Abstracts

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Abstract List

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Strain rates and stresses beneath the surface inferred using inverse methods

Robert Arthern

There is now a long history of using inverse methods and satellite observations to recover basal drag coefficients and ice stiffness. These parameters are useful in forecasting the behaviour of the ice over coming centuries, but they also allow the vertical structure of ice flow within the ice sheet to be inferred, revealing how stress and strain rates vary with depth. Examples of such depth variations are presented from Thwaites Glacier and Rutford Ice Stream. Several potential applications of inverse methods for testing the mechanical assumptions of ice sheet models, and for helping to parameterise important processes are also considered.

Evolution of supraglacial lakes on an East Antarctic ice shelf over decadal timescales

Jennifer Arthur, *Chris R Stokes, Stewart S R Jamieson, Rachel J Carr and Amber A Leeson*

Supraglacial lakes are an important precursor for ice shelf disintegration on the Antarctic Peninsula. However, very little multi-year analysis exists of supraglacial lake evolution on East Antarctic ice shelves, meaning our understanding of lake behaviour and impact on this ice sheet is limited. Here, we present a multi-year analysis of lake evolution on Shackleton Ice Shelf, Queen Mary Land from optical satellite imagery (Landsat and Sentinel). Understanding patterns of surface melt on this ice shelf is important because it experiences high annual melting, buttresses a large upstream catchment, and is at risk of future instability. We find lakes present in their thousands on the ice shelf and in their hundreds on grounded ice upstream of the shelf. Lake clustering around the grounding zone of Shackleton ice shelf is strongly linked to the presence of blue ice and exposed rock, associated with an albedo-lowering melt-enhancing feedback. Lakes either drain supraglacially, refreeze at the end of the melt season, or appear to shrink in-situ, suggesting englacial drainage. These results provide new insights into the multiyear evolution of SGLs in East Antarctica, which can support informed predictions of the future stability of Shackleton and other ice shelves.

Meltwater percolation, impermeable layer formation and runoff buffering on Devon Ice Cap, Canada

David Ashmore, *Douglas W. F. Mair and David O. Burgess*

The retention of meltwater in the pore space of the accumulation area of the Greenland Ice Sheet and other Arctic ice masses buffers their contribution to sea level change. Devon Ice Cap in the Canadian Arctic Archipelago is a natural laboratory for investigating these processes, owing to its relative wealth of surface mass balance (SMB) and sub-surface data, and its exposure to extreme warming over the last ~15 years. Here, intense surface melting has resulted in refrozen, impermeable subsurface ice layers many metres thick. Field evidence is unclear on how these near-surface ice layers affect the retention of meltwater, raising questions about how to represent them in models of snow and firn processes.

In this study, we use a 1D, physically-based, high-resolution `tipping-bucket' model to simulate the SMB, percolation, refreezing, and runoff from across the high-elevation area of Devon Ice Cap from 2001-2016. We vary the thickness of the `impermeable' ice layer at which the underlying firn becomes impermeable to percolating melt water. Thick near-surface ice layers are established by an initial deep percolation, the formation of decimetre ice layers, and the infilling of interleaving pore space. Once established a balance between melting and percolation acts to limit their thickness. The cumulative SMB increases by 48% by varying impermeable layer thickness between 0.01 and 5 m. Within this range we identify narrower range of thicknesses (0.25-1m) that can simulate both the temporal variability in SMB and the observed near-surface density structure. Across this range, cumulative SMB variation is limited to 6% and 45-49% of mass retention takes places within the annually replenished snowpack.

Englacial architecture and age-depth constraints across the Weddell Sea Sector of West Antarctica

David Ashmore, *Robert G. Bingham, Neil Ross, Martin J. Siegert, Tom A. Jordan and Douglas W. F. Mair*

The englacial architecture of radar-imaged internal reflection horizons (IRHs) across ice sheets reflects the cumulative effects of net accumulation, basal melt and ice flow. IRHs, considered isochrones, have typically been traced in interior, slow-flowing regions. Here, we identify three distinctive IRHs spanning the Institute and Muller catchments that cover 50% of West Antarctica's Weddell Sea Sector and is characterised by a complex system of ice-stream tributaries. We place age constraints on the IRHs at intersections with previous geophysical surveys tied to Byrd Ice Core, and show their potential to nucleate a wider continental-scale IRH database for validating ice-sheet models. We present evidence of IRH drawdown potentially due to ice-dynamic or rheological effects, and basal melting near the ice divide possibly due to elevated geothermal heat flux. We further show where the oldest ice likely exists within the region; and that Holocene ice-dynamic changes were limited to the catchment's lower reaches.

Assessment of plume routing methods for calculating basal melt in an ice flow model

Jowan Barnes, *Hilmar Gudmundsson, Jan De Rydt and Adrian Jenkins*

Basal melting is a major driver of mass loss from Antarctic ice shelves, but is currently under-represented in ice flow models, often being parameterised as a function of depth. One way to include more realistic melt rates is to couple an ice flow model with an ocean model, but this greatly increases the time and computational power required to arrive at a solution.

The parameterisation of basal melt using a plume model (Lazeroms et al., 2019) is a compromise between unrealistically simplistic depth functions and the computational expense of a full coupled system. But the calculation requires information about the origins of the plumes. This means that a method must be devised to choose the sources of meltwater plumes affecting each point on the ice shelf.

We assess several such methods within the finite-element ice flow model Ua, investigating how different plume routing algorithms affect the modelled melt rate and distribution. In an effort to determine how effective each method is at replicating real melting, comparisons are made with melt rates calculated via flux divergence from observational data, and with results from a coupling with the ocean model MITgcm.

Glacier mass budgets in High Mountain Asia since 1960s

***Atanu Bhattacharya**, Tobias Bolch and Owen King*

High Mountain Asia (HMA) contains the largest concentration of glaciers and ice fields outside the Polar Regions and shows great climatic diversity. Several studies have shown how most HMA glaciers have lost ice mass during the last decades, however, substantial spatial variability has been observed in ice loss rates. In some regions in the westerly domain in HMA glaciers have been in balance or might have shown slight mass gain, whereas ice loss is pervasive in the central and eastern Himalaya. In this study we generated geodetic mass balance estimates for selected regions coincident with benchmark glaciers located in different climatic conditions for which in-situ mass balance measurements exist, over the period1964-2018. We develop a time series of digital elevation models from optical stereo imagery including declassified Corona and Hexagon spy satellite and multiple modern-era satellites, such as Pleiades, GeoEye, TerraSAR-X and ASTER, to analyse glacier ice mass loss in unprecedented temporal and spatial detail and compare them to existing in-situ measurements. Preliminary results showed moderate mass loss for Big and Small Almatinka valleys, northern Tien Shan (-0.17Â±0.03 m.w.eq./yr from 1964 to 2016), Naimoanamy Range, Central-West Himalaya (-0.13 ±0.07 m.w.eq./yr from 1966 to 2018) and Purogangri Ice cap, central Tibetan Plateau (-0.13Â±0.04 m.w.eq./yr from 1975 to 2018). However, glaciers in the Western Nyainqentanglha are losing considerable ice mass (-0.31Â±0.13 m.w.eq./yr) after 2000. In contrast ice mass loss of the glaciers at Muztagh Ata in Eastern Pamir revealed nearly balanced budgets for the last 50 years (1967 to 2016). Apart from heterogeneous variability in ice mass loss in different climatic conditions, similar heterogeneity can also be observed in same climatic conditions in different time period.

