of the particle-laden ice is much smaller than that of particle-free ice after a given amount of creep straining. This research was supported by NSF Office of Polar Programs, Arctic Natural Sciences Program (OPP 011737), Dr. Jane Dionne, Program Manager.

C31B-0407 0830h POSTER

A Snow Accumulation Map of Part of Greenland Derived From InSAR Correlation Observations

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We present here an improved method for estimating snow accumulation rates in the Earth's polar ice sheets from remote sensing observations. Microwave methods have often been used to extrapolate point accumulation rates to obtain continent-wide maps. Because ice is semi-transparent to microwave radiation, observations of the ice sheets reveal composition and structure of the top 10's of meters of firn when interpreted using electromagnetic scattering models. These in turn constrain estimates of ice accumulation rates, critical for determining the mass balance of the ice sheets. Typical approaches use radar reflectivity or emissivity measurements to obtain snow grain sizes, which are then related to accumulation rate. But reflectivity and emissivity depend not only on grain size, but also on the thickness of annual layers in the top few meters of firn. A radar image may appear bright because grain size is large, implying slow accumulation, or because the annual layers are thick, implying high accumulation. Using InSAR measurements of both reflectivity and correlation permits solution for both the layer thickness and the grain size at depth, hence the ambiguity in the brightness measurements is avoided. We developed an interferometric ice scattering model to relate ice grain size and layer thickness to accumulation. We propose a buried layer model based on the incoherent addition of echoes from hoar layer interfaces, in which the scattering from a single layer is found by small-perturbation methods. Because the model also depends on the total thickness of the layered region, we assumed a constant 6 m thickness for the layered region in Greenland's dry snow zone. Penetration depth estimates, also derived from InSAR, in this area are typically 20 m or more, so that much of the observed echo is from depths below the layers-scattering from individual grains is also significant in this region. The interferometric model describes the ERS amplitude and correlation data simultaneously and consistently, with variations in hoar layer spacing of 11-26 cm and grain radius of 0.6-2 mm providing the needed structural fluctuations for the observed range of cross-section and correlation. In situ accumulation measurements varies from about 15-25cm w.e./yr in our test area. Comparison of our model inversion results with in situ core measurements show that the spatially-varying trend in accumulation rates over our study area is consistent between both data sets, which is not the case in many published maps derived from radar reflectivity or radiometer data alone. Interestingly, straight contouring of the Greenland-wide ice core data disagrees in this region also as the data are very sparse. Because the remote sensing InSAR method using both correlation and reflectivity data provides closer agreement to the truth measurements inferred from the cores, it is likely that a full continent accumulation map would be more accurate also.

C31C MCC: Level 1 Wednesday 0830h

Ice-Ocean Interactions and the Cryosphere I Posters *(joint with OS, GC)*

Presiding: **K Grosfeld,** University of Bremen**; D M Holland,** Courant Institute of Mathematical Sciences, New York University

C31C-0408 0830h POSTER

Ice Shelf Front Readjustment in Response to Inflow Perturbations: Towards a new Model of Ice Shelf Disintegration

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The Ross Ice Shelf has in its recent past seen a significant reduction of ice influx. The stoppage of Ice Stream C, about 150 years ago, reduced inflow of ice by 20-30 km^3/yr. Adding to this trend is the current slowdown of Whillans Ice Stream, which has averaged 5 m/yr^2 over the last 23 years. The loss of annual ice influx may become as high as 50-60 km^3/yr should Whillans Ice Stream come to a complete stop as predicted by numerical models. This influx reduction constitute a major perturbation that could trigger a critical rearrangement of the ice shelf. The collapse of smaller West Antarctic ice shelves has shown that floating ice fronts can retreat rapidly. We have developed a new numerical ice shelf model that includes a mobile ice shelf front, which can adjusts to changes in ice thickness and velocity field. The dynamic ice front condition allows us to investigate the dynamics of collapsing ice shelves. Initial model results based on simplified ice shelf geometry showed that both location and curvature of the floating ice front change in response to inflow perturbations. We intend to use our model to predict future changes in the Ross Ice Shelf due to decreasing discharge from the Ross Ice Streams. Retreat of the Ross Ice Shelf front could expose up to 400,000 km^2 of new polar sea surface area. Such exposure may change the regional sea ice conditions and maybe even cause rearrangement of the thermohaline ocean circulation.

