C11B-0994 0830h POSTER

3D modeling of curvature-driven snow metamorphism: first results and comparison with experimental tomographic data

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Snow, from its fall until its full melting, undergoes a structure metamorphism governed by local temperature and humidity fields. Among the many possible mechanisms that contribute to snow metamorphism, those that depend only on curvature are the most accessible to modeling. The isothermal metamorphism of a dry snow sample near 0°C is addressed in this work. Near 0°C, the vapor pressure of water is high: the metamorphism can be considered,*in first approximation*, as fully curvature-driven. This corresponds to neglect crystallographic orientation and diffusion-limited effects.

A law for the growth of the ice phase can be analytically obtained from Kelvin and Langmuir-Knudsen equations. In this law, the local volume fraction variation is proportional to the difference between average and local mean curvatures. A simple iterative model inspired by the work of J. W. Bullard [1] was implemented in three dimensions and applied on real tomographic images. First, the mean curvature map [2] of the binary image is computed from the normal vector field [3]. Then the new surface of the image is obtained by applying the growth law to each point of the surface. Such an approach allows model solution by increments of matter (image voxels) instead of time, reducing the required number of time-consuming curvature evaluations.

First results will be presented on geometrical shapes and subsamples (200^3 voxel) of 3D images of natural snow obtained at the ESRF by X-ray microtomography [4, 5]. An experiment of isothermal metamorphism in cold room at -2°C followed by tomography at the ESRF was held this spring. The evolution of curvature distributions will be compared between natural and simulated metamorphisms.

References [1] - J. W. Bullard, *J. Appl. Phys.* vol 81(1), 159-68 (1997) [2] - J.B. Brzoska et. al., *Eur. Phys. J. AP.* vol 7, 45-57 (1999) [3] - F. Flin et. al., *Image Anal. Stereol.* vol 20, 187-191 (2001) [4] - J.B. Brzoska et. al., *ESRF Newsletter* vol 32, 22-23 (1999) [5] - C. Coléou et. al., *Ann. Glaciol.* vol 32, 75-81 (2001)

C11B-0995 0830h POSTER

Characterization of the Microstructure of Snow with TDR

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Snow microstructure is a significant element in the description of snow physical properties. However, microstructure characterization remains a complex and challenging task. The dielectric permittivity is an electromagnetic parameter of snow that is determined by composition and structure. Permittivity therefore, appears as a promising basis for an objective and quantitative characterization of snow microstructure. Many dielectric measurement instruments that are appropriate for field operation and telemonitoring have been designed. Among them, the time-domain reflectometry (TDR) technique is well documented following years of application in physical chemistry, earth sciences, engineering,and agriculture, and has showed some success for the characterization of snow. A few of the advantages of TDR over other instruments are that it is highly sensitive, it allows probe geometry optimization, and it is a broadband system yielding a full waveform response.

Experimental evidences have shown that density is the main determinant of snow permittivity, while dielectric models indicate an additionnal textural effect. However, density and microstructure of snow are to some extent coupled parameters. The objective of this study was to evaluate the relation between TDR response and structural parameters of snow. A database was established from over 35 measurements obtained in natural seasonal snowpack at 5 different locations. Pointers describing the snows complex permittivity were extracted from the time-domain TDR signal while a quantitative analysis of snow microstructure was performed from image analysis of snow thin sections and photographs of individual ice grains. Temperature, density, and chemical profiles of the snow samples were also obtained in the field in addition to descriptive observations on snowpack layering. Meteorological records and occasionnal visits over the season to the various locations yielded a dynamic picture of the snow cover corresponding to each measurements. Results show that different ice grain type exhibit different trends on the TDR response. Moreover, it appear possible to establish a classification of snow based on TDR-measured permittivity, where new snow, rounded grains, refrozen snow and metamorphic forms could be discriminated. Under certain circumstances, solid faceted grains and depth hoar grains can also be differentiated.

C11B-0996 0830h POSTER

Modeling the interface between two layers of snow using finite elements

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Although dry slab avalanches in maritime climates can occur due to failure within a layer, avalanches in more continental climates are often caused by a weak bond between layers, usually as a result of the presence of surface and/or depth hoar. This can make modeling such a situation complex, as the quantitative material properties of the strength between two layers are difficult to measure and poorly understood. In addition, it is well known that the strength of snow shows a large degree of spatial variability. Measurements indicate local areas of the snowpack can have a strength which is less than the overburden stress, while the slope remains intact. The stress due the weight of snow above these areas is redistributed to areas of greater strength, a phenomenon which has been termed "bridging". Interface elements for use in finite element analysis have been developed in structural mechanics, which simulate the interface between two different materials (i.e. layers) and allow modeling of discontinuities within in a continuous system, as well as allowing the traditional elements within the model to slip relative to one another. The interface elements exhibit non-linear strain softening behavior after failure is initiated. Preliminary finite element modeling with these interface elements in the context of snow slope stability indicate that they may provide a useful tool for modeling the transfer of stress from weak to strong areas within the snowpack, as well as fracture propigation of dry slab avalanches.