Application of the ArcticDEM for detecting active subglacial lakes beneath the Greenland Ice Sheet

Jade Bowling, *Amber Leeson, Malcolm McMillan, Stephen Livingstone and Andrew Sole*

Over 400 subglacial lakes have been documented beneath the Antarctic Ice Sheet, ranging from `active' lakes which periodically fill and drain, to ancient hydrologically isolated lakes. Active subglacial lake outburst events have been associated with accelerations in local ice flow velocity. The sudden discharge of water causes the subglacial lake roof to subside, which propagates to the surface resulting in the formation of collapse basins (typically 50-70 m in depth). These topographic features can be detected using remote sensing techniques. In our previous work we have discovered 56 subglacial lakes beneath the Greenland Ice Sheet, increasing the total of known lakes to 60. These Greenlandic lakes, of which 4 are hydrologically-active, are distinct from their Antarctic counterparts as they are mostly distributed towards the margin of the ice sheet, and some are likely to be recharged by surface meltwater inputs.

Here, we present a new semi-automated method for detecting surface signatures of active subglacial lake drainage events in Greenland, utilising the high-resolution (2 m), high coverage ArcticDEM repeat digital surface models (2009-2016). We apply our method for identifying collapse basins to test cases to evaluate this approach and unprecedented dataset. This will ultimately allow us to examine the potential influence of drainage events on ice dynamics. Improved understanding of the complex subglacial hydrological system in Greenland is crucial in order to constrain hydrological and ice dynamical models.

Subglacial Lake CECs Exploration program

Francisca Bown, *Andres Rivera, Rodrigo Zamora, Jose Andres Uribe, Pablo Paredes, Jonathan Oberreuter, Jorge Hernandez, Nicolas Donoso, Thomas Loriaux, Felipe Napoleoni, Margit Schwikowski, Andy Smith and Alex Brisbourne*

This poster reports the discovery, characteristics and future research plans for Subglacial Lake CECs (79º15'S / 87º34'W) a near 20 km2 fresh water body located underneath 2650 m of ice in West Antarctica on the ice divide between the Minnesota Glacier and the Institute Ice Stream. This lake was discovered during an oversnow traverse carried out in January 2014 when radio-echo sounding surveys were performed at the high plateau of WAIS. Since 2014 several field campaigns have collected radar, seismic (see separated poster by Andy Smithy et al., in this conference), meteorological and GPS data. These have allowed a detailed delineation of the lake and the surrounding subglacial topography, including the pathways of water flows potentially coming in and out the lake.

Thanks to the repeated survey of 30 metal poles drilled in 2014 a mean ice surface velocity of 83 cm per year and a surface snow accumulation of 23 cm water equivalent per year were obtained. This surface snow accumulation value is very close to the mean accumulation between 1986 and 2014 obtained by the isotopic analysis of 2 shallow firn cores retrieved from the area. An Automatic weather station (AWS) installed on the ice sheet surface at 2057 meters above sea level nearby the centre of the lake, has discontinuously recorded data since 2014. Thanks to power improvements carried out in December 2016, the station was able to measure and transmit data in real time during the entire Antarctic winter when an absolute minimum air temperature of -59ºC was reached. Data collected at a permanent GPS station installed next to the AWS showed vertical movement commeasurable to the surface mass balance. Remotely sensed surface elevation data collected were compared to in situ GPS data without any indication of elevation changes in connection to possible water volume changes within the lake.

All these new insights are confirming the advantages of this subglacial lake as a target for a deep exploration program. CECs together with the British Antarctic Survey (BAS) are already working on this task aiming to drill into the lake in a couple of years’ time for lake water and sub-bottom sediment sampling.

Is there a global warming signature in the observed record of glacier mass balance?

Roger Braithwaite

Increased melting of all ice bodies on earth as a result of global warming has long been discussed as a theoretical possibility. Surface mass balances have been measured for longer and shorter periods on many glaciers in the past eight decades. Informed by previous modelling of the temperature sensitivity of glacier mass balance, it is assumed that global warming will involve a trend of increasingly negative mass balance over the most recent decades. Analysis of the available mass balance data shows that glaciers generally had balances close to zero, or slightly negative, for the three decade reference period 1961-1990. Some glaciers, notably those in the Alps, already started to show a negative trend at the end of the 1961-1990 period while other glaciers only started after the year 2000. Glaciers in the high arctic show a weaker trend towards negative balances than Alpine glaciers, while some Scandinavian glaciers show anomalies. The study uses the few multi-decade records of surface balance that are available so the geographical coverage of this study is poor. Much better geographical coverage can be achieved by remote sensing of glacier volume changes for the most recent 1-2 decades but earlier decades will be poorly covered.

Remote control of Filchner-Ronne melt rates by the Antarctic Slope Current

Christopher Y. S. Bull, *Nicolas Jourdain, Adrian Jenkins, Irena Vakovį, Pierre Mathiot, Paul Holland, Ute Hausmann and Jean-Baptiste Sallee*

The Filchner-Ronne Ice Shelf System (FISS) located at the southern boundary of the Weddell sea is the largest body of floating ice in the world, its tributary ice streams have a combined discharge of over 100 Gtons yr-1 or ~19% of the Antarctic continent. In the future, the FISS system then, has the potential to be a major component of Antarctica's contribution to sea level rise. Future projections studies by Hellmer et al. (2012, 2017), suggest that the intrusion of warm circumpolar deep water could lead to dramatic, irreversible changes for the ice shelf system in the future. First-order questions remain however, as to the present day oceanographic factors influencing FISS melt rates. Improving our understanding of the relevant ocean processes surrounding FISS is crucial if we wish to provide accurate representations of the ice-shelf for future ocean ice-sheet coupled simulations.

In this study, we use eddy-permitting NEMO regional ocean model hindcast simulations with static ice-shelves, to study the influence of changes in the strength of the Antarctic Slope Front on melt rates in FISS. Using ApRES observations collected by the British Antarctic Survey, we evaluate the mean and variability of the model. Contrary to previous work, we find that remote changes in salinity (not temperature) influence the mean FISS melt rate. We detail the pathway of the perturbed salinity, via the Antarctic Slope Front and show that the response is rapid, and transient, with a recovery time-scale of 5-15 years depended on the size of the perturbation. We discuss how these results are relevant for hindcast simulations and future projections of FISS.

Investigating controls on seasonal variations in iceberg calving at a large Greenlandic tidewater glacier, inferred from time-lapse image analysis

Charlie Bunce, Pete Nienow, Andrew Sole, Tom Cowton and Ben Davison

Iceberg discharge from tidewater glaciers is a major component of ice loss from the Greenland Ice Sheet (GrIS). However, it remains unclear how changes in atmospheric and oceanic temperature translate into changes in calving style, magnitude and frequency, partly because of a sparsity of observations at sufficiently high spatial and temporal resolutions.