URL: http://es.ucsc.edu/~poul

C31C-0409 0830h POSTER

Sea Ice Drift and Transports in the South Pacific: Model Results and Observations

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The first comprehensive study of sea ice drift, transports and formation rates in the southeastern Pacific sector of the Southern Ocean on time scales ranging from daily to interannual variability is presented. Sea ice drift in the Amundsen Sea and its forcing and variability is analysed using data from three buoys deployed on the ice in March 2000 and results of the coupled ice-ocean model BRIOS (Bremerhaven Ice Ocean Simulations). Three drift regimes are identified with wind as the main driving force and weak oceanic influence. A first sea ice budget is presented for the Amundsen Sea with meridional and zonal transports of almost equal magnitude and weak import from the Bellingshausen Sea. Transport magnitude and variability at the western boundary towards the Ross Sea depend strongly on the interplay between zonal easterlies and westerlies and meridional winds, which leads to accumulation of sea ice in or export from the southern Amundsen Sea. The latter strongly affects sea ice conditions in the eastern Ross Sea, while western Ross Sea ice is formed locally. An enhanced northward export of from the western part of the Ross Sea induces a large import of Amundsen Sea ice into its eastern part, because the export allows the Amundsen Sea ice to move further westward. The existence of two independent sea ice regimes in the Ross Sea with exceptionally high formation rates in the western part correlates positively with a zonal salinity gradient in the water column along the Ross Ice Shelf edge and possibly reduces the need for subsurface upwelling onto the western continental shelf.

C31C-0410 0830h POSTER

About the Freshwater Contribution of the Eastern Weddell Ice Shelves to Water Mass Formation in the Weddell Sea

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The interface between the Antarctic Ice Sheet and the Southern Ocean corresponds to the bases of floating ice shelves which constitute about one half of Antarctica's coast line. Heat and mass fluxes across this interface, associated with melting and freezing processes, directly affect the ice shelf glacial system. Furthermore, modifications of dense water masses due to melting and freezing at the ice shelf base is directly linked to the formation of deep waters at the continental shelf break. Hence, the export of Ice Shelf Water (ISW) from the extensive ice shelf cavities, especially in the Weddell- and Ross Seas, represents an important component for the ventilation of the world ocean abyss. However, the smaller ice shelf regions in the Weddell Sea, the Larsen and the Eastern Weddell Ice Shelves (EWIS) represent important contributors to this process. Their role in this discussion is up to now possibly underestimated. In this study we concentrate on the eastern Weddell Sea sector as an important inflow region for the subsequent following upstream regions, the Filchner Ronne Ice Shelf and the Larsen Ice Shelf. Applying a three dimensional ocean model with as realistic as possible bathymetry and ice thickness data based on the BEDMAP data set, we simulated the flow regime in this region and calculate the freshwater flux, formed at the base of the ice shelf. Our analysis will lead to sensitivity studies for the influence of increased ocean temperatures, possibly caused by global warming and different ice shelf–ocean boundary conditions, affecting the melting and freezing rates. EWIS is of special interest, as it is separated from the coastal current by a narrow continental shelf margin and partly overlaps the deep sea. Hence, direct interaction of the coastal current with the ice shelf is expected to lead to high melting rates.

C

C31C-0411 0830h POSTER

Can the recent thinning and acceleration of Pine Island Glacier, West Antarctica be explained by changes in its ice shelf?

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There is a wealth of evidence implying that Pine Island Glacier, West Antarctica (PIG) is presently undergoing rapid change. Much of this evidence is associated with PIG's ice shelf and ice plain. This includes a retreat of the grounding line by 5 km from 1992 to 1994; a contemporaneous acceleration of flow in the same area by 18%; as well as various calving and crevassing events over the last 30 years. One of the most intriguing observations is of widespread thinning over PIG's full extent up to 150 km upstream of the grounding line at rates of approximately 0.5 m/yr. If this thinning has been caused by the ice shelf/plain changes then it implies a far closer linkage between grounded and floating ice than previously thought possible. We investigate this possibility by using a three-dimensional, numerical model of ice flow. The model incorporates the temporal changes in ice thickness generated by changes in ice flow. We investigate coupling between PIG and its ice shelf in a series of perturbation experiments in which the shelf is thinned and shortened, and the grounding of the ice plain is reduced. Results imply a two-stage process in which initial changes in the shelf have an immediate, mechanical effect up to 50 km inland from the grounding line. These changes are sufficient to initiate a kinematic wave of thinning, steepening ice that propagates rapidly (approximately 5 km/yr) upstream and affects the entire ice stream after approximately 20 years. The propagation mechanism of this wave is the increase in gravitation driving stress consequent on local steepening of the ice surface, which feeds directly into the force balance determining the velocity of the ice stream.

C31C-0412 0830h POSTER

Submarine Melting at Temperate Tidewater Glacier Termini: How Significant is it?

