We discussed gravity data collected in 1981, 1993 and 1995 and found a favorable comparison between decreasing trends in the gravity data and the increasing trends in more densely sampled observations of changing elevation. However, our analysis of those data also suggested that while the elevation of the ice sheet was increasing, the magnitude of the change in gravity did not support concluding that there was a comparable increase in mass. This year we report on the analysis of an additional set of gravity and surface elevation measurements collected at the same locations. During June 2003, we measured surface gravity and geodetic positions at six locations separated by about 20 km at a site located on the South-central Greenland Ice Sheet. We used two gravimeters and each was tied to the International Gravity Station Network before and after each set of field observations. A GPS unit operated at each field site and a base station unit recorded data for differential post-processing of the GPS data. The same measurement sites were occupied in 1981 and all were part of a hexagonal network of geodetic and glaciological measurements established by The Ohio State University in 1980. Additional gravity observations were acquired at three of the sites in 1993 and 1995. Gravity data were collected in conjunction with Doppler satellite measurements of position and elevation in 1981 and global positioning system measurements subsequently. The use of satellite navigation techniques permitted reoccupation of the same sites in each year to within a few 10's of meters or better. After detrending the gravity data, making adjustments for tides and removing the residual effects of local spatial gradients in gravity, we observe an average secular decrease in gravity of about 0.01 milligal/year, but with tenths of milligal variations about the mean trend. The trend is consistent with a nearly linear increase in surface elevation of between 7 to 10 cm/yr (depending on location) as measured by repeated airborne laser altimeter, surface Doppler satellite and GPS elevation measurements. We go on to discuss differences between the residual gravity anomalies after free air correction in terms of local mass changes.

C22A MCC: 3010 Tuesday 1340h

Glaciers and Ice Sheets III *(joint with G, H, OS, PP)*

Presiding: **J Harper,** University of Wyoming**; D G Vaughn,** British Antarctic Survey

C22A-01 1340h INVITED

A Macroscopic Approach to the Response of Glaciers to Climate

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We explore a drastic simplification of the theory of glacier response to small climate changes, a "macroscopic" one in which the distribution of thickness change is replaced by its integrated value, the total volume change. We also deal with change of area near the terminus rather than change in length. In the resulting area-volume relationship there are three parameters: an "area" time scale characterizing the time for area to respond to changes in volume, a thickness scale, and area characterizing the condition of the initial state. The first two characterize the dynamics of the glacier, and are 8 years and 123 meters for South Cascade Glacier as obtained by a fit of cumulative balance and area data from 1977 to 1997. Combining the area-volume relationship with a version of mass continuity expressed in terms of these same variables produces a theory of response of area and volume to climate in which a second time scale appears, the "volume" time scale. It is about 48 m for South Cascade Glacier, and differs from the usual estimate in that it includes the effect of both glacier length and surface elevation. The macroscopic theory characterizes a glacier as a damped oscillator forced by climate. For climate driving frequencies that are not too high, it reproduces the response of South Cascade Glacier predicted by the more complicated traditional theory of Nye; the analogous oscillator is critically damped. The response can be expressed in terms of a single "reaction" time scale, the geometric mean of the area and volume time scales.

C22A-02 1355h

Why Do Ice Streams Have Fast Velocities in Transtion Region of Low Surface Slope?

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It seems generally accepted that when water at the base of a glacier flows mainly through channels (cut into the basal ice) the basal water itself has little influence on the sliding speed of the glacier. On the other hand, sliding speed can be increased if channel water flow is disrupted and water is forced to flow in some kind of broad distributed pattern. (If basal till underlies the ice mass these statements still may hold if flowing basal water is largely confined between ice and till.) In an early paper (Weertman, *Rev. Geophys. Space Phys.* (1972), **10**, 287-333) we analyzed the basal pressure gradient in the direction normal to a channel axis and showed that the presence of the basal shear stress can change the sign of the pressure gradient. The distance from the channel at which the sign reversal first occurs is smaller the larger is the shear stress and the greater is the water pressure within the channel. Water is driven away from a channel in the region of sign reversal. This effect makes it more difficult for water flow to occur primarily through channels and more likely that basal water will cause increased sliding velocity. In this presentation it is pointed out that the same sign reversal effect occurs if a longitudinal (with respect to the channel axis direction) deviatoric stress exits within the basal ice. A pressure gradient sign reversal around water channels arising from a longitudinal deviatoric stress that lead to speed up of sliding could be important in two physical situations. (1) In the transition zone where an ice stream of an ice sheet becomes part of an ice shelf. In this region the basal shear stress is greatly reduced (because the upper ice surface becomes almost horizontal). However, the longitudinal deviatoric stress is increased to almost the level of that of an ice shelf. (2) In a surging glacier. A surging glacier elongates by a significant fraction of its length in a relatively short period of time. As a consequence, a large longitudinal deviatoric stress must exist during a surge. In each of these situations the presence of a large longitudinal deviatoric stress will help disrupt water flow through channels and lead to increased speed of sliding. This mechanism may be the solution to the existing vexing problem: Why do ice streams have fast velocities in the transition region of low surface slope?