Here we present high-resolution (photos every 30 minutes) time-lapse image analysis of calving activity and meltwater plume presence at Kangiata Nunaata Sermia (KNS), southwest Greenland, during the 2017 melt season (May-Oct), which we analyse in conjunction with satellite-derived ice velocities and modelled subglacial discharge. Our results suggest that variations in iceberg calving at KNS are likely controlled primarily by variations in runoff and, by extension, the subglacial hydrological system. Early in the melt season, we infer a distributed subglacial hydrological network that promotes widespread submarine melting and terminus undercutting, which subsequently enhances terminus-wide calving and ice loss. Later in the melt season, we infer evolution to a channelized subglacial system, based on the observation of meltwater plumes at the fjord surface indicating focussed emergence of subglacial water. This hydrological switch coincides with a reduction in terminus-wide iceberg calving rate/magnitude/volume and a transition to a more complex terminus geometry characterised by embayments adjacent to meltwater plumes. These observations suggest that the seasonal formation of subglacial channels, and consequent spatial-focussing of runoff-enhanced submarine melting, reduces the impact of runoff on terminus-wide calving activity. We suggest that seasonal variations in both runoff volume and subglacial hydrology therefore exert considerable influence on calving activity at KNS and that their potential role in driving ice loss from tidewater glaciers at an ice-sheet wide scale needs further investigation.

Accelerated volume loss in glaciers of NE Greenland

Jonathan Carrivick *and Clare Boston*

Mountain glaciers at the periphery of the Greenland ice sheet are a crucial freshwater and sediment source to the North Atlantic and strongly impact Arctic terrestrial, fjord and coastal biogeochemical cycles. In this study we mapped the extent of 1848 mountain glaciers in NE Greenland at the Little Ice Age (LIA). We determined area and volume changes for the time periods LIA to 1980s and 1980s to 2014. There was at least 172.76 ± 34.55 km3 volume lost between 1910 and 1980s, i.e. a rate of 2.61 ± 0.52 km3 yr-1. Between 1980s and 2014 the volume lost was 90.55 Â± 18.11 km3, i.e. a rate of 3.22 ± 0.64 km3 yr-1, implying an increase of ~ 23 % in the rate of ice volume loss. Overall, at least ~ 7 % of mass loss from Greenland mountain glaciers and ice caps has come from the NE sector.

Glacier outburst floods in Greenland

Jonathan Carrivick *and Fiona Tweed*

The very largest glacier outburst floods have been termed `megafloods' given their volume and peak discharge. That definition might be revised because those floods have become understood due to their distinctive and pervasive landscape impacts. Glacier lake outburst floods (GLOFs) in Greenland might also have megaflood-type attributes given the enormous lake volumes drained. We therefore here present the first review of glacier outburst floods from ice-marginal lakes in Greenland: sites Isvand, Russell Glacier, Kuannersuit Glacier, Lake Tininnilik, two unnamed lakes near Amitsulooq Ice Cap, and Iluliallup Tasersua, Base Camp Lake, Lake Hullett, Qorlortorssup Tasia, Imaersartoq, Tordensa¸, North Midterna and an outlet glacier of the A. P. Olsen Ice Cap. There are very few reported impacts of glacier outburst floods in Greenland but in all cases they have been produced by ice-dam failure. This trigger mechanism, combined with the proximity of the Greenland glacier lakes to the coast, means that most proglacial channels in Greenland are flood-hardened and most landscape impact is likely to be offshore in estuaries and fjords. Future floods with megaflood-type attributes will occur in Greenland and will be induced by extreme weather and rapid ice melt. Any potential landscape impact of these future floods remains open to question.

Inter-decadal climate variability induces dichotomous ice response along Pacific-facing West Antarctica

Frazer Christie, *Eric J. Steig,Robert G. Bingham, Noel Gourmelen and Simon F. B. Tett*

West Antarctica has experienced dramatic ice losses contributing to global sea-level rise in recent decades, particularly from Pine Island and Thwaites Glaciers. Here, we derive the first comprehensive inter-decadal record of glacier retreat around West Antarctica's Pacific-facing margin and compare this dataset to contemporaneous estimates of ice flow, thinning and the state of the Southern Ocean and its atmosphere. Between 2003 and 2015 net glacier retreat and acceleration were extensive along the Bellingshausen Sea coastline, but slowed into the Amundsen Sea. We attribute this to an east-west-graduated weakening of offshore westerly winds, which reduced warm water inflow to the Amundsen Sea ice margin. The along-coast gradient in westerlies is most enhanced in austral wintertime, strongly implicating remote atmospheric forcing from the central tropical Pacific, rather than depletion of stratospheric ozone, as the primary driver of West Antarctic ice losses over the observational period.

The dynamics and impacts of the December 2017 catastrophic mass flow Villa Santa Lucia, Chile

***Holly Chubb**, Andrew J. Russell, Alejandro Dussaillant and Stuart Dunning*

Landslides and mass flows are dynamic processes that involve the movement of rock, debris and earth downslope and present a major hazard in mountainous regions such as Chile. On Saturday 16 December 2017, a catastrophic mass flow (aluvian) partially destroyed the village of Villa Santa Luca and a 5 km long reach of the Panamerican Highway resulting in 22 fatalities. The apparent trigger was an intense rainfall event of 124 mm in 24h associated with an elevated 0ËšC isotherm (1600 m.a.s.l.) that led to the failure of 5.5 - 6.8 x 106 m3 mountainside in the uppermost catchment of Rio Burritos near the SE end of the Cordan Yelcho Glacier. The landslide transformed rapidly into a highly mobile debris flow, travelled into the proglacial lake at the foot of the Yelcho glacier, incorporating additional meltwater and glacier ice.

This paper characterises the geomorphological impacts and dynamics of the 2017 mass flow. Post-event DEMs, aerial photos and satellite imagery provided the basis for geomorphological mapping and terrain analysis. Fieldwork in January 2019 allowed sampling of mass flow deposits, logging of sedimentary sections and dGPS surveys.

The Villa Santa Luca aluvian had major erosional and depositional impacts. These included mass removal of trees and vegetation across the entire flow path, creation of a second river system, transportation and deposition of boulders and trees from the upper reaches of the path, creation of kettle holes, and stacking of trees and woody debris at the border of the flow deposit.

Erosion occurred predominantly in the first 7.9 km of the flow path due to high slope angles and the presence of a confined channel. The high proportion of coarse (boulder-sized) sediment in the flow enhanced basal scouring and erosion of the valley sides. The flow bulked up downstream due to entrainment of material along its path. A volume of 2x 4.8 x 106 m3 of sediment was deposited in the piedmont alluvial fan on which Villa Santa Luca is located.

The lack of clay particles and high proportion of sands and gravels in the sediment samples taken along the flow path suggest that the flow was non-cohesive nature and with a low viscosity. The low flow viscosity enhanced flow turbulence as the flow progressed downstream. Additional water acquired from the incorporation of glacier ice, proglacial lake water and river water will have further reduced viscosity and enhanced flow mobility.

Catastrophic mass flows like the event at Villa Santa Luca are likely to become more common around the world in the future as intense rainfall events become more frequent. This study may contribute to risk reduction by contributing to knowledge of the relationship between mass flow triggers, flow composition and resulting impacts.

