Abstracts of UK Sea Ice Meeting 2004

27 and 28 Sept, Centre for Mathematical Sciences

Iceberg impact on sea ice thickness measurements

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During March 2003 Autosub, the autonomous underwater vehicle (AUV) operated by Southampton Oceanography Centre, was deployed under sea ice as part of the Pine Island Bay Cruise. This talk will explain the use of the Acoustic Doppler Current Profiler (ADCP) to collect data on sea ice draft.

Preliminary measurements from an earlier cruise to the Weddell Sea suggest that icebergs cluster within the edge of the sea ice zone. We will also discuss ongoing work looking at the spatial distribution of icebergs using statistical techniques for analysing spatial point processes. This work will provide information on the representativeness of icebergs identified on an Autosub mission.

Changing Marine Access in the Arctic Ocean: The Arctic Climate Impact Assessment

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Marine access in the Arctic Ocean changed in unprecedented ways during the second half of the 20th century and the early years of the 21st century. The Arctic Climate Impact Assessment (ACIA) has documented substantial evidence that the Arctic sea ice cover is undergoing profound changes including: a steady decrease in extent during all seasons; a decreasing area of multi-year sea ice in the Central Arctic Ocean; and, thinning of sea ice throughout the Arctic Ocean (as measured primarily by submarine sonar). These changes have significant implications for many marine uses of the Arctic Ocean including Arctic shipping, offshore development, fishing, indigenous hunting, tourism, and scientific exploration. These environmental changes have also been accompanied by icebreaker voyages that have attained summer access to nearly all regions of the Arctic Ocean. During 1977-2004, 52 transits have been made to the Geographic North Pole for tourism and scientific exploration; polar icebreakers from Russia, Sweden, Germany, Canada, USA and Norway have made successful voyages to the Pole. During the decade of the 1990's five historic, trans-Arctic voyages were also accomplished in summer. The work of ACIA also included projected changes in Arctic sea ice coverage for the 21st century. Simulations of five different global climate models (GCMs), each forced by the moderate, Intergovernmental Panel on Climate Change (IPCC) B2 scenario of increasing greenhouse gas concentrations, were run for the time periods 2010-2030, 2040-2060, and 2070-90. There is a considerable range among the sea ice retreats projected, but generally there are increasing ice-free areas throughout the Arctic coastal seas in summer; one model projects an ice-free Arctic Ocean in summer by mid-century. ACIA included two regional assessments for the Northwest Passage (NWP) in the Canadian Arctic and the Northern Sea Route (NSR) along the northern Eurasian coast. For the NWP, the GCMs could not resolve the complex geography of the Canadian Archipelago, and the observed sea ice trends (from the Canadian Ice Service), although negative for sea ice extent since the late 1960's, indicated a very high inter-annual variability of coverage. Sea ice simulations for the NSR using the GCMs were more successful and these indicated decreasing sea ice coverage and plausible increases in the length of the navigation season throughout the 21st century. The sea ice analyses conducted during ACIA represent a first-order, strategic guide to future marine access in the Arctic Ocean.

Response of sea ice to NAO anomalies in HadGEM1

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The North Atlantic Oscillation is the dominant mode of winter variability in the North Atlantic region and influences the Arctic climate through perturbations in surface air temperature and precipitation. Arctic sea ice concentration and thickness also respond to NAO anomalies with a high NAO Index associated with increased ice concentration in the Labrador Sea – Davis Strait region and reduced ice concentration in the Greenland and Barents Seas. This study uses a new version of the Hadley Centre climate model known as HadGEM1 to look at the response of Arctic sea ice to anomalies in the NAO Index through the relative contribution of dynamic and thermodynamic processes. The significance of these processes with respect to the model's background climatology is also considered.

Sea Ice Elevation from Laser Altimetry using ICESat/GLAS

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NASA's Ice, Cloud and land Elevation Satellite (ICESat) mission, which was launched in January 2003, carries the Geoscience Laser Altimeter System (GLAS) onboard and facilitates wide spatial and temporal coverage of the Polar Regions. GLAS extends coverage to 86^{o} latitude, thus providing the first opportunity to study high-resolution

satellite laser altimetry data over sea ice in the Arctic Basin. Our research project is based on the feasibility of using GLAS altimetry data to determine sea ice freeboard. One of the major challenges when using satellite laser and radar altimetry to derive sea ice freeboard is accurate knowledge of the mean sea surface. Therefore our current focus is to determine a precise reference sea surface from the available geodetic and altimetric data. We analysed GLAS data collected during February and March 2003 with the aim of compiling time series of sea ice elevation. We applied various geodetic models to the GLAS range data as well as a mean sea surface topography generated from 4 years of ERS radar altimetry data. The results of the derived sea ice freeboards are presented here. The use of current geoid models as a reference mean sea surface is compared with sea surface heights derived independently using radar and laser altimetry techniques. Future work will be to explore the reasons for the differences in sea ice freeboard generated using the various techniques presented. We will improve our reference surface by using a hybrid geoid model composed of a combination of satellite and ground-based gravity data in tandem with the satellite-derived mean sea surface. In addition we will investigate further comparisons between coincident laser and radar altimetric sea ice freeboard measurements to obtain estimates of snow thickness on sea ice.

