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

for FOAM towards the present and expansion of the positive mass balance areas, mainly due to decreased snow ablation; in CSM the opposite trend occurs but changes are smaller and less systematic. The result from FOAM shows that the likelihood of ice sheets developing on the Tibetan Plateau may have increased since 11000 years ago, which is consistent some glacial records.

C22B-07 1740h

Possible Asynchronous Glacial Expansion During Climatic Warming in the Holocene, Glacier Bay Region, Alaska

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Glacial expansion is commonly thought to occur during cold climatic periods whereas thinning and recession follow as the climate warms. However, data from Glacier Bay, Alaska, on the location and timing of ice margin positions suggest that ice growth of the terrestrial and tidewater systems continued long after warming began. Radiocarbon dating of trees overridden by glacial advance provide rates and positions of ice margins over the last 9500 years BP. Major periods of ice advance were initiated prior to 9500 yrs BP and continued through at least 6000 yrs BP. Similarly ice returned to the region around 4900 yrs BP and continued to expand apparently without interruption through 3200 yrs BP. Data from more recent periods of ice advance are not as well constrained but appear to suggest ice filled much of the bay, perhaps including parts of the ice mass remaining from the 4.9 K advance, during three separate periods including the Little Ice age. Current investigations are evaluating signals in the tree ring record for causes, including signals developed by external forcings such as El Nino, the Pacific Decadal Oscillation (PDO) and Arctic Oscillation(AO).

C22B-08 1755h

Oases on Snowball Earth: Confluence of Ice Dynamics Modeling and Geological Observations

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Recent model experiments suggest that marine ice dynamics are important in the initiation and development of a snowball Earth. Ice-line advance is facilitated by the transport of latent heat and freshwater associated with Ekman forcing in the zone of westerlies (Lewis et al., 2002 this meeting) and with equatorward glacial flow of thick, multi-annual, marine ice (Goodman and Pierrehumbert, 2002 this meeting). After ice lines meet at the equator (snowball Earth), continued invasion by marine glaciers from higher latitudes maintains tropical marine ice >2.25 times thicker (<450 m) than static ice at thermal dynamic equilibrium (G & P, 2002). The dynamics imply that the tropical ocean will remain ice covered even after rising atmospheric pCO_2 drives tropical sea surface temperatures to the melting point. However, landfast marine ice on low-latitude continental shelves and inland seas that are protected from invasion by marine and terrestrial glaciers will melt away, creating 'oases' on a snowball Earth. Snowball oases should occupy a small fraction (<5%) of the global surface area but they might significantly enhance water vapor transport and accumulation rates of adjacent terrestrial glaciers. Despite acidification by high pCO_2, warming may cause critical oversaturation with respect to calcite or dolomite in snowball oases that are buffered by carbonate-rich bedrock and glacial debris (Fairchild, 1994). As snowball oases are small pools of water in contact with a pCO_2-rich (>0.1 bar) atmosphere, the carbon isotopic composition of any carbonates they precipitate should evolve accordingly. Initially, oasis water may resemble evolved snowball seawater, which will be dominated by hydrothermal activity buffered by dissolution of seafloor carbonate (Higgins and Schrag, G-cubed, 2003). Oasis water should evolve rapidly towards equilibrium with the atmospheric reservoir, whose isotopic composition is set by volcanic outgassing, not by the ocean. Oasis carbonate strata should exhibit a rapid rise in δ^{13}C with time, and may well have values substantially greater than 0 per mil PDB. We believe there are numerous examples of snowball oases in the geologic record associated with the Neoproterozoic Sturtian and Marinoan glaciations. Examples in NE Svalbard, SW Oman, SE California, and central and South Australia are well documented. In all but the first, the lithologic and isotopic evidence has been cited as precluding a snowball Earth altogether. In contrast, we consider that oases are a natural and important part of the snowball Earth cycle. Our concept of snowball oases combines insights from geophysical modeling and geology.

C31A MCC: 3010 Wednesday 0800h

NASA's Ice, Cloud, and Land Elevation Satellite (ICESat) Mission: Scientific and Technological Achievements I *(joint with A, B, G, H, OS)*

Presiding: **H J Zwally,** NASA Goddard Space Flight Center**; B E Schutz,** Center for Space Research, University of Texas at Austin**; C A Shuman,** NASA Goddard Space Flight Center

C31A-01 0800h INVITED

NASA's Ice Cloud and Land Elevation Satellite (ICESat): Advancing Our Understanding of Ice and the Earth System

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As part of NASA's mission to "Understand and protect our home planet" the Earth Science Enterprise's cryospheric sciences program has as its primary focus understanding what changes are occurring in the mass of the Earth's ice cover, and the relationships between the Earth's dynamic ice and the rest of the Earth System. Recent observations using a comprehensive suite of both spaceborne and airborne instruments developed within NASA's Earth Science Enterprise and through our interagency and international partnerships have revealed the very complex and spatially variable behavior of the Earth's great ice sheets, with some very dynamic areas losing mass rapidly while others regions show positive mass balance. Recognizing that a tremendous amount of information about an ice sheet's behavior is manifest in its shape and how that shape changes with time, NASA's ICESat mission is designed to precisely measure ice elevations and elevation changes to determine the ice sheets' contributions to sea level and understand the mechanisms that govern those contributions. With a 94-degree inclination and pulsing at a rate of 40 times per second, ICESat provides measurements all over the world at 170-meter intervals along-track, with centimeter-scale accuracy over the ice and meter-scale accuracy on land. As such, detailed topographic measurements that were previously unachievable can be obtained the world over. While other remote sensing instrumentation provides critical spatial information, ICESat represents a groundbreaking mission that has as its focus measurements in the critical vertical dimension utilizing tremendous advances in laser ranging capabilities, orbit determination, and pointing accuracy. The ICESat mission will provide unprecedented insight into the behavior of ice, land cover, cloud characteristics, as well as some promising insights into the behavior of other geophysical systems.

