to the NSIDC DAAC for archival, and the ECS protocols required to ensure delivery; and c) the services and "value-added" products that the NSIDC DAAC provides to the user community in support of the Aqua (AMSR-E) and ICESat missions.

IP22B-0704 1330h POSTER

Geoscience Laser Altimeter System (GLAS) Data Products from the Ice, Cloud, and land Elevation Satellite (ICESat) Mission

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The Geoscience Laser Altimeter System (GLAS) is the sole instrument being developed to fly on the Ice, Cloud, and land Elevation Satellite (ICESat). The ICESat mission is an integral part of the NASA Earth Science Enterprise (ESE). The ICESat satellite will have a near circular and near polar orbit with an altitude of approximately 600 km and coverage to 86 degrees latitude. The projected launch date for the GLAS instrument on the ICESat satellite is June 1, 2002.

The ICESat mission has two sets of objectives. The primary objectives utilize altimetry to study the cryosphere. These goals are to provide accurate, high resolution elevation measurements of the Greenland and Antarctic ice sheets. Time-series of elevation changes will enable determination of the present-day mass balance of the ice sheets and estimation of present and future contributions of the ice sheets to global sea level rise. These data will also increase our understanding of the way that changes in the ice sheets affect changes in polar climate, such as precipitation, temperature, and cloudiness.

The secondary objectives utilize Light Detection and Ranging [LIDAR] to study the atmosphere, and altimetry to study land and oceans. These goals are to measure cloud heights and the vertical structure of clouds and aerosols in the atmosphere, land topography and vegetation canopy heights, sea ice roughness and thickness, ocean surface elevations, and surface reflectivity.

The ICESat Science Investigator-led Processing System (I-SIPS), at Goddard Space Flight Center (GSFC), will produce level 1A, 1B, 2 and 3 data products. The National Snow and Ice Data Center (NSIDC) will archive level 0 data shortly after ICESat launches, and will archive, distribute, and support all the higher level data products as they become available.

URL: http://nsidc.org

IP22C MC: 125 Tuesday 1330h

Ice: From Molecules to Ice Sheets (A Special Session in Honor of W. Barclay Kamb) III *(joint with NG, H, T, MR, HG)*

Presiding: **C F Raymond,** University of Washington**; H Engelhardt,** California Institute of Technology**; T Pfeffer,** University of Colorado

IP22C-01 1335h INVITED

Climatic Effects in Unstable Glacier Response

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Climate can trigger two different kinds of unstable response in ice masses, the first a change in the flow regime, and the second a rapid growth or decay without significant change in flow. In the first category, a comparison of the twentieth century surge history of Variegated Glacier with mass balance information, some of it obtained by correlation with long term climate data, shows that surges occur when the cumulative balance at a representative point in the accumulation area reaches a critical level. This provides a basis for understanding the surge intervals, which vary from 12 to about 18 years. In the second category, it has been known for many years that glaciers and ice sheets with low surface slope are particularly sensitive to climate because a small climate warming, for example, can increase the equilibrium line elevation enough to cause a large reduction in the accumulation area. This would cause a large ultimate reduction in the size of the ice mass or even its disappearance. Consideration of the effect of the elevation of the terminus on the mass balance rate there suggests, surprisingly, that steep glaciers may exhibit a similar large or unstable response. The effect is a non-linear one and does not show up in the traditional linear theory. It suggests that some (perhaps many) glaciers are so close to instability that their future behavior under present climate conditions is essentially unpredictable with any model.

IP22C-02 1355h INVITED

The Past and Future Dynamics of Columbia Glacier, Alaska

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In 1977-78, Columbia glacier had a length of 66.5 km and an ice speed at the terminus of 2.1 km/yr. In 1999-2000 its length had decreased to 54 km but its speed at the terminus increased to more than 9 km/yr (25 m/day). This large ($\sim$ 1000 km2 area), dendritic, iceberg-calving glacier is undergoing an irreversible retreat due to calving instability, which will open up a new fjord in Alaska in a few decades. The base of the glacier near the terminus is very close to flotation, but a study of the strain-rate field indicates that basal drag is still a significant resistive force. Thinning flux ($\sim$9 km3/yr dominates balance flux ($\sim$1 km3/yr) at the present terminus. Projecting the future retreat scenario for this glacier is difficult; the terminus retreat depends on the difference between the calving flux and the combined thinning+balance fluxes. Several calving relations that have been suggested (water-depth, extension-rate, buoyancy) are used to estimate a future calving-flux scenario. Changes in the future mass balance probably will have little effect on the retreat. Significant thinning has extended upglacier to <28 km from the head. The critical issue is how to estimate changes in glacier sliding rates for a glacier that is close to flotation. A range of values can be suggested based empirically on past history, and from these a retreat scenario proposed.