Granular Flow in the Marginal Ice Zone

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The region of sea ice near the edge of the sea ice pack is known as the marginal ice zone (MIZ) and its dynamics are complicated by ocean wave interaction with the ice cover, strong gradients in the atmosphere and ocean, and variations in sea ice rheology. This paper focuses on the role of sea ice rheology in determining the dynamics of the MIZ. Here, sea ice is treated as a granular material with a composite rheology describing collisional ice floe interaction and plastic interaction. The collisional component of sea ice rheology depends upon the granular temperature, a measure of the kinetic energy of flow fluctuations. A simplified model of the MIZ is introduced consisting of the along and across momentum balance of the sea ice and the balance equation of fluctuation kinetic energy. The steady solution of these equations is found to leading order using elementary methods. This reveals a concentrated region of rapid ice flow parallel to the ice edge, which is in accordance with field observations, and previously called the *ice jet*. Previous explanations of the ice jet relied upon the existence of ocean currents beneath the ice cover. We show that an ice jet results as a natural consequence of the granular nature of sea ice.

Spatial variability of first order Bragg response to HF radar in an Antarctic polynya

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We present the results of a field experiment carried out within framework of the CLIMA project of the Italian National Programme for Antarctic Research (PNRA) and in cooperation with the Scott Polar Research Institute of Cambridge. During the second period (02/12/1999-23/01/2000) of the XV Italian expedition, an Ocean Surface Current Radar (OSCR) was deployed on the Antarctic coast to characterize the current field in the area of Terra Nova Bay (TNB). The experiment was to provide surface current measurements in the area of TNB polynya, one of the most important coastal polynyas of the Ross Sea. The ability to estimate the fully resolved current structure of the polynya was dependent on the simultaneous operation of two radar stations, however, much of the time only one of the two stations was operational, so fully resolved current information is sparse. There is much more environmental information available from the radar data than just surface currents. Sufficient Doppler spectral data were recorded to reconstruct many features of the full radar Doppler backscatter spectrum. Estimates of the total integrated backscattered energy show spatially coherent patterns that seem to be related to the presence of sea ice in the polynya. This poster shows our preliminary exploration of this relationship.

Radar and Laser Altimeter measurements over Arctic Sea Ice

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In order to estimate sea ice thickness from satellite radar altimeter measurements we must understand the interaction of the radar with the snow/ice system. Laboratory evidence suggests that the dominant scattering mechanism from snow covered sea ice is surface scattering from the snow/ice interface. However these experiments were performed in controlled conditions on a small section of saline ice. The electromagnetic properties of snow and sea ice depend on both the radar characteristics and their physical characteristics, which can change rapidly. The Laser Radar Altimetry field experiment (LaRA) provided the opportunity to observe the scattering characteristics of radar, in the field, and compare the results with laser observations and digital photographs. The work presented here describes the experiment, data processing, error analysis, preliminary results and future work.

Observations of platelet ice growth and oceanographic conditions during winter 2003 in McMurdo Sound, Antarctica

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Almost all that is known about sea ice growing attached to the Antarctic landmass has been measured in the spring and summer when the sea ice has grown to over 1 m thick. Platelet ice is the name given to ice crystals that nucleate in the ocean and grow either at depth in the sea water or loosely attached to the ice water interface. It appears to form in sea water cooled below its freezing point, and was first observed in McMurdo Sound by scientists of Scott's Discovery Expedition of 1901–1904. It is known that the formation of platelet ice is linked to the proximity of ice shelves, however the exact freezing mechanism is a matter of some conjecture. In this study we have spent the winter months (February–September) 2003 on the sea ice in McMurdo Sound simultaneously measuring ice and oceanographic conditions in order to increase our understanding of platelet ice formation. Results indicate the presence of a relatively warm, dynamic water layer in April which has been replaced by a cooler, stable water column by early June. Episodic intrusions of cold water into the mixed layer were observed from this time onwards. Signal returns from an Acoustic Doppler Current Profiler (ADCP) indicate that these episodic intrusions may be coupled with the presence of frazil ice crystals in the near surface water. The water near the ice - water interface is found to be consistently supercooled from mid June onwards. Ice coring data reveals that the first layer of platelet ice incorporated into the sea ice sheet did not appear until the ice was around 0.7 m thick, even though platelet ice was observed on wires and ropes suspended in the water column when the ice was significantly thinner.