C11B-0997 0830h INVITED POSTER

Microstructural Studies on Bonds and Crystal Growth in a Snowpack

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The role of microstructure in a snowpack influences virtually all of its thermo-mechanical properties. Density, grain size and importantly the structure of the bonds between grains have a very significant influence. We have focused on the microstructure of snow in a number of studies. Among these, the restructuring of a processed snowpack subjected to a persistent temperature gradient resulted in a microstructure, which metamorphosed from an essentially isotropic configuration into what appears to be transversely isotropic. Considering the geometric relationship of the bond to grain to be the significant microstructural consideration, a fabric tensor for snow has recently been developed and demonstrated by application to the evolving microstructure of the processed snow. Although the specific form of the tensor is not unique, it demonstrates promise for using a fabric tensor as a means to quantify the microstructural configuration of a snow pack.

Using a scanning electron microscope (SEM) to examine the bonds between grains of well-sintered snow, a raised feature that encircled the contact between grains, which we termed a grain boundary ridge, was revealed. The ridge has implications to grain boundary diffusion as a sintering mechanism and may be influenced by contamination concentrated at the grain boundary. Focusing the SEM on the attachment or bond area of very well developed depth hoar crystals revealed a complex microstructure, (of much smaller scale than the crystal itself) which merge into the large striated crystal. The many vacancies and sharp corners in this region should lead to stress concentrations, however, the mechanism of formation and a definitive notion on the role of these microstructural features on strength, beyond mere speculation, is unknown. In another study relevant to depth hoar crystal development, a substrate of large crystals of known crystallographic orientation where placed in a supersaturated vapor environment. The numerous hopper crystals that developed adopted the same crystal orientation as the substrate. Crystal habit is a function of the environment under which it is grown, based predominantly on temperature and supersaturation. This led to the hypothesis of a dominant grain growth theory whereby nucleation onto existing crystals optimally oriented for given conditions would dominate resulting in crystallographically oriented regions within a snowpack.

C12A MCC: Hall C Monday 1330h

Glaciers and Ice Sheets IV Posters

(joint with A, H, GC, PP)

Presiding: **S Marshall,** University of Calgary**; H A Fricker,** Scripps Institution of Oceanography

C12A-0998 1330h POSTER

Spatial Accumulation-Rate Pattern Inferred from Radar Internal Layers and Point Measurements of Velocity and Accumulation near Taylor Mouth, Victoria Land

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Internal layers in ice sheets, as measured by ice-penetrating radar, are most likely isochrones. The depth to a shallow internal layer is proportional to the local accumulation rate. However, low-frequency radars often do not record very shallow layers. High-frequency radars (GPR) record shallow layers, but cannot detect the deeper layers that reflect longer-term patterns of climate. Older, deeper layers are also influenced to an increasing degree by accumulated strain due to ice flow, and by the upstream accumulation rate. For this Geophysical Inverse Problem, our Forward Model is a steady-state ice-flow model with measured ice-sheet surface topography, ice thickness, and flowband width, which tracks particles to create modelled internal layers. Ice motion is driven by the input flux into the upper end of the flowband, and by the accumulation pattern along the flowband. To solve the Inverse Problem, our observations comprise depth of an internal layer, and point measurements of accumulation rate and surface velocity. Associated uncertainties are also required. We use Least-Squares or Singular-Value Decomposition to solve for model parameters (input ice flux, piece-wise linear accumulation-rate profile, and layer age) that minimize the mismatch between the data and the model estimates of the data. If the layer age and its uncertainty are known independently, they can also be used. Variable weights can be assigned to each type of data. The data-resolution matrix shows that, for shallow layers, we can resolve high-wavenumber variations in accumulation rate. For deeper layers, we resolve spatial averages of accumulation rates.

We apply the model to a flowband at Taylor Mouth between Taylor Dome and Taylor Glacier. The model finds more variation in the inferred accumulation-rate profile than in the depth-profile of an internal layer. The new accumulation-rate profile produces an improved chronology for an ice core collected along the flowline.