Supraglacial lake drainage at a fast-flowing Greenlandic outlet glacier

***Thomas Chudley**, Poul Christoffersen, Samuel Doyle, Marion Bougamont, Charlotte Schoonman, Bryn Hubbard, and Mike James*

Supraglacial lake drainage events influence Greenland Ice Sheet dynamics on hourly to interannual scales, yet direct observations are rare, and to date no in-situ studies exist in fast-flowing sectors of the ice sheet. Here, we present new observations of a rapid lake drainage event at Store Glacier, West Greenland. The lake drained when a surface fracture opened, transporting 4.8 x 10^6 m^3 of meltwater to the glacier bed in 5 hours, reducing the lake to a third of its original volume. In response, the local ice surface raised by 0.55 m and surface velocity increased from 2 m d^-1 to 5.3 m d^-1. However, dynamic responses were greatest 4 km downstream from the lake, indicating important non-local influences by subglacial hydrology. Repeat aerial UAV imagery shows that drainage initiated when the lake expanded and intersected a moulin. This hydrological connection reactivated a pre-existing fracture that had been responsible for a lake drainage event one year earlier. Since formation, this fracture had advected ~600 m from the lake's deepest point, resulting in only partial drainage. Partial lake drainage events have previously been assumed to occur slowly via lake overtopping, with a reduced dynamic influence. Furthermore, remote sensing studies typically stipulate a volume reduction threshold of 80â€“90% to positively identify rapid drainage. Our analysis suggests that such events ` being both rapid and partial' are likely to be both more important and more common than previously reported, especially in marine sectors of the ice sheet where fractures are numerous and advection fast.

Contamination from nuclear fallout in glaciers across the global cryosphere: cryoconite's anthropogenic memory

***Caroline Clason,** Edyta Lokas, Giovanni Baccolo, Will Blake, Nick Selmes, Geoff Millward, Alex Taylor, Przemyslaw Wachniew, Phil Owens, Joseph Cook, & Ralph Fyfe*

Fallout radionuclides (FRNs) are a product of nuclear accidents and weapons testing, and are known environmental contaminants. There has been extensive research into the legacy of events such as the 1986 Chernobyl disaster and the 2011 Fukushima nuclear meltdown with respect to the impact on human and ecosystem health, however, this research has rarely extended into the cryosphere. Recent studies have revealed that FRNs, and other environmental contaminants, are being stored within and released from glaciers following deposition onto the ice/snow surface years or decades before present. Furthermore, we now know that the high concentrations of FRNs found in cryoconite are not confined to a limited geographical area. Our collective research has revealed widespread incidence of FRNs in cryoconite across multiple sites in the Arctic (Sweden, Iceland, Greenland and Svalbard), the European Alps, the Caucasus, British Columbia, and Antarctica. The levels of FRNs found in many cryoconite samples from these glaciers are orders of magnitude higher than those detected in other environmental matrices such as mosses and lichens, which are known to be efficient accumulators of FRNs. Indeed the highest concentrations of FRNs found in cryoconite are only exceeded by levels of radioactivity measured within nuclear exclusion zones. This raises important questions around the role of glaciers, and specifically cryoconite and its interaction with meltwater, in concentrating levels of FRNs to above those found in the surrounding environment. As FRNs and other contaminants are released into the proglacial environment through glacier melt and retreat they may act as a secondary source of environmental contamination many years after the nuclear events of their origin. Given the widespread occurrence of super-concentrated FRNs in glacier catchments, the impacts on downstream water and environmental quality, including uptake of FRNs into flora and fauna, should be a focus of future research efforts, and requires an interdisciplinary approach. Furthermore, given the high efficiency of cryoconite in accumulating FRNs, consideration should be given as to whether it could be used for biomonitoring of atmospheric contaminants in glaciated regions, as mosses and lichens have been used in other environments.

Topographic Influences on the Distribution of Icy Material in the Nereidum Montes; Mars

Jake Collins-May, *Dr. Rachel Carr, Dr. Matt Balme, Dr. Stephen Brough, Dr. Colman Gallagher, Dr. Neil Ross and Prof. Andy Russell*

Mars possesses a suite of water-ice features in its mid-latitude regions, between 30° and 60° north and south of its equator, yet these features could not have formed in these regions under the climate regime that is dominant on the planet today. It is hypothesized during periods of high (>30) obliquity, that ice is redistributed from polar to lower mid-latitude regions. However, it is currently unknown how local topography influences this process of ice deposition and subsequent preservation.

On Earth, the distribution of ice is the result of the interaction of precipitation and temperature, which are influenced by latitude, as well as local topographic factors, including altitude, slope, aspect and relief. Such topographic factors also likely play an important role in determining the distribution of icy material on Mars. To evaluate the importance of these topographic factors, we investigated the distribution of icy material in the Nereidum Montes mountain range in Mars's southern hemisphere. We mapped all icy deposits at a scale of 1:25,000 using CTX imagery, and investigated the elevation, slope, relief and aspect of this material and the surrounding landscape with reference to the MOLA digital terrain model.

Our data show that latitude, altitude, elevation, slope and relief influence the presence of icy material. In line with theory, the area of icy material increases at higher latitudes. However, this relationship is not linear, and there are localized areas where the concentration of icy material is greatest, suggesting that latitude is not the only factor influencing ice deposition. Elevation shows a complex relationship with ice distribution when normalized for area, with three distinct peaks in abundance at: -3500 m to -3500 m, -500 m to 0 m and 2000 m to 2500 m. Relief (local elevation range) is strongly linked to the presence of icy material. Areas of the Nereidum Montes with high relative relief almost always possess icy material, whereas areas with low relative relief are almost entirely devoid of any deposits. Icy material is comparatively rare on flat surfaces compared to moderate slopes (i.e. between 3-6°). While pole-facing slopes do exhibit more icy material than north-facing ones, aspect does not appear to be strongly tied to the presence of icy material. However, even in regions with apparently ideal combination of latitude, elevation, slope and relief, there are areas not covered in ice. This suggests that more localized factors, such as wind patterns, may influence ice formation or preservation at smaller scales. Our results indicate that topography does influence where ice is deposited and preserved in the Nereidum Montes, and future work will assess how these results relate to outputs from numerical climate models.

Validating a fully coupled model of calving, subglacial hydrology, proglacial plumes and ice flow at Store Glacier, West Greenland, using high-resolution radar interferometry

Samuel Cook, *Poul Christoffersen, Joe Todd, Donald Slater, Nolwenn Chaucha and Martin Truffer*

Tidewater glaciers are complex systems, which present numerous modelling challenges with regards to integrating several important processes occurring over different timescales. At the same time, understanding these systems is critical to being able to accurately predict the evolution of the Greenland Ice Sheet and the resulting sea-level rise, as the fifteen largest Greenland outlet glaciers are responsible for 77% of the additional mass loss from the ice sheet due to acceleration since 2000. In this study, we present preliminary results from a coupled numerical model of Store Glacier in West Greenland to constrain the form of the subglacial drainage system and melt rates from the resulting plumes, and the effect both these little-investigated components have on ice dynamics and calving behaviour. The model was run for a 6-year period, from January 2012 to December 2017, in order to capture seasonal variation across both high- and low-melt years. We suggest that current water inputs to the subglacial system are insufficient to develop a truly efficient subglacial drainage system at Store Glacier, and that therefore future higher surface melt and runoff may lead to an increase in basal water pressures and thus an increase in ice velocity and calving. We also posit that the pattern of plume melting under higher runoff values, where high melt rates are modelled to become very localised, encourages further calving by creating an indented calving front with ˜headlands' that are laterally unsupported and therefore more vulnerable to collapse.

One challenge with complex models such as the one presented here is validation, given the use of easily observable parameters, such as surface velocity, as inputs to the modelling process. We consequently also consider how the model results can be validated using a record of calving events at the terminus of Store Glacier gathered using a terrestrial radar interferometer emplaced one kilometre from the front over three weeks in July 2017. This observational record shows an approximate doubling of calving rates after melange break-up, and also shows 40% more calving events in the presence of visible subglacial plumes. Comparing this record to the spatial distribution, magnitude and timing of calving events seen in the model output will allow us to validate the model in an independent manner.