IP22C-03 1415h INVITED

Hydrology of Temperate Glaciers: Utility of Steady-State Models of Basal Water Flow and Insights From the Study of Hydraulic Transients

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The theoretical foundations of glacier hydrology deal almost exclusively with idealized steady-state flow. Röthlisberger and Shreve, in their seminal papers on water flow through channels surrounded by ice, showed that in the steady state there exists an inverse relationship between water pressure and discharge, and concluded that this would favor development of an arborescent drainage system. Steady-state basal linked cavities, in contrast, should (as shown most clearly by Barclay Kamb) exhibit characteristics of what is known in current parlance as a "distributed" drainage system: a direct relationship between water pressure and discharge, no tendency to develop arborescence, and relatively slow water flow. The two theoretical constructs–steady-state arborescent- and distributed drainage systems–have dominated the interpretation of field data. Yet no temperate glacier is in a steady state hydrologically: meltwater runoff rate commonly varies by a factor of 3 or 4, say, on a diurnal basis, and by orders of magnitude on a seasonal basis. The "success" of a classification scheme grounded in steady-state theory thus seems paradoxical and suggests that some key piece of physics has received short shrift. In our view, the interaction of qualitatively different bits of the basal drainage system–between arborescent- and distributed-like portions–in both time and space should be more thoughtfully regarded. We already know something of the time-dependent interaction: Barclay Kamb showed that a linked-cavity system is unstable to large pressure perturbations and would transform to an arborescent system; an arborescent system in turn is likely to collapse when discharge plummets during the accumulation season. These instabilities probably have a great deal to do with the evolution of the drainage system during the course of the ablation season and with the abrupt release of water from storage. Our own work on the drainage of glacier-dammed lakes casts light on interactions of drainage-system components in space. The picture that emerges is that of a "patchy" basal drainage system, comprising at the height of the ablation season an arborescent channel system poorly linked to a distributed system that covers most of the glacier bed. The patchy drainage system can accommodate substantial variability in discharge and pressure–variability that cannot be accommodated if the drainage system consists wholly of either arborescent channels or linked cavities.

IP22C-04 1435h

A Bed-Deformation Experiment Beneath Engabreen, Norway

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Although deformation of sediment beneath ice masses may contribute to their motion and may sometimes enable fast glacier flow, both the kinematics and mechanics of deformation are controversial. This controversy stems, in part, from subglacial measurements that are difficult to interpret. Measurements have been made either beneath ice margins or remotely through boreholes with interpretive limitations caused by uncertain instrument position and performance, uncertain sediment thickness and bed geometry, and unknown disturbance of the bed and stress state by drilling.

We have used a different approach made possible by the Svartisen Subglacial Laboratory, which enables human access to the bed of Engabreen, Norway, beneath 230 m of temperate ice. A trough (2 m x 1.5 m x 0.4 m deep) was blasted in the rock bed and filled with sediment (75 percent sand and gravel, 20 percent silt, 5 percent clay). Instruments were placed in the sediment to record shear deformation (tiltmeters), dilation and contraction, total normal stress, and pore-water pressure. Pore pressure was manipulated by feeding water to the base of the sediment with a high-pressure pump, operated in a rock tunnel 4 m below the bed surface.

After irregular deformation during closure of ice on the sediment, shear deformation and volume change stopped, and total normal stress became constant at 2.2 MPa. Subsequent pump tests, which lasted several hours, induced pore-water pressures greater than 70 percent of the total normal stress and resulted in shear deformation over most of the sediment thickness with attendant dilation. Ice separated from the sediment when effective normal stress was lowest, arresting shear deformation. Displacement profiles during pump tests were similar to those observed by Boulton and co-workers at Breidamerkurjkull, Iceland, with rates of shear strain increasing upward toward the glacier sole. Such deformation does not require viscous deformation resistance and is expected in a Coulomb material, a model for till advocated by B. Kamb.