C12A-0999 1330h POSTER

Investigation of the Glacial History of the Siple Coast Using Radar-Detected Internal Layers and the Ice Core from Siple Dome

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The spatial patterns of post-glacial thinning on the West Antarctic Ice Sheet have evidently been complex; for example, Roosevelt Island has thinned more than 300m in the past 4000 years (Conway et al., Science 286, 1999), while 300 km to the south at Siple Dome, there has been little or no thinning (Nereson and Raymond, J. Glac. 47, 2001; J. White, pers. comm., 2002). Understanding past patterns of thinning and recession of the ice sheet is a crucial step toward understanding future possible changes.

Radio-echo sounding of ice reveals internal reflecting layers, most of which are thought to result from the deposition of volcanic fallout on past ice sheet surfaces, and which hence represent isochrones. The age-depth relationship form the Siple Dome ice core (Taylor et al., JGR in review, 2002) allows dating of radar layers that are continuous for more than 100 km across the Dome. However, extending the timescale across the rest of the Siple Coast is problematic because the ice streams surrounding Siple Dome have disrupted the continuity of internal layers. Here we present preliminary results on the development of methods to extrapolate spatially the age-depth relationship from Siple Dome, using core data and data from the University of Washington monopulse radar, and beginning in particular with Ridge BC. In brief, these methods are:

1) Deconvolution of (an estimate of) the radar transmit waveform from radar echograms, so as to distill out the electromagnetic response of ice that depends only on essential, rather than changeable, characteristics of the radar.

2) Correspondence of radar layers with ice core measurements on Siple Dome, which shows fairly isolated radar layers linked to electrical conductivity (ECM) and volcanic sulfate features at 150, 190, 340, and 480 meters depth. An unusually large and thick ECM event at 215m depth marks the onset of a very distinctive radar layer that can be traced entirely across Siple Dome. 3) Identification, on the basis of initial accumulation and flow modeling as well as radar layer location and characteristics, of the Siple Dome distinctive layer with a similarly distinctive layer at slightly shallower depth on Ridge BC.

This process illustrates our developing method of using ice flow and accumulation modeling to constrain possible correspondences of isolated or otherwise distinctive radar layers, and thus to transfer the Siple Dome age-depth relationship to adjacent ridges on the Siple Coast.

C12A-1000 1330h POSTER

Radar Response Modeling of Airborne Ice Sounding Radar Data from Jakobshavn, Greenland

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The output ice mass from the polar ice sheets is influenced in part by the output flux from ice streams and fast-flowing outlet glaciers. For many regions, the depth of the outlet glaciers is a major unknown. As part of the NASA Program in Arctic Regional Climate Assessment (PARCA), radar ice sounder data are collected over many outlet glaciers using the University of Kansas airborne system.

Radar responses for the ice sheet surface and subsurface were generated for various conditions by modeling PARCA radar data from the area around the fast-moving outlet glacier located at Jakobshavn, Greenland. To account for ice surface and subsurface roughness, scattering behavior is generated from classical electromagnetic scattering models. For this study, subsurface-to-surface clutter ratios (SCR) are estimated over radar frequency, ice temperature and surface roughness (i.e. smooth or heavily crevassed).

The University of Missouri Research Board funded this study through grant #URB-01-027.

C12A-1001 1330h POSTER

A High-resolution Digital ice Thickness map of Jakobshaven Isbrae, Greenland

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Ice sheet thickness measurements play a critical role in assessing net ice sheet mass balance and glacier flow characteristics. The downslope gravitational driving stress at the bed, for instance, is directly proportional to the product of the ice thickness and the surface slope. Numerical models that simulate glacier dynamics require ice thickness to be well characterized over the model domain.

Along the margin of Greenland, outlet glaciers play a major role in ice discharge, accounting for about half of the total mass loss from the ice sheet. Jakobshaven Isbrae (69.2 degrees North, 49.9 degrees West) is located on the west coast of Greenland, and is among the most active outlet glaciers in the world in terms of ice discharge flux. An airborne coherent radio echo sounder operating at a center frequency of 150-MHz has been used to collected a large number of geo-referenced ice thickness data over the Jakobshaven Isbrae region during the past decade as part of NASA's Program for Arctic Regional Climate Assessment (PARCA). The radar system uses pulse compression and coherent processing, which gives it the capability to measure ice thickness of deep outlet glacier channels. The uncertainty of the radar ice thickness measurements are plus or minus 10 m.