Subglacial roughness of the Greenland Ice Sheet: relationship with contemporary ice velocity and geology

***Michael A. Cooper**, Thomas M. Jordan, Dustin M. Schroeder, Martin J. Siegert, Christopher N. Williams, and Jonathan L. Bamber*

The subglacial environment of the Greenland Ice Sheet (GrIS) is poorly constrained, both in its bulk properties, for example geology, presence of sediment, and of water, and interfacial conditions, such as roughness and bed rheology. There is, therefore, limited understanding of how spatially heterogeneous subglacial properties relate to ice-sheet motion. Here, via analysis of two decades worth of radio-echo sounding data, we present a new systematic analysis of subglacial roughness beneath the GrIS. We use two independent methods to quantify subglacial roughness: first, the variability of along track topography enabling an assessment of roughness anisotropy from pairs of orthogonal transects aligned perpendicular and parallel to ice flow; and second, from bed-echo scattering enabling assessment of fine-scale bed characteristics. We establish the spatial distribution of subglacial roughness and quantify its relationship with ice flow speed and direction. Overall, the beds of fast-flowing regions are observed to be rougher than the slow-flowing interior. Topographic roughness exhibits an exponential scaling relationship with ice surface velocity parallel, but not perpendicular, to flow direction in fast-flowing regions, and the degree of anisotropy is correlated with ice surface speed. In many slow-flowing regions both roughness methods indicate spatially coherent regions of smooth bed, which, through combination with analyses of underlying geology, we conclude is likely due to the presence of a hard flat bed. Consequently, the study provides scope for a spatially variable hard bed/soft bed boundary constraint for ice-sheet models.

Unearthing the Forgotten Record of Glacier and Ice-sheet Change

***Michael A. Cooper**, Paulina Lewinska, David M. Rippin, William A. P. Smith, Edwin R. Hancock*

Prior to the satellite era (pre-1970s) knowledge of long-term glacier change is sparse. Although some glacier-wide mass balance datasets are available, few records extend beyond twenty years in length, or indeed, start prior to the 1980s; as such, identifying long-term trends between glacier change and global temperatures is difficult. Therefore, extending the record of glacier change will not only help to identify such trends, but may also facilitate more robust understanding of future glacier response under a perturbed and varying climate.

Since the `heroic age of Arctic (and Antarctic) exploration,' many photographs of polar environments have been captured and stored for historic interest. These photographs, however, have the potential to house a significant, and, as of yet untapped, geographical and glaciological resource: depicting images of past glaciers and ice sheet margins. Using computer-vision methodologies, we aim to reconstruct georeferenced models from historic imagery dating from the late 19th century (up to mid-20th C) in order to extract quantitative information pertaining to changing glacial extent and volume.

This is a Leverhulme-funded project working with the Scott Polar Research Institute (SPRI), who house one of the most comprehensive collections of polar imagery in the world. In this presentation I will introduce the project, present some initial surface reconstructions from a 1930s flyby of southeast Greenland, as well as some extracted glaciological information."

Impact of submarine melting on tidewater glacier retreat governed by plume location

Tom Cowton, Joe Todd and Douglas Benn

The response of tidewater glaciers to ocean warming remains a key uncertainty in sea level rise predictions. Here we use a 3-D numerical model to examine the response of an idealised tidewater glacier to spatial variations in submarine melt rate. Whilst melting towards the centre of the terminus causes only a localised increase in mass loss, melting near the lateral margins triggers increased calving across the width of the glacier, causing the terminus to retreat at several times the width-averaged melt rate. This occurs because melting near the margins has a greater disruptive impact on the compressive stress arch that transfers resistance from the sidewalls to the body of the glacier. We suggest that the rate of terminus advance or retreat may thus be governed by the difference between ice velocity and submarine melting in the slow flowing zones away from the glacier centre.

Calving cycle of the Brunt Ice Shelf, Antarctica, driven by changes in ice-shelf geometry

***Jan De Rydt**, Hilmar Gudmundsson, Thomas Nagler andJan Wuite*

The Brunt Ice Shelf in East Antarctica has recently received considerable attention in the public domain due to the formation of two 50-km long rifts and the imminent calving of a significant portion of the ice shelf. Calving events like these are part of the natural life cycle of every Antarctic ice shelf, but the underlying physical processes are poorly constrained, and we don't currently understand the true relevance of calving for the future of the Antarctic Ice Sheet. Although a revolution in satellite products has raised awareness and provides powerful images that help further our understanding, they need to be supplemented by a diagnostic framework to identify the key mechanical drivers that will allow us to predict future calving events and their impact. Here we use a unique 50-year timeseries of ice flow velocities, in combination with an ice dynamics model, to explain the timing and location of the recent rifting events on the Brunt Ice Shelf. Based on modeled changes in the englacial stress distribution, we argue that both rifts originated in areas of high tensile stress, generated by the growing ice shelf and regrounding at a local pinning point. Rifts subsequently propagated along directions defined by the maximum tensile stress and the inhomogeneous structure of the ice shelf. Lessons learnt for the Brunt Ice Shelf are directly transferable to calving elsewhere in Antarctica.

Seasonal Variations in the Surface Hydrology of Antarcticas Ice Shelves

Rebecca Dell*, Ian Willis, Neil Arnold, Alison Banwell and Hamish Pritchard*

The collapse of four major Antarctic Peninsula ice shelves since the 1950s, including most notably, the catastrophic collapse of the Larsen B Ice Shelf in 2002, highlights the need to better understand the drivers of ice-shelf instability under current climate warming trends. Surface and basal melting, firn densification, meltwater ponding-induced flexure and fracture, vertical hydrofracturing, horizontal fracture propagation, and ice shelf edge retreat are all factors that have been identified as potential contributors to past ice shelf collapse events. To further investigate the potential precursors to ice shelf instability, we analyse remotely sensed data from several Antarctic ice shelves. As the collapse of Larsen B was likely caused by the near instantaneous drainage of numerous melt ponds, we calculate the volume of surface water on present-day ice shelves that occurs in deep (~ 0.1 m) water bodies (lakes and streams) relative to the volume of surface water that occurs as slush (defined as water < 0.1 m deep), and investigate their changing patterns and seasonal trends. We use optical imagery from Sentinel-2 and Landsat-7/8, together with REMA DEMs, of the Nivlisen and George VI ice shelves, which both show extensive surface meltwater features. Results from the 2016-2017 melt season on the Nivlisen Ice Shelf reveal that slush accounts for up to 99 % of the total volume of surface meltwater for some time periods; however, the proportion of deep water vs. slush increases during periods of intense melt, as meltwater propagates up to ~ 24 km towards the ice shelf edge through a series of increasingly deep interconnected melt ponds and defined meltwater channels.

<u>Active subglacial lakes of Foundation Ice Stream, Antarctic Ice Sheet</u>

Lauren Derby, *Ross N, Ferraccioli F, Carr R, Jordan T, Siegfried M, Paxman G, Matsuoka K, Forsberg R and Casal T.*

Subglacial lakes beneath the Antarctic Ice Sheet were first identified using radio-echo sounding (RES) in the 1970s with more than 400 lakes now reported. Subglacial lakes can influence ice sheet dynamics, as the release of subglacial water has the potential to increase ice velocity leading to mass loss. The dynamics of subglacial lakes can be inferred at the ice sheet surface when ice surface elevation varies in response to the subglacial filling and draining of lakes (Smith et al., 2009). However, investigation of these `active' subglacial lakes with RES has suggested that surface elevation anomalies are often not underlain by the bright specular basal reflection typical of deep-water subglacial lakes.