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One of the most important unresolved questions concerning temperate tidewater glaciers is the role that submarine melting and proglacial convection play in controlling terminus stability. Little is known about ocean thermal forcing of temperate tidewater glaciers even though its seasonal and long-term variation may significantly influence calving speed, terminus dynamics and ocean convection. Relationships developed from field, experimental, and analytical studies on icebergs drifting and melting in seawater have been used to estimate submarine melting at calving termini. However, these calculations give estimates that are typically a small fraction of total calving rate. Recently, Motyka et al. (2003) used heat and mass balance analysis based on glacier and fjord measurements at LeConte Glacier, a tidewater glacier in southeast Alaska that terminates in 250-m-deep water, to estimate submarine melting. They found that proglacial convection was substantial and that submarine melting contributed significantly to ice loss at the terminus during late summer. Melting was at least as significant as calving in controlling terminus position - if not more. In a similar study at Columbia Glacier, Walters et al. (1988) also found that melting there was seasonally significant, with melt being about half the iceberg calving flux during the summer. These field studies indicate that iceberg analogies do not accurately reflect the dynamic process of turbulent convective flow along the terminus face that is driven by discharge of buoyant subglacial and englacial water. In our model we propose that turbulent upwelling of subglacial freshwater draws in warm ocean waters and that the mixture rises along the submarine face and melts ice. A consequence of this model is that submarine melt rates should vary as a function of ocean water temperature and subglacial discharge. We suggest that seasonal fluctuations in the terminus position of tidewater glaciers are directly related to seasonal changes in submarine melting, much as termini of land-terminating glaciers are affected by seasonal changes in surface ablation. Submarine melting may also be involved in controlling the long-term stability of tidewater glacier termini through direct oceanic thermal forcing. Submarine melting could help explain the correlation between annual "calving speed" and water depth found for many well-grounded tidewater glaciers. This is because the percentage area of the terminus face exposed to submarine melting would increase as a function of water depth. Buoyancy-driven submarine ablation and seawater temperatures could also help explain the order-of-magnitude disparity in "calving speeds" between tidewater and lacustrine settings. The lack of a strong density contrast and the generally cooler water temperatures encountered at lacustrine calving glaciers would inhibit convection and melting at a sublacustrine face in contrast to submarine environments. Lastly, there may be a spectrum of submarine melting regimes, from polar ice shelves with little subglacial discharge (e.g., Pine Island, Antarctica) to those with significant subglacial discharge (e.g., Jakobshavn, Greenland) to temperate tidewater glaciers with no floating tongue and strong seasonal subglacial discharge.

C31C-0413 0830h POSTER

Giant Tabular Icebergs as Surrogate Ice Shelves in Field Studies of Antarctica's Response to Environmental Warming.

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The past 3 years have witnessed approximately 6000 km^3 of ice calved from the Antarctic ice sheet as a handful of extremely large tabular icebergs in the Ross and Weddell Seas. Several of these icebergs are comparable to many of the smaller, fringing ice shelves that surround the continent, and which have become the subject of concern since the recent sudden breakup of Larsen B ice shelf on the Antarctic Peninsula. While the drift and melting of these giant icebergs over the coming decades will undoubtedly have some impact on oceanic conditions beyond the Antarctic, the principal interest in these great wandering ice masses is motivated by the "natural experiments" their evolution in response to northward drift entails. In particular, the melting (both surficial and basal) and fragmentation of these icebergs in response to warmer conditions encountered in the Southern Ocean beyond Antarctica may closely resemble the effects future climate change may have on the stationary ice shelves along the coast of Antarctica. In recognition of this opportunity, we have been maintaining a suite of instruments, including GPS, automatic weather stations, ice-sounding sonars and seismometers on two icebergs in the Ross Sea (B15a and C16), and intend to place such a suite on the Drygalski Ice Tongue in anticipation of it's future calving (to be performed in October, 2003). Our poster summarizes the observations made so far, and discusses the potential for deploying new sensors and undertaking additional field campaigns to examine how these icebergs will ultimately disintegrate.

C31C-0414 0830h POSTER

Downslope flow across the Ross Sea shelf break (Antarctica)