We have combined all the valid ice thickness measurements over the Jakobshaven Isbrae region collected between 1993 and 2001 to produce a high-resolution digital ice thickness map using the ArcGIS System. The individual ice thickness measurements were made on 20 individual days and total 60,669 measurements. Each ice thickness measurement has been geolocated using differential GPS, and represents an average ice thickness over a 130 m segment of the flight path. We will provide a visual representation of our digital ice thickness map of the Jakobshaven Isbrae region, and will show validation results using independent measurements of ice thickness within the domain, such as borehole measurements.

C12A-1002 1330h POSTER

Surge Initiation and Termination Dynamics of Sortebrae, East Greenland

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Glacial surge mechanisms are poorly understood, in part due to a lack of sufficiently extensive and timely observations of ice flow. The manner in which a surge initiates and propagates, the flow characteristics during the surge, and the mode and timing of termination all provide evidence of the nature of the surge trigger, and the mechanism by which fast flow occurs. The collection of such data is, however, hampered by the unpredictability of surge events, the remote location of most surge-type glaciers, the impracticality of working on a heavily crevassed and rapidly deforming surface, and the large spatial and temporal scale of the measurements required.

Synthetic Aperture Radar (SAR) intensity tracking is a simple, robust technique employing automated image cross-correlation to determine two-dimensional surface displacements. This technique allows measurement of velocity even through cloud cover or during the polar night. In this study, the tracking technique was optimised to give relatively high-resolution, extensive measurements of flow through surge initiation, full surge and termination, at speeds which at times exceeded 20 md-1 and over intervals as long as 105 days, for the 65 km long tidewater-terminating glacier Sortebrae in East Greenland. These measurements could not have been made using SAR interferometry or optical image tracking.

The surge of Sortebrae began in late 1992 in the lower glacier, which is grounded below sea level. The zone of accelerated flow propagated up-glacier, confined initially within the central of three flow units, as a front with sharp lateral boundaries along medial moraines. On reaching a tributary confluence, upglacier propagation occurred rapidly in a diffuse manner, incorporating the major upper-glacier tributaries into the surge through the spring of 1993. Termination occurred very rapidly between May and July 1995, and propagated downglacier as a widespread deceleration from between 10 and 22 m per day to 0 to 6 m per day over much of the glacier. A small upper tributary persisted in surging through to the following spring.

C12A-1003 1330h POSTER

De-striping of MODIS Optical Bands for Ice Sheet Mapping and Topography

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Over the past 20 years, optical band data from the Advanced Very High Resolution Radiometer (AVHRR) sensor with a spatial resolution of 1100 meters and a radiometric resolution of 10 bits (1 part in 1024) have been used to map both surface features and topography in great detail over large regions of the earth's ice sheets. The Moderate Resolution Imaging Spectroradiometer (MODIS) instrument flying on the Terra and Aqua satellites has even greater potential for these applications, due to its improved spatial and radiometric resolution. Band 1 (620-670 nm = red) and band 2 (841-876 nm = near infrared) each have a spatial resolution of 250 meters per pixel and a radiometric resolution of 12 bits (1 part in 4096). Based on the success with AVHRR-based photoclinometry, MODIS should be capable of mapping ice sheet surface slopes as low as 0.0002 vs. about 0.0007 for AVHRR.

However, Terra MODIS Level 1b 250 meter data (MOD02QKM data) have known inter-detector variations as large as 1 per cent, leading to distinct horizontal striping in contrast-enhanced ice sheet images. This primary striping pattern appears to be due to poor calibration among the 40 detectors that constitute a single scan of MOD02QKM data. A secondary change-in-brightness pattern appears to alternate between successive 40-line scans that is probably due to mirror side effects in the double-sided MODIS scan mirror. And finally, band 1 and particularly band 2 images also show a pronounced change in brightness in every fourth pixel along each line of data for detectors 29 and 30. These three artifacts limit the usefulness of MODIS imagery over ice sheet surfaces since they constitute changes in brightness that are as large or larger than the subtle shading effects that delineate low-slope surface features such as flow lines.

Although the design requirements for signal-to-noise ratios (SNRs) for bands 1 and 2 are stated to be only 128 and 201, respectively, the fact that the observed artifacts have regular patterns allows for their possible removal and the production of images having effective SNRs better than 1000. We describe here a series of empirical techniques for dampening the observed artifacts in MOD02QKM data that have proved useful in producing high quality maps and improved Digital Elevation Models (DEMs) over large regions of Antarctic ice sheets and ice shelves.