Here, we compare the extent and surface elevation changes associated with active subglacial lakes recorded in the Smith et al., (2009) ICESat (2003 â€" 2008) inventory to PolarGAP RES data from Foundation Ice Stream. We evaluate whether the Foundation lakes are associated with basal radar reflection consistent with subglacial water. We analyse radargrams, ice surface and bed elevation, ice thickness and the hydropotential of four active lakes. We find that these four height anomalies do have physical characteristics consistent with the presence of subglacial water bodies beneath them, but the existing geometry of these features requires revision. This investigation provides a more complete characterisation of active subglacial lake systems beneath Foundation Ice Stream and further highlights the potential importance of active subglacial lakes for the dynamics of the Antarctic Ice Sheet.

Subglacial water pressure records from a fast-flowing, marine-terminating Greenlandic outlet glacier

Samuel Doyle, *Bryn Hubbard, Poul Christoffersen, Marion Bougamont, Robert Law, Tom Chudley, Mike Prior-Jones and Charlotte Schoonman*

Glacier and ice sheet motion is resisted by basal traction that can be reduced significantly by pressurised water at the ice bed interface. Fast-flowing, marine-terminating glaciers account for approximately half of total ice discharge from the Greenland Ice Sheet. Despite this, few records of subglacial water pressure have been collected from beneath such glaciers owing to the difficulty in drilling boreholes to the bed in areas that are often heavily-crevassed, and through ice that deforms rapidly and ruptures sensor cables within weeks. Here, we present pressure records and drilling observations from two sites located 30 km from the calving front of Store Glacier in West Greenland, where ice flow averages ~600 m yr-1. In 2018 boreholes were drilled 950 m to the bed near the margin of a large, rapidly-draining supraglacial lake. In 2019, multiple boreholes were drilled ~1030 m to the bed within the drained lake bed, and in close proximity to a large, active moulin. All boreholes drained rapidly when they intersected or approached the ice bed interface, which is commonly interpreted as indicating connection to an active subglacial drainage system. Neighbouring boreholes responded to the breakthrough of subsequent boreholes demonstrating hydrological or mechanical inter-connection over some tens of metres. Differences in the water pressure time series indicate that each borehole intersected a distinct component of the subglacial hydrological system. Boreholes located within 250 m of the moulin reveal clear diurnal cycles either in phase or anti-phase with moulin discharge. Pressure records from boreholes located on the lake margin, however, show smaller amplitude, and less distinct, diurnal cycles superimposed on longer-period (e.g. multi-day) variability. We compare these datasets to those in the literature and investigate consistencies and inconsistencies with glacio-hydrological theory.

Antarctic slopes fall down - MAAT controlled rockfall erosion rates and sediment fluxes

Stuart Dunning, *Matthew J. Westoby, John Woodward, Andrew S. Hein, Shasta M. Marrero, David E. Sugden and Kate Winter*

Mass movements lower ice-free bedrock slopes above glaciers and ice sheets. In the absence of significant fluvial activity, landslides and glacial erosion dominate total bedrock erosion in Antarctica. While erosion rates for subaerially-exposed bedrock surfaces are known amongst the lowest on the planet, the rates for Antarctic landslides have never been quantified. Using annual high-resolution surveys we show Antarctic rockfalls are capable of significant change, with annual face-averaged subaerial erosion rates decreasing from 0.096 mm yr-1 to 0.005 mm yr-1 along a latitudinal transect between 67°- 80°S. We find the decreasing erosion rate follows decreasing mean annual air temperature (MAAT). MAAT controls bedrock frost-cracking duration and intensity, simple 1D modelling link this ice segregation damage to the measured rockfall failure depths. The derived rockfall erosion rates are amongst the lowest globally, but, are comparable to glacial erosion rates elsewhere, which are also partially MAAT / latitude-controlled. Using the REMA elevation model, Landsat derived bedrock area, and, our latitude-erosion rate relationship we quantify rockfall derived fluxes from the Antarctic Peninsular down to the Ellsworth Mountains by latitudinal bands. Our results demonstrate rockfalls in Antarctic landscapes play a key role in altering bedrock topography, providing a previously unquantified supply of debris to its glaciers and ice sheets. As MAAT rises, rockfall rates will increase, and, more bedrock area will become ice-free to contribute material.

Cold Ice in a Warm Bath? News from an Arctic calving front (mid-field season)

Adrian Dye, *Joseph Mallalieu, Francesca Falcini, David Rippin and Rob Bryant*

A series of calving events above a thermally eroded notch and ice proximal lake temperatures of 3oC were reported from previous fieldwork (2017) in the Arctic for the first time. Studies in Patagonia, Nepal and New Zealand have also shown that where glaciers terminate in proglacial lakes, this contact accelerates glacier mass loss through thermal and mechanical processes, particularly through the formation of thermal notches in the ice front. Despite this there are limited studies into the thermal regime of proglacial lakes and very limited observations of temperature near the ice water contact point. The abundance and temperature of these proglacial lakes in Arctic glacier systems has received relatively little attention. This needs to be further addressed given recent extreme heat events and the Arctic Amplification of increased air temperatures.

We present preliminary recorded proglacial lake temperatures, sonar analysis and time lapse imagery from the second field season at the front of an actively calving Arctic glacier (67.954878°N, 18.561535°E), which rapidly lost 10,523m2 of ice (0.67% of area in RGI, 2008) between 2014 to 2018. The changing geometry of the glacier terminus during this retreat is recorded throughout the melt season via time lapse imagery. We present observations directly from the ice front in July 2019 from the innovative use of sonar and thermistor temperature surveys. Previous melt models for lacustrine terminating glaciers have been compromised by a lack of data from the hazardous water to ice contact point and assume a uniform temperature (e.g. 1oC). We address this previous limitation here and work towards developing a time series of iceberg calving volume from SfM analysis of time lapse imagery (Mallalieu et al., 2017). Advances in this research are particularly pertinent given reported warming trends of 0.08oCy-1 in lakes across Northern Europe (Hook and Schneider, 2010) and future projected increases in air temperature (IPCC, 2013).

Turning snow models the right way up on tundra

***Richard Essery**, Spencer Read and Nick Rutter*

Earth System and Numerical Weather Prediction models are beginning to use more sophisticated representations of snow on the ground, drawing on snow physics models that were first developed for avalanche prediction. These models have mostly been evaluated for deep mid-latitude mountain snowpacks, however, and they neglect important physical processes occurring in shallow Arctic snowpacks subjected to high winds and low temperatures. Tundra snowpacks typically have hard, fine-grained, high density wind packed surface layers overlying loose, large-grained, low density basal layers, but traditional models of snow compaction invariably predict profiles with density increasing towards the base of the snow. Improved models of snowpack structure will be important for representing the thermal properties of Arctic snow and exploiting information from microwave remote sensing over snow-covered surfaces. Recent field experiments, collation of results from long-term monitoring and improved atmospheric reanalyses are now providing data for diagnosis of errors in existing snow models and development of new models.

Regional linear retreat patterns of Greenlandic tidewater glaciers over the past 34 years in response to climate forcing

***Dominik Fahrner**, James M. Lea, Alec Davies, Jakob Abermann and Martin Olsen*

Greenland's tidewater glaciers (TWG) have contributed 66±8 % to the total mass loss of the Greenland Ice Sheet over the past 46 years and their calving dynamics are a controlling factor on ice sheet mass balance. Yet a comprehensive annual data set of terminus positions during the satellite era is still lacking.