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IP22C-05 1450h

Looking at Basal Processes in Glaciers and ice Sheets With Borehole Photography and Video

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Spatial and temporal distribution of ice sliding velocity is determined by processes taking place at or near the ice base. In addition to their importance in ice dynamics, basal and subglacial zones of glaciers and ice sheets are also crucial from the point of view of glacial erosion, transport, and sedimentation. Significant insights into the physics of basal and subglacial processes come from borehole photography and video images. In this talk, I will discuss the scientific importance of photographs and videos collected during two decades of borehole studies by the Caltech glaciological team on Blue Glacier, Variegated Glacier, and Ice Stream C.

IP22C-06 1525h

West Antarctic Ice Stream Dynamics

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Ice stream motion is mostly determined by basal processes, especially the basal heat balance. High geothermal flux favors melting at the base, high water pressure, and sliding. Like surge glaciers, ice streams are cyclic. During the active phase, the catchment areas are being drained, the ice streams are thinning, the overall mass balance is negative; the opposite is true in the dormant phase. The thermal regime of ice streams is continually changing is response to surface and basal boundary conditions, ice flow, and ice thickness. Temperature profiles of the ice streams, and video clips of the basal zone of Ice Stream C are revealing important processes controlling the dynamics of ice streaming.

URL: http://glaciology.caltech.edu

IP22C-07 1540h

ICE BOREHOLE VIDEO OF BASAL DOMAIN OF ICE STREAM C IN THE 2000-2001 FIELD SEASON

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Since acquiring valuable data from interpretation of photographs taken at the glacier beds in the 1960's, it had been the desire of Prof. Kamb and coworkers to acquire video data of the basal environment of West Antarctic ice streams. In the period prior to the 2000-2001 field season while preparations were underway to revisit Ice Stream C, the ideal opportunity arose in the form of a collaboration between the Caltech Glaciology Program and a group of scientists and technologists at the Jet Propulsion Laboratory; these teams found a mutual interest in acquiring in-situ optical data in the deep glacial subsurface. The Caltech-JPL team designed and built the Ice Borehole Camera which was subsequently deployed in three hot-water drilled holes in Ice Stream C. The scientific objectives of the deployments were to develop an understanding of subglacial accretion of ice and debris with emphasis on differences between sticky spots and the (slowly) streaming ice, to directly observe ice-bed interactions including, if possible, the nature of water flow and ice-rock relative motion, and to visually examine other ice sheet properties in-situ. The deployments were successful, and good data were acquired on a number of phenomena. Results will be shown to illustrate surprising debris loads observed to greater depths above the bed than anticipated, an unexpected subglacial "lake" of about 1.4 m depth was entered on the shoulder of the sticky spot, and debris distribution in the ice suggesting variation in subglacial freezing rates consistent with current research in premelting of ice. The design of the Ice Borehole Camera will also be discussed.

IP22C-08 1555h

Why Barclay Kamb Developed an Interest in Tiny Fossils

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With a flurry of publications during the late1980s on till deformation came the realization that the availability and rheology of unfrozen and unconsolidated subglacial sediments may be a critical component of modern West Antarctic ice stream dynamics. The vision and engineering ingenuity of the team of Kamb and Englehardt (with NSF backing, naturally) resulted in the development of borehole methods that provided access to the bed for in situ experiments, and for recovery of subglacial material. The sediments recovered contain marine microfossils (largely diatoms) of mixed ages, including, significantly, rare diatoms known to represent Quaternary marine deposition. The occurrence of Pleistocene-age diatoms beneath the ice sheet demonstrates that the WAIS has a history of episodic disintegration. These observations are important for Pleistocene climate and ice sheet reconstructions, but are somewhat ancillary to Barclay's hypotheses regarding modern ice stream behavior. Diatom fossils in the samples are variable in abundance, preservation, and species content, indicating more sedimentary complexity than simple textural analyses can elucidate. As sedimentary particles with known initial conditions (e.g., size, shape, age, environment of origin)they are powerful tracers of sediment mixing, comminution, and transport. Quantitative analysis of diatoms and diatom fragments in the WAIS till cores has demonstrated that in nearly all cases of an unfrozen bed, well-preserved diatoms are concentrated in the narrow zone directly subjacent to basal ice. Tills more than 5cm beneath contain only rare and poorly preserved diatoms or diatom fragments. These observations (among others) suggest that the till layer beneath the fast-flowing ice streams is largely composed of relict, previously sheared material, and that sediment deformation and fluid flux in these regions is currently restricted to a very narrow zone at the bed. Shearing Holocene Ross Sea diatomaceous sediment in Neal Iverson's ring shear device has allowed the development of objective criteria that may be used to characterize conditions beneath past and present marine ice sheets, thus further our ability to map the position and character of past ice streams. Diatoms are no longer just cute microscopic curiosities. They shed light on some of Barclay Kamb's burning questions.