C12A-1004 1330h POSTER

Optimal Estimation of Ice-Sheet Mass Balance: Application to Berkner Island, Antarctica.

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Changes in ice-sheet mass are presently monitored either by elevation survey or by estimating the separate components of the mass-budget. Here we present

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a combined approach. We seek maximum-likelihood estimates of the three dominant terms in the continuity equation (1) the rate of change of surface elevation, (2) the rate of snow accumulation, and (3) the local divergence of the ice flux. This approach makes use of all relevant, available measurements. The weighting of these measurements is derived using constraints imposed by the physics of ice sheet flow, together with the known covariance of measurement errors. We take full account of statistical correlations between the three quantities introduced when snow accumulation varies randomly in space and time. In this case we enforce realistic covariance among the three terms using a linearised model of ice-sheet flow. We test the approach by applying the algorithm to synthetically generated measurements, which we produce using a forward model of ice sheet flow, with randomly generated noise added to simulate measurement errors of realistic magnitude. The spatial and temporal sampling of the synthetic fields is chosen to represent plausible measurement locations and times. Having demonstrated that the algorithm performs well in these simulations, we apply the method to real measurements from Berkner Island, West Antarctica, to derive a new estimate of the state of balance of this region.

C12A-1005 1330h POSTER

Application of Control Method on a West Antarctic Glacier

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We use surface velocity inferred with Interferometric synthetic-aperture radar and a control method to estimate unknown basal characteristics of a fast-moving glacier in West Antarctica, Pine Island Glacier.

Previous modelling experiments on Pine Island Glacier have shown that using a coupled ice-stream/ice-shelf flow model in a forward approach (trial and error method) we were able to reproduce fairly well the surface velocity. Some discrepancies remained, however, that are partly due to uncertainties in the thickness map and incertainty in our chosen basal stress distribution (because of the non-unicity of the solution).

The control method allow us to take the basal stress (or basal friction, since they are related through the velocity), as an unknown parameter. Results given by the control method should provide better reliable inputs for further modelling experiments. We investigate the results' sensitivity to the initial value of the basal stress. The inferred ratio basal drag/driving stress seems to be always low upstream, 60 to 80 km upstream of the grounding line, as if the ice stream was behaving like an ice shelf, and also reveals the presence of a snake shape channel of low ratio basal drag/driving stress, surrounded by a higher ratio, in the main flow of increasing velocity, from 20 to 40 km upstream of the grounding line.

C12A-1006 1330h POSTER

Studying the effects of strain heating on glacial flow within outlet glaciers from the Heimefrontfjella Range, D.M.L., Antarctica.

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A one-dimensional numerical thermodynamic model is used to study the effects of strain heating on temperature profiles along the flowline of two outlet glaciers in Dronning Maud Land, Antarctica. Measurements of ice surface velocities on the glaciers show higher speeds (and lower ice viscosity) than surface speeds calculated using Glens flow law. These calculations are based on ice temperature distributions excluding strain heating in the general heat equation. The incorporation of strain heating in the general heat equation produces higher ice temperatures, and calculated ice surface speeds that match the measured values. It is found that relatively short scale temporal and spatial steps in basal topography are enough to drive the ice flow into a positive feedback loop as long as the bedrock step produces a stress that overcomes the advection of cool ice from the surface. In this case, where surface temperatures are 25 degrees C stresses of 0.4 MPa are enough to drive the base of the ice to the melting point within 100 years.

C12A-1007 1330h POSTER

Modeling Subglacial Permafrost Evolution

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Permanently frozen ground was present both beneath and peripheral to the Quaternary ice sheets. In areas where the ice sheet grew or advanced over permafrost, the ice sheet insulated the ground, leading to subglacial permafrost degradation. This has created distinct signatures of ice sheet occupation in the Canadian north and in Alaska during the last glacial period, with greatly diminished permafrost thickness in regions that were ice covered for an extended period. In contrast, areas peripheral to the ice sheet, including the Midwest United States, were cooled by the glacial climate conditions and the regional cooling influence of the ice sheet, leading to permafrost growth.

We have developed a sub- and proglacial diffusion based permafrost model that utilizes a logarithmic grid transformation to more efficiently track the changing depth of permafrost with time. This model is coupled with the ice sheet thermodynamic model of Marshall and Clarke [1997a] to explore the geologic signatures of the last glacial cycle in North America. This offers the potential for new constraints on modeled ice sheet history. Preliminary model runs show that the overlying ice sheet has a significant effect on the underlying and peripheral permafrost degradation and formation.