We present a data set of annual late summer terminus positions for 208 TWGs in Greenland for the period 1984--2017 based on Landsat 4 â€“ 8 and Sentinel 2 imagery. The data set was manually digitised using the cloud-computing based Google Earth Engine Digitisation Tool (GEEDiT) and changes were quantified using the curvilinear box method within the Margin Change Quantification Tool (MaQiT; Lea, 2018). The results were analysed alongside seasonal oceanic and atmospheric climate data (air and sea surface temperatures), which were subsequently subjected to the application of the supervised tree ensemble machine learning method Random Forests.

After clustering the TWGs and normalising the terminus behaviour, our analysis highlights distinct linear trends in the regional response of TWG termini. The south-west, north-west and south-east regions are all found to display analogous behaviour (advance/stability until mid-1990s followed by sustained retreat until 2017). The north-east, however, showed sustained retreat until 2004/2005 followed by accelerated retreat until 2017.

The results of the machine learning analysis suggest the existence of oceanic and atmospheric temperature thresholds that may be predictors of advance/retreat behaviour. We foresee that the results presented in this study provide the possibility for the creation of simple empirically based models to predict TWG change on regional scales.

Are ice stream beds always smooth? Insights from contemporary and palaeo-ice streams

***Francesca Falcini**, David Rippin, Maarten Krabbendam and Katherine Selby*

The roughness of the bed beneath ice is an important control on ice stream location and dynamics. Previous bed roughness studies have typically used data from radio echo sounding (RES) transects over Antarctic and Greenland Ice Sheets. However, the coarse spacing of RES transects limits the connections that can be made between roughness and ice flow. Deglaciated terrain provides the opportunity to explore bed roughness in greater detail and over larger areas compared to glaciated terrain. Here, we use a palaeo-ice stream to investigate basal controls on contemporary ice stream behaviour. Transects were set up over the Minch Palaeo-Ice Stream (NW Scotland) with the same spacing as RES flight lines over Institute and Muler Ice Streams (Antarctica). We investigated how data-resolution, transect orientation and spacing, affected roughness measurements. The MPIS had a rough bed along major flow paths in the onshore onset zones, whilst smooth areas of the bed occurred over bedrock and sediment cover. This differs from the majority of previous studies, which found that fast ice flow occurred over smooth, soft beds. The results from the MPIS demonstrated that the presence of sediment does not necessarily correspond with fast flowing ice. The IMIS tributaries had rough and smooth beds, showing that palaeo and contemporary-ice stream bed roughness is comparable. We suggest that spacing of RES transects (10 x 30 km) used to measure bed roughness under contemporary-ice streams was too wide to capture bed roughness of MPIS glacial landforms, and that transect orientation impacts bed roughness measurements of contemporary and palaeo-ice streams.

The Debris-covered Glaciers Working Group: Melt Model Intercomparison Experiment

Adria, Fontrodona-Bach*, Francesca Pellicciotti, David Rounde, Lindsey Nicholson, Michael McCarthy and Working Group Members*

Many mountain ranges across the globe support abundant debris-covered glaciers, and the proportion of glacierised area covered by debris is expected to increase under continuing negative mass balance. We present the main motivations, objectives and activities of the newly established Working Group (WG) on debris-covered glaciers, and progress to date on its current main task.

The WG overarching aim is to advance understanding of how debris impacts glacier response to climate at the local, regional, and global scale. This is necessary to accurately represent debris-covered glaciers in models of regional runoff and sea-level change projections. In particular, we present the first set of results of the melt model intercomparison project, which compares at the point scale of automatic weather stations in distinct climatic regimes simulations of ice melt rates under varying debris thickness obtained with models of different complexity. We include energy-balance models with a variety of structural choices and model components, as well as simplified empirical approaches that have been to date applied with calibration of model parameters. A total of 15 models are assessed in 9 different climatic settings. We provide a first assessment of how well the models perform under different climate forcing and attempt to identify models strengths and limitations against validation data from the same sites.

Water flow through supraglacial debris

Catriona L. Fyffe*, Ben W. Brock, Evan Miles and Francesca Pellicciotti*

There have been few investigations of water flow within supraglacial debris and knowledge of both the rates and mechanisms of water movement within debris is lacking. Such understanding is imperative to allow accurate representation of this part of the hydrological system within debris-covered glacier hydrological models. The proportion of debris which is saturated also influences the debris thermal conductivity and heat transfer processes, and hence the rate of sub-debris melt. To date, this lack of data has precluded the inclusion of varying melt water saturation levels within debris-covered glacier melt models. This study aims to address these problems by identifying both the form and rates of water flow through the debris matrix using a combination of observations and dye tracing experiments conducted on Miage Glacier, Italy and Langtang Glacier, Nepal. Measurements of variations in debris water content along with supraglacial discharge are used to understand the temporal variations in the saturation of the debris layer. These reveal that the saturation level of debris within the lower 0.025 m varies on a diurnal cycle with a range of around 2% volumetric water content. A key new finding is that drainage within the debris follows preferential flow paths. On Miage Glacier this takes the form of minor depressions in the ice surface topography (width ~0.05-0.3 m, with ~1 m spacing) or, occasionally, micro-streams incised into the ice surface. On Langtang Glacier preferential drainage is also evident but the level of the stream bed can be within or on top of the debris surface. A map of continuous ablation created from repeat UAV DEMs corrected for ice flow also demonstrates that ablation is enhanced following the preferential flow paths.

Saddle Collapse of the Eurasian Ice Sheet in the North Sea caused by combined ice flow, surface melt and marine ice sheet instabilities

***Niall Gandy**, Lauren Jeremy, Stephen Cornford, Chris Clark, and David Hodgson*

Despite growing empirical evidence, the pattern of, and mechanisms that led to, deglaciation of the North Sea sector of the Eurasian ice sheet remains unresolved. The sector is dominated by the large Norwegian Channel Ice Stream that had a width comparable to the contemporary Thwaites glacier. Reconstructing the deglaciation of the North Sea is thus important to provide insights into marine ice sheets, the behaviour of large retreating ice streams, the subsequent marine transgression of the North Sea, and future sea level changes in the region. Numerical simulations of the deglaciation of the North Sea have struggled to capture the confluence and separation of the British-Irish and Fennoscandian Ice Sheets as shown by the empirical data.

We ran an ensemble of 70 experiments simulating the deglaciation of the North Sea between 23-18ka BP using the BISICLES ice sheet model. We employed mesh refinement capability to target the North Sea. Experiments are forced with HadCM3 climate simulations of the last deglaciation, varying initial ice sheet geometry and model parameters to account for uncertainty in climate, ocean, and ice dynamics. We then compared model outputs to empirical data for ice flow, extent and retreat ages using a suite of quantitative model-data comparison tools to identify the range of plausible scenarios for North Sea deglaciation.

In the ensemble members that best match the empirical data, the North Sea deglaciated through the collapse of the marine-based Norwegian Channel Ice Stream, unzipping the confluence between the British Irish Ice Sheet and the Fennoscandian Ice Sheet. Thinning of the Norwegian Channel Ice Stream causes surface temperature feedbacks, rapid grounding line retreat, and ice stream acceleration, further driving the separation the British Irish and the Fennoscandian Ice Sheets through the saddle collapse mechanism. The results allow for further work comparing model data to sea level records to create a Bayesian calibrated model reconstruction of North Sea deglaciation.