C31A-02 0815h INVITED

Overview of ICESat's Laser Measurements of Polar Ice, Atmosphere, Ocean, and Land

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NASA's Ice, Cloud and Land Elevation Satellite (ICESat) mission was designed to measure changes in elevation of the Greenland and Antarctic ice sheets, vertical distributions of clouds and aerosols globally, land topography, vegetation canopy heights, and sea-ice elevations. Time-series of ice-sheet elevation changes will enable determination of the present-day mass balance of the ice sheets, study of associations between observed ice changes and polar climate, and estimation of the present and future contributions of the ice sheets to global sea level rise. ICESat was launched in January, 2003 and acquired science data for about 36 days from February 20 to March 29 with the first of three lasers of the Geoscience Laser Altimeter System (GLAS). Data acquisition with the second laser is scheduled to commence in mid-September. GLAS has a 1064 nm laser channel for surface altimetry with a designed range precision of about 10 cm. Vertical distributions of clouds and aerosols with 75 m resolution have been obtained with the 1064 nm channel and will be obtained with the more sensitive 532 nm channel after the 532 nm detectors are turned on in September. The laser footprints are about 60 m on the surface and are spaced at 172 m along-track. The on-board GPS receiver enables radial orbit determinations to an accuracy better than 5 cm. The star-tracking attitude-determination system should enable footprints to be located to 6 m horizontally when attitude calibration is completed. The orbital altitude is around 600 km at an inclination of 94 degrees with a 8-day repeat pattern for the calibration and validation period. After laser 2 is turned on, another 8-day cycle will be completed before going to a 91-day repeat orbit with a 33-day sub-cycle. The spacecraft attitude is planned to be controlled to point the laser beam to within ± 35 m of reference surface tracks over the ice sheets and to point off-nadir up to 5 degrees to targets of interest. ICESat was designed to operate for 3 to 5 years and was intended to be followed by successive missions to measure ice sheet changes for at least 15 years. Results from the initial 36 days of ICESat data demonstrate a unique capability to measure ice and land elevations with unprecedented accuracy, measure the vertical distributions of clouds and aerosols with an unprecedented sensitivity and global detail, measure vegetation canopy heights, and the elevations of sea ice. Data to be acquired at intervals of six months with the additional lasers should demonstrate the capability to measure ice sheet elevation changes to the planned accuracy of 1 cm/year, observe seasonal and interannual changes in global cloud cover, and other laser-unique capabilities.

C31A-03 0830h INVITED

ICESat Laser Altimetry: Calibration/Validation

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The Geoscience Laser Altimeter System (GLAS) was launched on ICESat in January 2003 into a 600 km altitude, near polar orbit from Vandenberg, California. The GLAS instrument has been developed by NASA Goddard and it was mated to the spacecraft bus, built by Ball Aerospace, in June 2003. GLAS laser-1 was activated in orbit on February 20, 2003 and elevation profiles of the Greenland and Antarctic ice sheets, as well as land and ocean profiles, have been produced using the 1064 nm wavelength. The laser pulse has a divergence of about 0.11 mrad, which illuminates a spot on the surface with a 66 m diameter. The 170 m spot separation on the surface is determined by the ICESat orbital motion and the 40 Hz laser pulse repetition rate. Unlike wide pulse radar altimeters, accurate knowledge of the laser beam direction is required for the laser altimeter to produce accurate surface profiles. The laser pointing direction is determined with the assistance of an innovative system of CCD cameras plus calibration/validation methodologies. The combination of the laser pulse round trip time of flight and the pointing determination system provides an altitude vector. Determination of the direction of the altitude vector has an accuracy requirement of about 1.5 arcsec (or about 4.5 m on surface). In addition to the instrumentation required to produce the altitude vector, the position of a GLAS reference point with respect to the center of mass of the Earth is required. The ICESat BlackJack GPS receiver from NASA JPL has enabled determination of the radial component of the orbit to a few centimeter accuracy level. Laser-1 operated in orbit with a ground track that was controlled to within 800 m of an 8-day repeat reference track. During laser-1 operation and after the laser ceased firing on March 29, experiments were conducted to assess and improve the accuracy of off-nadir pointing, a unique capability to enhance the science return. This paper will provide an assessment of the accuracies achieved by laser-1 and during laser operations with the additional GLAS lasers. On-orbit factors, such as thermal and jitter effects, that may limit the achieved accuracy will be discussed. These assessments will draw on calibration/validation experiments that have been conducted as well as the analysis of the on-board instrumentation.