Subglacial permafrost is also important because its evolution influences the basal temperature of the ice sheet, critical for evolution of subglacial hydrology and fast flow instabilities (e.g. ice streams). We present results of permafrost conditions under the last glacial maximum ice sheet and the effect of permafrost on basal temperature evolution through the last glacial cycle in North America.

Marshall, S. J. and G. K. C. Clarke, 1997a. J. Geophys. Res., 102 (B9), 20,599-20,614.

C12A-1008 1330h POSTER

Thickness Evolution of the Scandinavian Ice Sheet in Western Norway From the Last Glacial Maximum to the Lateglacial: A Model Study

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Whereas the morphological and sedimentary evidence provide good constraints on the maximum and deglaciation extents of the Scandinavian Ice Sheet, its thickness and surface profile are more difficult to establish and have long been disputed due to divergent geologic evidence, especially in the mountainous areas of western Norway. It is essential to be able to reconstruct these parameters in addition to ice extent, because the dimensions and volume of the ice sheet strongly influenced global sea level and ocean and atmospheric circulation.

We use a two-dimensional, time-dependent, thermomechanically coupled flowband ice model along a transect running at ca. 62°N from the present glacier of Jostedalsbreen to the west, through the Nordfjord and onto the shelf, in order to investigate the thickness evolution of the Scandinavian Ice Sheet in this area. The model is mainly driven by temperature and precipitation. A paleoclimate record from Krkenes, located directly at the flowline, yields climate information for the time of 13800 to 9200 years BP. Estimates of LGM climate conditions in the area are taken from various GCM and regional climate model studies. The GRIP d18O record has been adapted to the local data in order to provide us with a continuous temperature record necessary as input for time-transient model runs. Known ice extents through time are used for model validation.

Last Glacial Maximum ice extent in the model experiments was reached at ca. 28 ka BP and lasted until ca. 23.5 ka BP, peaking at 24 ka BP. Ice surface elevation was at its maximum early during this timespan. It reached ca. 1700-1750 m and then stabilized between 1650 and 1700 m at the eastern end of the transect. These results are in good agreement with thickness values derived from cosmogenic dating in a neighboring area (E. Brook and H. Linge, pers. comm.). At 21 ka BP, ice had already retreated by ca. 50 km from its maximum position, and the ice surface elevation at the eastern end of the flowline had declined to 1500-1550 m. Model values for the Younger Dryas ice thickness in the inner Nordfjord correspond well with a trimline identified at ca. 1100 m in the area.

C12A-1009 1330h POSTER

Persistent Heterogeneity in Bedrock Erosion Rates Beneath the Laurentide Ice Sheet

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Much of the area formerly covered by the Laurentide ice sheet (LIS) is a landscape shaped by glacial erosion. Landforms found in this area are potentially bedforms in equilibrium with the ice sheet, or relict landforms inherited from preglacial topography. Attainment of steady-state equilibrium between the ice sheet and landscape implies higher total erosion and/or longer-term duration of subglacial erosion relative to a non-equilibrium landscape. Steady-state equilibrium is thus potentially characterized by spatially uniform erosion rates irrespective of bedrock composition during the final stages of glaciation. The record of erosion preserved in Late Wisconsinan tills over an area with two contrasting bed lithologies in the central portion of the former LIS indicates the presence of non-equilibrium landforms, implying limited cumulative bedrock erosion during Pleistocene glaciation.

Bedrock east of Lake Nipigon, Ontario consists of Archean greenstones, intruded by a west-dipping Proterozoic diabase sill. Today, the diabase forms a scarp with 50 m of relief over the surrounding greenstone. The last phase of Wisconsinan glaciation advanced westward over the area to the 9.5 ka bp Nipigon moraine. Tills formed during this advance are coarse-textured, derived predominantly from local bedrock, and occur as a thin mantle over bedrock (1m thick). Diabase forms a distinctive indicator dispersal train. Diabase concentrations in tills overlying the diabase outcrop, and in downice tills overlying greenstone indicate erosion and entrainment rates (eroded and entrained mass per unit bed area per unit flowline length) are 10^2 higher over the greenstone. Given basal velocities of 10s of m/a during till formation, the indicator dispersal train formed over a few hundred years.