IP22C-09 1610h

Variation in flow speed on Ice Stream B

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Several groups have measured variations in flow speed on ice stream B. We have compared previous velocity measurements with a map of velocity covering nearly all of Ice Stream B, which was generated using data collected during the first RADARSAT Antarctic Mapping Mission. Our results confirm earlier estimates of deceleration and greatly expand the number of observations, revealing a pattern of slowdown that extends from the upper reaches of Ice Streams A and B to well downstream of the grounding line. Deceleration appears to have been fairly steady at a rate of 5.5 m/yr^2 on the ice plain a sustained over intervals of upto 34 years. If this rate continues, the ice plain will shutdown completely in 70-80 years. We have used a model for the centerline velocity an ice stream [Raymond, 1996] and the plastic bed model [Tulaczyk et al, 2000] to examine the possible causes for decelaration. At UpB, it is difficult to explain the slowdown as the direct result of the thermo-dynamic evolution of a plastic bed. Instead, a reduction in the driving stress caused by decreases in slope as the ice stream thins appears to be a likely cause. On the ice plain, either a reduction in driving stress or a strengthening of a plastic bed due to basal freezeon provides plausible explanation for the deceleration.

IP22C-10 1625h

Possible Abrupt Changes in Ocean Circulation and Climate Due to the Changing Behavior of Ross Ice Streams, West Antarctica

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One of the most important recent results of glaciological research in West Antarctica is the discovery that ice discharge from Ross ice streams may have been decreasing for at least as long as ∼150 years. This decrease may be driven by changes in the ice-stream basal thermal regime (Kamb 2001). The magnitude of the decrease amounted to ∼1 cm less of global sea level rise in the last century than we would have otherwise experienced. Changes in discharge from Ross ice streams may also have important implications for near future stability of the Ross Ice Shelf (RIS), which is nourished by these ice streams. If ice-stream discharge will continue its recent decrease, RIS will thin and may start to retreat or break up. Additional impetus for retreat or break up of the RIS may come from future climatic warming that appears to have helped to destabilize some smaller ice shelves along the Antarctic Penninsula. Break up of RIS alone would expose ∼0.5 mln km^2 of new sea surface area and could have significant implications for exchange of energy and water between the ocean and the atmosphere-cryosphere system in the region. Moreover, brine exclusion during sea-ice formation could turn this newly exposed polar continental shelf into a key source of bottom ocean water. This strengthened Antarctic Bottom Water formation could outcompete the North Atlantic source of Bottom Water and switch the global ocean into a new mode of thermohaline circulation, with global climatic implications (Denton, 2000). At the present time, we begin to quantify the effects of removing West Antarctic ice shelves on global thermohaline circulation using a coupled, global sea-ice-ocean circulation model developed at LANL. Qualitatively, however, there is a strong potential for significant impact of the recent changes in flow rates of the West Antarctic ice streams on regional and global atmospheric and ocean circulation.

IP22C-11 1640h INVITED

Continental Ice Sheets at LGM:Sea Level Constraints Upon Regional Form and Total Volume

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The net volume of grounded continental ice that disappeared from Earth's surface during the most recent glacial-interglacial transition is strongly constrained by observations of post glacial relative sea level history. In order to apply the constraint provided by such data,however,one requires a theory that is able to accurately predict the history of sea level change that should occur at any point in the global ocean from which high quality relative sea level observations may be available. The extended form of the Sea Level Equation that I have developed (see Peltier 1998,Rev. Geopohys.,36,603-689 for a review) is well suited to this task. Analyses recently performed using this extended theory constrain the net eustatic rise from LGM through the Holocene epoch to a value that is very close to the commonly accepted value of approximately 120m and firmly rule out the possibility that the net eustatic rise could have been as high as 135m as recently suggested on the basis of an invalid analysis by Yokoyama et al.(2000,Nature,406,713-716), the results of which have been repeated in Lambeck and Chappell(2001,Science,292,679-686). The constraints upon regional ice sheet form provided by relative sea level data are also important, as they have been taken to imply an aspect ratio for the Laurentide ice sheet that is inconsistent with the rheology usually assumed to govern the flow of a continent scale ice mass.This non-Newtonian rheology is referred to as the "Glen flow law". Recent analysis of the constraints upon the flow law that follow from inferences of LGM ice sheet form will also be discussed.