Experimental Study of Sliding Friction and Stick-Slip on Faults in Floating Ice Sheets

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With the aim of incorporating, into geophysical-scale sea-ice models, and thence into climate-predicting general circulation models, the effect, on the ice stress-strain relationship, of frictional sliding on faults, we have undertaken double-direct-shear friction experiments, with floating ice sheets.

Mostly, the sliding took a stick-slip form: sliding velocity and shear stress, at a given position on the fault, were episodically time-dependent, shear stress dropping as sliding accelerated.

When we seek a local, instantaneous friction law, this militates in favour of proposed laws, in which the shear stress decreases with increasing speed, and against those, in which the shear-stress is velocity-independent or grows with increasing speed. We can

test friction laws further by plotting the measurements, in combinations of variables, for which each proposed law predicts a simple graphical form.

The velocity and shear stress are non-uniform in space as well as in time. Measurements of the same stick-slip cycle, at several positions along the fault, allow us to identify a nucleation zone, which begins to slip before the rest of the fault, and to relate this spatial variation of velocity and the temporal variation of shear stress; the slipping region, therefore, behaves like a wave-packet, propagating away from the nucleation zone.

Autonomous Underwater Vehicle Measurements Under Antarctic Sea Ice Daniel R. Hayes[1], A. Jenkins[1], S. McPhail[2]
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The March 2003 deployment of Autosub in the Antarctic was the first field study under the Autosub Under Ice programme of the UK Natural Environment Research Council. Several missions were run under sea ice in the western Bellingshausen Sea at depths ranging from 90 to 200 m. Data from the vehicle's upward-looking ADCP indicate a strongly oscillating horizontal velocity at and near the ice underside due to ocean swell. Swell period, height, direction, and directional spread are computed every 800 m from the ice edge to 10 km inward. Period-dependent attenuation of swell by sea ice is observed. Directional spectra show slow changes in swell properties during propagation through the ice pack.

Ice Shelf Water plumes and Frazil ice modelling

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Results are presented from a modelling study of various aspects of Ice Shelf Water (ISW) plumes. Buoyant ISW plumes form near the grounding line of ice shelves due to ice melt and, due to the pressure variation of seawater's freezing temperature, become supercooled as they ascend along the underside of an ice shelf. Frazil crystals form and multiply in the supercooled ISW. As the frazil crystals are buoyant, they can precipitate onto the ice shelf base to form marine ice. In a one-dimensional (vertical) section through an ISW plume, a novel formulation of ice crystal precipitation allows a closer examination of the vertical balance of forces governing frazil deposition, and the effect of depth-dependent supercooling within the plume is also examined. Preliminary results from a depth-averaged model in a two-dimensional horizontal plane give early indications of the important effects of the Coriolis force on ISW plumes.

Constraining sea ice model parameters using remote-sensed sea ice data

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A stand-alone sea ice model is tuned and validated using satellite-derived, basin-wide observations of sea ice thickness, extent and velocity from the years 1993 to 2001. This is the first time that basin-scale measurements of sea ice thickness have been used for this purpose. The model is based on the CICE sea ice model code developed at the Los Alamos National Laboratory, with some minor modifications, and forcing consists of ERA-40 and POLES data. Three parameters are varied in the tuning process: C_a, the air-ice drag coefficient; P*, the ice strength parameter; and α, the broadband albedo of cold bare ice, with the aim being to determine the subset of this 3-dimensional parameter space that gives the best simultaneous agreement with observations. We find that observations of sea ice extent and velocity alone are not sufficient to unambiguously tune the model, and that sea ice thickness measurements are necessary to locate a unique subset of parameter space in which simultaneous agreement is achieved with all three observational data sets.

Salinity of sea ice: in situ measurements and modelling

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In most sea-ice models the bulk salinity is assumed to be uniform or is prescribed empirically as a function of ice thickness. Therefore, the temporal evolution of both the salinity field within the ice and the salt fluxes into the ocean can not be studied in great detail. The reason for this lies partly in the lack of a concise theoretical understanding and a lack of high resolution measurements of the temporal and spatial evolution of the salinity field. To guide the development of alternative models, we present results from an analytical model in which the full coupled thermodynamical and fluid-dynamical equations for the evolution of the two-phase, two-component system sea ice are solved. The model results show that so-called brine expulsion does not lead to any salt loss from the ice, but only to a re-distribution of brine within the ice itself. Brine expulsion is the movement of brine within the ice caused by the change in density during solidification.