C22A-03 1410h

Load Sensitivity of a Surge-Type Glacier

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During the winter season Trapridge Glacier, Yukon, Canada, is subject to puzzling short-lived mechanical events. Such events are characterized by a pronounced increase in icequake activity, abrupt changes in the internal ice strain, and rapid local adjustments of the mechanical interaction between the glacier and its bed. Although the events are closely monitored by a network of englacial and subglacial instruments (including geophones and sensors to measure vertical strain, subglacial water pressure, basal sliding, and sediment strength) it has been unclear, until recently, whether the events are internally or externally triggered. Observations during the winters of 1999–2000 and 2002–2003 indicate that the events are externally triggered and that the forcing mechanism is rapid barometric and/or precipitation loading of the glacier surface. Such sensitivity to small changes in loading is unexpected and suggests that some fraction of the sediment substrate of Trapridge Glacier is near the threshold for mechanical failure. Winter triggering of glacier surges might be explained by fast surface loading.

C22A-04 1425h

Glacier-Scale Variability of the Subglacial Drainage System: Year-Long Records from Boreholes at Sites Along the Length of a Glacier

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Borehole measurements are used to examine the long time/space evolution of the subglacial drainage system. Over the course of two field seasons more than 50 boreholes were drilled to the bed of Bench Glacier, a temperate valley glacier in Alaska. The holes are located at 15 sites that span the 8 km from the headwall to the terminus of the glacier. Each site has at least two boreholes and one site has a grid of 16 boreholes spaced 20 x 20 m. The ice depth at the sites ranges from 70 to 190 m. Each borehole was fitted with instrumentation for measuring borehole water level and water flow velocity, and some boreholes were also fitted with conductivity and turbidity probes. Data have been collected at 15 minute intervals for a period in excess of one year. The boreholes were also imaged by video camera and used for slug/pump experiments, and high time/space resolution measurements of surface velocity were collected in the vicinity of the borehole grid. Observations reveal important details about the evolution of the subglacial drainage system over the length of the glacier, and over the course of the year: 1) the onset of summer diurnal variations in water pressure does not undergo an up-glacier spatial progression as is commonly assumed; 2) the termination of summer diurnal variations in water pressure is simultaneous along the length of the glacier; 3) the accumulation and ablation areas of the glacier have actively changing, but differing pressure fields; 4) short-lived subglacial events impact all sites along the length of the glacier, including those in the accumulation and ablation areas and those above and below an ice fall. These findings have diverse implications for the processes dictating the time/space evolution of the subglacial drainage system and the link between hydrology and glacier sliding.

URL: http://research.gg.uwyo.edu/joelh/benchglacier

C22A-05 1440h

Subglacial Bed Topography and Ice Sheet Surges

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Bed topography at the scale of the ice thickness can lead to multiple flow states for an ice sheet. By analogy with classical hard-bed sliding, ice flow over this type of bed obstacle, which occurs commonly in the form of drumlins and similar bedforms, leads to the generation of drag on the ice, particularly when ice flow is rapid. In this presentation, we investigate the effect of this drag on the bulk dynamics of the overlying ice sheet. A crucial difference with classical sliding is that the upper, free surface of the ice has a significant effect on the sliding process through the formation of a standing wave. The shape of this wave not only depends on bed topography and sliding velocity, but also affects the stress field in the ice and hence the sliding velocity. The consequent nonlinearity in the sliding process leads to the possibility of multiple flow states, that is, of multiple surface wave configurations corresponding to different possible sliding velocities for the same large-scale ice sheet geometry. Using a theoretical model, we demonstrate that such multiple flow states are indeed possible, and that they lead to oscillatory behaviour in the ice sheet which can be interpreted as ice sheet surges.