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The analysis of some high-resolution hydrological data sets acquired during the 1997, 1998, 2001 and 2003 austral summers across the Ross Sea continental shelf break are here presented. The main focus of these cruises carried out in the framework of the Italian National Antarctic Program was the investigation of the downslope flow of the dense waters originated inside the Ross Sea. Such dense waters, flow near the bottom and, reaching the continental shelf break, ventilate the deep ocean. Two Antarctic continental shelf mechanisms can originate dense and deep waters. The former mechanism involves the formation, along the Victoria Land coasts, of a dense and saline water mass, the High Salinity Shelf Water (HSSW). The HSSW formation is linked to the rejection of salt into the water column as sea ice freezes, especially during winter, in the polynya areas, where the ice is continuously pushed offshore by the strong katabatic winds. The latter one is responsible of the formation of a supercold water mass, the Ice Shelf Water (ISW). The salt supplied by the HSSW recirculated below the Ross Ice Shelf, the latent heat of melting and the heat sink provided by the Ross Ice Shelf give rise to plumes of ISW, characterized by temperatures below the sea-surface freezing point. The dense shelf waters migrate to the continental shelf-break, spill over the shelf edge and descend the continental slope as a shelf-break gravity current, subject to friction and possibly enhanced by topographic channelling. Friction, in particular, breaks the constraint of potential vorticity conservation, counteracting the geostrophic tendency for along slope flow. The density-driven downslope motion or cascading entrains ambient water, namely the lower layer of the CDW, reaches a depth where density is the same and spreads off-slope. In fact, the cascading event is inhibited by friction without entrainment. The downslope processes are important for the ocean and climate system because they play a crucial role in the formation of oceanic deep water responsible for ocean/continental shelf exchange of organic carbon, suspended material and dissolved gases around Antarctica. In this context, this work presents the analysis of the 1997, 2001 and 2003 high-resolution surveys carried out in the western Ross Sea near Cape Adare, where the HSSW flows down the continental slope. The second study area was investigated during the 1998 survey of the Italian National Programme for Antarctic Research of the CLIMA Project, in order to follow the ISW overflow path at the shelf break in the central Ross Sea. A 3D primitive equation model was also implemented as a first step in the construction of a high-resolution process study model to explore the dynamical constraints involved in the downslope motion.

C31C-0415 0830h POSTER

Numerical Investigation of Inertial and Tidal Variability in Arctic Sea-Ice Deformation

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Recent investigations of inertial variability in ice-mixed-layer ocean models by Heil and Hibler (2002) have demonstrated that if artificial water drag is removed from sea ice models, realistic inertial variability in both sea ice drift and deformation may be modeled. Modeled variations were found to be in good agreement with both ice buoy drift and deformation far from shore. These inertial variations were found to increase ice mass up to 20 per cent compared to traditional ice models with passive water drag, and hence can play a significan role in the fresh water budget of the Arctic Ocean. To investigate the additional effects of tidal forcing on the ice as well as feedback between the ice motion and high frequency wave effects in the ocean, a diagnostic free surface ice ocean model is constructed for the Arctic Basin. This model is forced with daily varying wind fields as well as barotropic tidal forcing. The model results are analyzed to demonstrate the significant increase in ice mass that can occur when both these forcings are included in ice ocean models and in stand alone models. As a comparison case, an ice only model with inertial imbedding and tidal forcing is also analyzed to determine to what degree these high frequency effects are dominated by ice mechanics interacting directly with tides and boundary layer inertial motion independent of ocean wave and wind driven vaariability. The results are compared to high frequency buoy drift and deformation and compared to existing ice model simulations.

C31C-0416 0830h POSTER

Use of a rate- and state-dependent friction law to parameterize subglacial tills

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Recent studies show that small-amplitude stress changes associated with ocean tidal variations can control large-scale ice stream motion and trigger subglacial stick-slip behavior. The forcing of ice stream flow by the tides is observed under a surprisingly varied set of glacial and subglacial conditions. Ice stream basal seismicity, modulated by ocean tides, is present beneath the ice plain of rapidly flowing ice stream B; ice stream B has been hypothesized to be underlain by a plastic till which is actively freezing. Basal seismicity (also modulated by the tide) is present beneath much of ice stream C, which is slow-flowing and hypothesized to have a linear-viscous substrate. Ice stream D has a more-continuous rather than a stick-slip response to tidal forcing, with the flow speed of the ice stream changing by a factor of three over the course of a tidal cycle. Ice stream D is hypothesized to be underlain by a linear-viscous till similar to that beneath ice stream C and beneath the upstream segments of ice stream B. Reconciling these various observations is necessary to develop a sliding law for ice stream flow that can be generally applied. We propose the use of a rate- and state-dependent friction law to describe the behavior of the subglacial till layer. We suggest that subglacial tills can be classified as “velocity-weakening” (steady-state frictional strength decreases with increasing slip velocity, which is a necessary condition for stick-slip instability) or “velocity-strengthening” (steady-state frictional strength increases with increasing slip velocity, which results in inherently stable sliding). Whether a subglacial system is “weakening” or “strengthening” appears to be related to the hydrologic system and whether basal water is freezing-on (ice streams B & C which exhibit stick-slip) or not (ice stream D, no stick-slip). This model could also reconcile observations of the presence of pervasive subglacial till deformation (ice stream D, upper parts of ice stream B) and thin-layer plastic deformation at the boundary between the ice and till (ice stream B and C). A layer that exhibits velocity-strengthening would be expected to exhibit pervasive deformation whereas a weakening layer would fail on discrete slip planes.