines the need for incorporation of fracture mechanics into models of ice sheet dynamics. Key components for fracture mechanics models include qualitative models of the brittle processes in ice shelf fracture and experimental measurements of fundamental fracture parameters. We have adopted an integrated experimental and theoretical approach which is validated against field and satellite measurements. Our procedure has been first to quantify experimentally and physical behaviour of Antarctic ice core, then to use these measurements in fracture criteria describing the spatial distribution of crevasses, the depth and height of top and bottom crevasse penetration and the effect of tidal flexure. Up to now these have been crack initiation criteria. Here we discuss two extensions to our work: 1) to describe the statistical nature of ice fracture; 2) to describe crack propagation in ice. We find there that the statistical nature of ice shelf fracture can arise from the inhomogeneous size distribution of initiation cracks. We infer that crack propagation in ice can have strong environmental controls. We describe how these aspects of ice fracture can be incorporated into ice shelf models.

C12B-06 1510h

A Description Of Crevasse Formation Using Continuum Damage Mechanics

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Continuum damage mechanics describes the progressive deterioration of material subjected to loading. For polycrystalline ice, a local isotropic damage evolution law coupled to Glen's flow law allows the description of creep to failure. The damage evolution law has been derived from mesoscopic tests performed in traction and shearing. Damage initiation is controlled by a size dependent stress threshold, which has been inferred from published data of laboratory experiments. Crack healing is considered by a simple dynamic law. The rheology of the damaged ice is implemented in a FE model to describe the formation of crevasses at a macroscopic scale. A level set method is applied to model the evolution of the glacier geometry. The main purpose of this investigation is the modelling of the destabilization of large ice masses from hanging glaciers. The rupture of large ice chunks has been computed for different hanging glaciers in Switzerland. Numerical results compared with field observations and measurements showed good agreement. The ability of the model to describe phenomena connected to crevasse opening seems to be promising for other glaciological applications such as rift opening or ice stream margin formation.

C12B-07 1525h

An Investigation Into the Causes and Limiting Factors of an Active Rift on the Amery Ice Shelf: Fieldwork and Modeling Results

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The Amery Ice Shelf rift system, colloquially known as the "Loose Tooth", consists of two longitudinal (parallel-to-flow) rifts that formed about 15 years ago, and two transverse rifts that together with the western longitudinal rift, form a triple junction. A variety of satellite imagery spanning more than one decade has shown that the transverse rifts have both been actively propagating over the past decade, and have been, on average, speeding up (Young et al, this session). This past Antarctic field season (2002-2003), we instrumented the main transverse rift with 6 GPS and 8 vertical component seismometers. Results indicate that there are several periods of high seismic activity during which the rift widens rapidly. Comparison of experimental values of the critical stress intensity factor (a measure of the strength of the ice) with the stress acting at the tip of the rift calculated for an elastic ice shelf, suggest that the rift should propagate unstably. In an attempt to resolve this paradox we consider two possible explanations. First we examine the effect of a viscoelastic rheology of ice on dissipation of the stress at the tip of the rift; the associated time scale competes with the time scales attached to the loading mechanisms which control the rate of stress accumulation. In contrast the effect of an array of longitudinal crevasses on the stress field concentrated ahead of the rift is largely geometrical. Rift propagation is hindered because the crevasses create areas that are effectively weaker than the surrounding ice. We use a boundary element model to evaluate the effect of an array of crevasses on the stress concentrated at the tip of the rift.

C12C MCC: 3004 Monday 1600h

Planetary Permafrost I *(joint with B, P)*

Presiding: **C McKay,** NASA Ames Research Center**; R T Pappalardo,** University of Colorado, Boulder

C12C-01 1600h

Formation of Obliquity-Driven Subsurface Ice Deposits on Mars: Study With a General Circulation Model

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The discovery by Mars Odyssey of large deposits of subsurface ice in regions where surface ice is no longer stable has raised questions about putative past climatic conditions under different orbital states. We have used the GFDL Mars General Circulation Model (MGCM) as a tool for examining these questions, and suggest that these deposits may be quasi-stable permafrost remnants from an earlier period of high obliquity, covered by a sublimation lag deposit formed when the mean annual temperature exceeded the local frost point temperature. We have incorporated a thermal and vapor diffusion code into our GCM to simulate the