C22A-06 1455h

Outburst Flooding and Surge Initiation

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Antarctic subglacial lakes are well-known, and published geomorphic evidence from Pine Island Bay and from the Transantarctic Mountains suggests outburst flooding from subglacial lakes at different times in the past. Sedimentary evidence also indicates that abundant meltwater was involved in Heinrich events from Hudson Strait despite cold conditions, suggesting outburst flooding. Trapping of subglacial water is favored by development of a locally reversed ice-air surface slope, and by freeze-on; either may be sufficient singly, and both together should be sufficient. A cycle of ice-shelf grounding, freeze-on and development of slope reversal, thickening, thawing, and outburst flooding explains many observations, and is consistent with new modeling and with a range of observations from ice streams and ice shelves, although the ice-shelf step is not a necessary prerequisite.

C

C22A-07 1510h

Indication of active overthrust faulting along the Holocene-Wisconsin transition in the marginal zone of Jakobshavn Isbræ

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A zone of highly irregular ice motion has been detected within the ice sheet adjacent to Jakobshavn Isbræ, a fast moving ice stream in West Greenland. Two tilt sensors in different boreholes and frozen into the ice show angle variations of up to 0.1° and 0.3° within a 1200 second interval. The amplitude of these flutter oscillations increases towards the transition from Holocene to Wisconsin ice at 682 m depth, 150 m above bedrock. All other tilt sensors above and below show low background noise. A numerical model confirms that the stress configuration is exceptional in the neighborhood of the ice stream. Stress transfer from the ice stream to the margins causes an extra forcing of the basal ice at the drill site. Several possible explanations for the observed flutter oscillations are given, the most likely being dynamic rupture events or stick-slip motion along the Holocene-Wisconsin transition. If true, this would correspond to an active overthrust fault with very high loading rates.

URL: http://gi.alaska.edu/~luthi/

C22B MCC: 3010 Tuesday 1600h

Glacier-Climate Interactions II *(joint with A, H, OS, PP)*

Presiding: **S Marshall,** University of Calgary**; D E Lawson,** Cold Regions Research and Engineering Laboratory

C22B-01 1600h

Alpine Glacier Mass Balance Modelling: Development and Application of an Indexed Temperature and Radiation Model

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A mass balance model utilizing a temperature and radiation indexed approach is presented addressing the need for high temporal and spatial resolution capabilities with moderate demand for input data. This fully distributed model relies on inputs of short wave radiation, temperature, and elevation fields and incorporates an albedo submodel and surface shading algorithms to compute net short wave radiation and a time varying lapse rate for temperature distribution. Model development is described and performance is compared to a fixed DDF positive degree-day model and a temperature and radiation variable DDF positive degree-day model. We show that the described indexed approach is effective at capturing melt on hour-long timescales and has application to mass balance and discharge studies on alpine glaciers.

C22B-02 1615h

The Distributed Application of an Enhanced Temperature-Index Melt Model Including Albedo and Global Radiation

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An enhanced temperature-index (ETI) melt model is presented, in which the classical dependency on temperature is extended by considering global radiation and albedo. An additive form of the temperature index (TI) model is proposed, aiming at clearly separating the two important contributions to melt energy, namely the longwave radiation and turbulent fluxes in one term and the shortwave radiation in the other. The ETI model is a significant improvement over other formulations of the temperature-index method. This was shown by comparing melt rates computed by the temperature index based models with calculations obtained using a physically based energy balance model at five sites on Haut Glacier d'Arolla, Switzerland. Data were provided by five automatic weather stations located along two intersecting transects in 2001. The results show that the ETI model is capable of accounting for about 90% of the surface melt rate variation at all the stations tested. This is due, on one hand, to the fact that including albedo enables the model to capture the major increases in the surface melt rate due to snow metamorphism and the transition from snow to ice. On the other hand, the more physically-based melt process representation of the ETI model reduces the over-sensitivity to temperature fluctuations which is typical of simpler formulations of the TI approach. Once tested at the point scale, where the availability of high quality input data allowed to evaluate the model performance independently from errors introduced by parameterisations of the meteorological input data, the ETI model was applied in a distributed manner over the entire glacier. The paper discusses the distributed application of the ETI model and the differences in model performance from the point to the distributed scale, and highlights the robustness of the model when different extrapolation schemes for the redistribution of the input variables, namely temperature, albedo and global radiation, are used. In particular, a way of accounting for cloud cover in the parametric model used to compute global radiation is presented.