To test the model results against measurements we have developed an instrument that is capable of measuring the salinity and solid fraction of growing sea ice with a spatial resolution of up to 5 mm and a temporal resolution of up to fractions of a second. The technique is based on measurements of electrical impedance. The measurements confirm the prevalent understanding that the bulk salinity in ice-core measurements of sea ice is usually significantly underestimated in the lower parts of the core. Using the data in

connection with our sea-ice model allows for the quantification and thus parametrisation of gravitational effects of brine loss from sea ice.

Slip weakening model for arctic sea ice dynamics

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We have studied slip-weakening behaviour in laboratory and ice tank experiments in ice. We propose that sea ice dynamics is dominated by tensile fracture and frictional slip. Further, stick-slip behaviour, which has only recently been recognised by us, we believe to be an important deformation mechanism. We proposed that the slip-weakening model can capture the essential mechanical properties of ice in shear, including the transition from brittle to ductile behaviour with increasing normal stress and temperature, and the transition from stable frictional sliding to stick-slip behaviour, necessary for modelling sea ice dynamics.

Assimilation of Sea Ice Data into the FOAM Ocean-Sea-Ice Model.

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We are in the early stages of a project to improve the assimilation of sea-ice data performed by the Met Office Forecasting Ocean Assimilation Model (FOAM). Satellite derived sea ice concentration data has been assimilated for several one-month test integration periods, the results of which will be presented. These have shown that the assimilation has some success in bringing the modelled sea-ice closer to the satellite observations. However, significant biases between the model and observations remain in some regions.

Development of Geophysical Scale Sea Ice Rheology: Relationships between subgrid-scale and grid-scale.

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A simple model to calculate the instantaneous large-scale stress from an imposed large-scale strain-rate using the small-scale rheology is developed. The model uses a similar

construction to Ukita and Moritz [2000]. The model assumes that there is 100% ice concentration and that the ice between rigid floes deforms plasticly. For a simple geometry where all rigid ice floes are square tiles, the resulting large-scale yield curve is isotropic for orientations of square tile edges parallel and at 45 degrees to the large-scale strain-rate principal axes. For the orientation of 45 degrees it is found that there is scale-invariance in the shape of the yield curve (i.e. utilising an elliptic yield curve at the small-scale yields an elliptic yield curve at the large-scale). For other orientations of the square geometry the resulting large-scale yield curve is anisotropic. For a random geometry where the rigid ice floes are determined using a Poisson process, the resulting large-scale yield curve is almost isotropic and is similar in shape to the yield curve composed of a uniform ensemble of orientations of the square geometry. The methodology outlined demonstrates in a straight-forward way the relationships between the rheology at the large-scale and the rheology at the small scale.

Modelling Arctic Melt Ponds

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A thermodynamic sea ice model is applied to the summertime melting of sea ice. The sea ice model is based on the mushy layer equations. A mushy layer is composed of a solid matrix surrounded by a liquid phase. The model is coupled to a simple spectral two-stream radiative model and incorporates a straightforward temperature-based method to parameterise the sea ice optical properties. Numerical calculations have been performed using realistic daily-averaged forcing fluxes obtained from SHEBA (Surface Heat and Energy Budget of the Arctic). The model produces reasonable melt rates and temperatures and will be used in summertime Arctic simulations. Further work will incorporate brine drainage and autumn freeze-up of melt ponds. The results from these simulations have relevance in estimating the annual heat balance of the Arctic.

A Coupled Polynya-Atmospheric Boudary Layer Model

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During the liftime of a polynya event there is a large heat flux from the ocean to the atmosphere. This input of heat into the atmosphere acts to modify the local air temperature, which in turn acts to reduce the sensible heat flux from the ocean to the atmosphere. This process is modelled through the coupling of a polynya flux model and a lower atmopsheric boundary layer model. It is demonstrated that the coupled model significantly alters the steady-state polynya widths and opening times, compared to the decouped system. The impact of the atmospheric boundary layer is particularly noticable when the potential temperature of the atmopsphere at the coast is only slightly below the freezing point. In addition a cut-off atmospheric wind speed is shown to exist, above which a steady-state polynya cannot be obtained.

Anisotropic continuum model of granulated sea ice

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A continuum model describing sea ice as a layer of granulated thick ice, consisting of many floes, intersected by leads, is developed. We consider the evolution of mesoscale leads, formed under extension, whose lengths span many floes, so that the surrounding ice is treated as a granular plastic. The leads are sufficiently small with respect to basin scales of sea ice deformation that they may be modelled using a continuum approach. The model includes evolution equations for the orientational distribution of leads, their thickness and width expressed through second-rank tensors and terms requiring closures. The closing assumptions are considered for the case of negligibly small lead ice thickness and the canonical flows types of pure and simple shear, pure divergence and pure convergence. We present a continuum-scale sea ice rheology that depends upon the isotropic, material rheology of sea ice, the orientational distribution of lead characteristics and the thick ice thickness. Calculations show that the model produces physically reasonable behaviour.