From these data, a number of insights into the nature of erosion of hard (crystalline) bedrock by the LIS are evident: Erosion occurred at high rates over short periods of time, suggesting significant bedrock erosion on an ice sheet scale was spatially and temporally restricted. Erosion rates were about 10^2 higher over the greenstone than the diabase, indicating the persistence of significant bedrock heterogeneity with respect to the erosive power of the ice sheet throughout the period of active erosion. Finally, theory (Hallet, 1979, 1996) predicts higher erosion rates of the diabase due to enhanced plastic flow over the topographically high diabase sill. However, the inverse correlation of measured erosion rates with bedrock mechanical strength indicates bed mechanical strength was the dominant factor controlling erosion rates, implying that erosion had not proceeded to steady-state equilibrium despite $>>10^4$ a of continuous glaciation.

Contrary to previous studies suggesting that the Canadian Shield was subjected to pervasive and deep erosion by the LIS - 10^2 m or greater - our data suggest that Pleistocene glaciation may have accomplished little beyond removal of a preglacial cover of soft regolith from hard crystalline bedrock.

C12A-1010 1330h POSTER

Numerical modelling investigations of the conditions under the Southern Laurentide ice sheet

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The southern margin of the Laurentide ice sheet (LIS) is dominated by the presence of relatively thin and sensitive reacting ice lobes. Extent and dynamics is highly influenced among other factors by subglacial conditions, permafrost interaction, and the existence of the Great Lakes.

Experiments with two-dimensional flow-line models applied on individual lobes showed that sensible tuning is needed. The three-dimensional thermomechanical UBC ice sheet model is now being used to investigate the spatial distribution of subglacial conditions and interacting lobe dynamics. The model contains thickness evolution, ice flow, temperature evolution, isostasy, and basal processes including the thermal regime of the bed. The time dependent evolution of the whole LIS is calculated for the last glaciation cycle with primary attention on correct reconstruction of the southern margin.

The sensitivity of subglacial process assumptions was examined and compared with major results from the flow-line modelling. The transient physical conditions are being analysed with the aim of better understanding the reasons for the distribution of landforms produced by the southern LIS.

URL: http://www.geology.wisc.edu/~slip/

C12A-1011 1330h POSTER

Radiocarbon Dating of Overridden Trees, Glacier Bay Alaska: Insights Into Contemporary and Intraglacial Processes

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Determining glacial response to global climate change is a critical component to predicting future atmospheric and oceanic changes. Evidence of past glacial responses to climate change is often destroyed as glaciers respond to relatively small, but sometimes rapid climatic changes. In Glacier Bay, Alaska, we are analyzing glacial history and intraglacial climate during the Holocene while linking these data to the sedimentary record as dated by overridden in-situ stumps and buried logs. We have precisely located samples of 100 interstadial stumps that were presumably 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. Using conventional radiocarbon dating by Accelerated Mass Spectrometry (AMS), we determined the calibrated calendar ages, then analyzed the radiocarbon dates geo-spatially and temporally to provide an estimate of ice-marginal positions through the Holocene. The precise locations of the in-growth stumps (assuming this age represents the time of tree death) provide a first order estimate of tidewater glacier advance rates for periods of glacier activity. Past observations of modern tidewater glaciers suggest that these glaciers advance quite slowly (single meters per year) compared to rapid and sometimes catastrophic glacial retreats (tidewater glaciers in Glacier Bay have retreated 90km in 300 years, or 300 m/yr). By contrast, our calculations indicate that the advance of ice termini were highly variable, with some glacial advances of tens or possibly hundreds of meters per year. In addition, our preliminary data suggest that ice advanced asynchronously into Glacier Bay during at least four different periods. This leads us to speculate that erosion rates also varied within and between each glacial period and that such variations may be reflected in the marine record.

C12A-1012 1330h POSTER

Climatic implications of modern and paleo ELA's in the central Nepal Himalaya

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Orographic precipitation gradients across the Himalaya affect the altitudinal distribution of glaciers and indicate that these gradients underwent significant changes during the last local glacial maximum. Although many Himalayan glaciers are nurtured by avalanches from large headwalls, small glaciers permit reconstruction of both modern and past glacial snowlines. We focus on the Marsyandi River catchment in central Nepal, where we have established a meteorological network. In operation since 1999, these stations provide a direct measure of modern precipitation and temperature. The change in equilibrium line altitudes (ELAs) of this regions small glaciers is primarily influenced by summer precipitation. Weather stations above 3000 m record a pronounced, orographically controlled gradient in summer precipitation, ranging from $>$4300 mm on the southern, monsoon-side to $<$400 mm in the northern rainshadow, over a distance of 40 km. In response to the decreasing input of precipitation, the modern ELAs rise toward the north from 5000 m to 6000 m, assuming an ablation area ratio (AAR) of 0.65. Winter precipitation cannot be the cause of the ELA gradient, because it actually increases slightly towards the rainshadow side. The glaciers depend on summer snow for their accumulation, so they only accumulate at levels which are, at least occasionally, above the summer freeze level. Weather station records place the average June-September freeze level at $\sim$5400 m across this region and the headwalls of the lowest glaciers are found at about this level. During the last local glacial maximum ELAs were depressed by 1240 $\pm$ 280 m on the monsoon side, but only 780 $\pm$ 180 m on the dry northern side. The greater ELA depression to the south implies a complex climatic change involving a cooling on the order of 6° C and an increase in the effectiveness of the Himalayan Range as a barrier to moisture.