C22B-03 1630h INVITED

Forecasting glacier snout fluctuations in the western italian Alps.

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Glaciers in the western italian Alps show a long-term (centennial) widespread retreat, modulated by fluctuations on decadal time scales, lagging the variability of the regional temperature-precipitaion regime. The lag of maximum correlation is 8 years for temperature and 10 years for precipitation, which is considerably shorter than the response-time estimates based on linearized dynamics. We propose an empirical model aimed at establishing a quantitative relationship between the variability of the terminus positions of a set of selected glaciers in North-Western Italy and the corresponding climatic fluctuations, namely of precipitation rates and mean temperatures. The link is sought in the form of a stochastic lagged linear model. Linearity in glacier fluctuation response is assumed as the simplest working hypothesis. The stochastic component of the model aims at accounting for the unexplained dynamics that is always present in natural systems with a large number of degrees of freedom. As usual, we require the stochastic term to be gaussian and uncorrelated. Surrogate data techniques based on the generation of synthetic datasets are used for robust estimation of the model parameters and hyptesis testing. The linear stochastic model describes about 66% of the variance of the average snout fluctuation and precipitation appears to give the major contribution to the explained variance. Using temperature and precipitations data from a large set of local wheather stations, the average trend for the snout of the glaciers is forecasted for the next.

C22B-04 1650h

Climate Reconstructions Derived From Global Glacier Length Records

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Glaciers have fluctuated in historic times and the length fluctuations of many glaciers are known. These length records provide useful information about past climate. In order to derive a climate signal from numerous glacier length records, a model is needed that takes into account the main characteristics of a glacier, but uses little information about the glacier itself. Therefore, we developed a simple analytical model. It calculates a climate reconstruction described in terms of a reconstruction of the equilibrium line altitude (ELA) or the mass balance. The model takes into account the geometry of the glacier, the length response time and the mass balance-surface height feedback. It was tested on seventeen European glacier length records. The results reveal that the ELA of these glaciers increased on average 54 m between 1920 and 1950. We then derived historic fluctuations in the ELA on the basis of nineteen glacier length records from different parts of the world. The results show that all glaciers of our data set experienced an increase in the ELA between 1900 and 1960. Between 1910 and 1959, the average increase was 33 m. This implies that during the first half of the twentieth century, the climate was warmer or drier than before. The ELAs decreased to lower elevations after around 1960 up to 1980, when most of our ELA reconstructions end. These results can be translated into a global temperature increase of about 0.8 K for the period 1910-1959.

C22B-05 1705h

Spatial Temporal Distribution of Greenland Melt Anomalies

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A new algorithm for identifying melt extent and melt intensity on the Greenland ice sheet has been developed utilizing the am and pm orbital data from the DMSP passive microwave satellites. The new approach is utilized to develop a set of probability surfaces describing the likelihood of any given pixel melting at some point in time during the melt season. The 2002 and 2003 melt anomalies are analyzed in terms of their probability of occurrence given the previous 22 year satellite record. The general synoptic conditions contributing to the melt anomalies are described based on the GC-NET network of automatic weather stations and NCEP/NCAR reanalysis.

C22B-06 1720h INVITED

Present and Past ice Sheet Mass Balance Simulations for Greenland and the Tibetan Plateau

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Net annual mass balance was evaluated for Greenland and the Tibetan Plateau using the meteorological forcings from the NCEP reanalysis and two GCMs (FOAM1.0 and CSM1.4) for modern climate and for different time periods extending back to the beginning of the Holocene (11,000 years ago) for the climate models. The ice sheet budget calculations, using the degree day methodology, were performed on a finer grid than the model output by interpolating monthly precipitation and surface temperature and correcting the latter to account for the GCM's smoothed topography. The computed net mass balance for Greenland in the present day is positive and it ranges between 245 to about 297 mm water equivalent (w.e.)/year for NCEP and CSM1.4 respectively. The past climate simulations show that the Greenland mass balance has become slightly more positive since the beginning of the Holocene. The Tibetan Plateau's present day area average net mass balance is negative for the three datasets (it ranges between -1160 to -1985 mm w.e./year for FOAM1.0 and CSM1.4 respectively), although the balance is positive over small regions of the plateau. The calculated past mass balance shows an increasingly less negative value