C12A-1013 1330h POSTER

Wintertime High Altitude Surface Energy Balance of a Bolivian Glacier, Illimani, 6340 m Above sea Level (a.s.l.)

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The objective of this study is to evaluate the surface energy balance (SEB) of a cold, high-altitude tropical glacier, Illimani (16°39 S ; 67°47 W, 6340 m above sea level (a.s.l.)), where a 137 meter ice core was drilled down to the bedrock in June 1999. During the dry austral winter, tropical glaciers are known to experience strong sublimation which may be responsible for snow composition changes through post-depositional processes. In order to help toward the interpretation of this climatic archive, SEB experiments were carried out in 1999, 2001 and 2002, during the dry season (mostly clear and cold atmosphere, strong westerly winds). The daily net all-wave radiation is usually negative during this austral dry winter because of the highly reflective snow surface and of reduced incoming long-wave radiation due to a low cloudiness compared to outgoing long-wave radiation. The turbulent heat fluxes were evaluated using the bulk aerodynamic approach, including stability correction. The roughness parameters are deduced from direct sublimation measurements and serve as calibration parameters. The sensible heat flux strongly heats the surface at night but changes to negative values during daytime unstable conditions (between 10:00 and 16:00 LT). The latent heat flux is always negative which means that the surface loses mass through sublimation, particularly in the daytime (sublimation rates are -1.2 mm w.e. d-1, -0.7 mm w.e. d-1 and 0.8 mm w.e. d-1 during the 2001, 2002 and 1999 measuring periods respectively). The winter SEB of this high-altitude cold tropical glacier is comparable to the summer SEB over snow surfaces of the intermediate slopes of Antarctica.

C12A-1014 1330h POSTER

An Annual Cycle of Cloud Base Height Measurements at Summit, Greenland

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Clouds have an enhanced role in governing surface radiation balances in the dry polar atmosphere, yet their frequency, thermodynamic properties and radiative properties are poorly understood over the high plateau of Greenland. This research investigates the seasonal and diurnal variability in cloud base heights over one year at Summit Camp, Greenland [3220 m.a.s.l.] using data from a ceilometer that was installed during the summer 2001 field season. The ceilometer sounds the atmosphere with a laser pulse, monitoring cloud base height every 15 seconds. The cloud base heights from a mid-summer sample period were found to be much lower over Summit Camp than other locations in the Arctic. Over half of cloud base height detections indicated a cloud ceiling height lower than 500 m. More surprisingly, over 90% of cloud base height detections indicated a cloud ceiling height lower than 1700 m. The statistical analysis of the data further indicates the presence of an unexplained bi-modal cloud height distribution that has also been observed over the South Pole, Antarctica. This research also uses the high frequency ceilometer data to assess the frequency of cyclonic activity and the dynamics of frontal systems over the high plateau of Greenland.

C12A-1015 1330h POSTER

Distribution of cryoconite on the surface of a glacier derived from a Landsat TM image

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Cryoconite, biogenic surface dust on the glacial surface, can affect the surface albedo of snow and ice thereby accelerating ablation. Distribution of cryoconite on the surface of an Alaska glacier (Gulkana Glacier in the Alaska Range) has been analyzed using Landsat TM band 2 and 5 ratio. The band ratio was relatively lower in the area near terminus and snow line in the ice area, suggesting higher cryoconite concentration in this area. In situ measurement of cryoconite on the glacier agreed with the cryoconite distribution derived from the band ratio. The biological analysis of the cryoconite collected from the glacier revealed that the cryoconite distributed in the area near the terminus mainly consisted of mineral particles, and that the cryoconite near the snow line, on the contrary, contained large amounts of snow algae and dark-colored organic matter. Results suggest that the albedo reduction by biological activity is significant in the area near snow line on the glacier.

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