What can subglacial hydrochemistry reveal about upstream glaciological conditions?

Joseph Graly, *Kathy Licht, Neil Humphrey and David Bish*

Significant progress has been made in characterizing the chemistry of the subglacial waters of Greenland, Antarctica, and alpine glaciers. Existing chemical datasets show diverse chemical compositions, with mineral dissolution variably driven by carbonation reactions, sulfur oxidation, or brine formation. In temperate regions with large seasonal changes in water flux, the hydrochemical response to low-flow conditions varies substantially from site to site. For instance, at some sites, relative sulfur oxidation increases during winter, whilst at others it increases during summer. Distributed points collected from the glacial bed often differ substantially from waters collected at integrating glacial termini.

From these observations, it is often difficult to disentangle the influence of subglacial processes, hydrology, geology, etc. on the resulting hydrochemical signal. Some of the fundamental factors include the relative freshness of the sediment (i.e. the extent to which it is recently comminuted from rock), the relative abundance of subglacial water and whether the water sources from basal melt (where equilibration with the atmosphere is unlikely) or from surface melt (where atmospheric gases are drawn in). To isolate these factors, we've focused on chemical and isotopic tracers found in subglacial sediment. At several sites, we have compared the mineralogy and chemistry of subglacial sediments to that of underlying rocks, assessing the freshness of sediment and the degree of chemical alteration. We have employed meteoric 10Be, which forms in the atmosphere and is delivered to subglacial sediment from melting ice, as a tracer of the input of meltwater system. The incorporation of 10Be into clays and oxides traces their formation to a subglacial or surface environment.

In a case study at a site in the central Transantarctic Mountains, we have shown that the mineral balance between rock and sediment aligns well with the meteoric 10Be content of the sediments. This site suggests basal meltwater cycles through the subglacial environment at a rate far higher than the outflux of sediment, allowing for significant alternation of the underlying sediment. This sort of hydrochemical information can provide a critical insight into the physical conditions in the subglacial environment.

Instantaneous Antarctic ice-sheet mass loss driven by thinning ice shelves

G. Hilmar Gudmundsson, *Fernando S Paolo, Susheel Adusumilli and Helen Amanda Fricker*

It has been suggested that warming oceans are responsible for some of the observed ongoing changes in the ice-flow of the Antarctic Ice Sheet. However, to date no attempt has been made to quantify the direct effect of ocean-induced ice-shelf change on upstream glacier flow. Here we use a new data set derived from multi-mission satellite radar altimetry (1994-2018) of ice-shelf thinning to calculate for the first time the impacts on ice-flow caused by changes in ice-shelf buttressing. We carefully distinguish between long-term transient changes due to mass redistribution, and instantaneous changes due to changes in ice-shelf buttressing. Our modelling approach allows us to separate these processes and focus exclusively on the latter. We provide new estimates of ice loss, for the whole Antarctic Ice Sheet, due to observed changes in ice-shelf thickness over the last 25 years.

Formation, breaching and burial of a large moraine system, Skeiaer¡rsandur, Iceland

***Devin Harrison**, Neil Ross, Andrew J. Russell and Stuart Jones*

The sedimentary record of ice-contact depositional environments provides valuable information regarding changes in glacier margins, relative sea-level and the processes that drive the evolution of glacigenic outwash environments. Skeiar¡rsandur, south-east Iceland, is the largest active outwash system in the world, covering an area of up to 1300 km2 with an estimated sediment volume of 100-200 km3. The sandur is the primary depositional environment for Skeiar¡rkull, an outlet of the Vatnajkull ice cap and one of the largest glaciers in Iceland. The Sandgigar moraines, on the western flanks of Skeiar¡rsandur located down-sandur of the large Little Ice Age-moraines, have a relatively subtle geomorphic expression (typically 125 m wide and 7 m high). There is limited information regarding the formation of the SandgigÃºr morainic system and no adequate dating control on their age, hence the importance of further study at the site. Sections through the moraines crests reveal stratified sands and gravels which are lithified/cemented to a depth of 1.5 m. We present a low-frequency (40 and 100 MHz) ground-penetrating radar (GPR) survey of the Sandgigar moraines and the surrounding sandur. GPR observations reveal a much larger and more extensive buried moraine system that extends to depths of up to 50 m, and pre- and post-moraine sedimentary structures. Analysis and interpretation of the GPR data allows for the development of a conceptual model detailing the evolution of the Sandgigar moraines, from formation to their present-day morphology. Burial and breaching of the moraine system is likely to have been the result of outburst flood events, though their preservation reveals that this system has not been affected by jakulhlaup events in recent history. Our results provide new insights into the Holocene to present-day evolution of Skeiar¡rsandur and Skeiara¡rjakull, with implications for quaternary reconstructions of Iceland, moraine formation, and conceptual models of the evolution of glacigenic depositional environments.

Modelling the response of Petermann Glacier to ice shelf loss

***Emily Hill**, Hilmar Gudmundsson, Rachel Carr and Chris Stokes*

Ice shelves restrain flow from the Greenland and Antarctic ice sheets. Climate-ocean warming could force thinning or collapse of floating ice shelves, and subsequently accelerate flow, increase ice discharge, and raise global sea levels. Petermann Glacier in northwest Greenland has one of the ice sheet's last remaining ice shelves, but it lost 50-60% of this via two large calving events in 2010 and 2012. The glacier showed a limited velocity response to these calving events, but it is unclear how sensitive it is to future ice shelf loss. Here, we use an ice flow model Ua to assess the sensitivity of Petermann Glacier to changes in ice shelf extent. To do this, we perform two sets of experiments: 1) remove large sections of the shelf and calculate the instantaneous change in velocity due to a loss of buttressing, 2) perform transient experiments to assess the long-term (100 year) glacier response and estimate potential mass loss and sea level rise contribution. Our results reveal that the outermost portions of the ice shelf (> 12 km away from the grounding line) provide limited buttressing and removing them does accelerate flow inland of the grounding line. Once calving occurs closer to the grounding line, loss of these thicker and stiffer sections of the ice shelf could perturb stresses enough to substantially increase inland flow speeds (900 m a-1) and grounded ice discharge. However, the global impact of removing the ice shelf is limited to only 0.87 mm of sea level rise after 100-years. Further ice loss appears to be limited by grounding line stability at a topographic high approximately 12 km inland. This indicates that Petermann Glacier is largely insensitive to ice shelf loss, and the absence of a widening and deepening fjord further inland suggests it may remain insensitive to changes at a grounded terminus in the future.

Reconstructions of Antarctic palaeotopography since the Eocene-Oligocene boundary and implications for ice sheet behaviour

Stewart Jamieson, *Guy Paxman, Edward Gasson, Katharina Hochmuth, Karsten Gohl, Mike Bentley, Fausto Ferraccioli and Neil Ross*

Antarctica's bedrock topography exerts a fundamental control on ice sheet behaviour, having evolved significantly throughout the last 34 million years of glacial history. Accurate models of past Antarctic ice sheets therefore require a realistic reconstruction of bedrock topography at the time interval of interest. Here, we present ice sheet simulations over new reconstructions of past Antarctic topography at four time slices during the Cenozoic: the Eocene-Oligocene boundary (ca. 34 Ma), the Oligocene-Miocene boundary (ca. 23 Ma), the mid-Miocene climatic optimum (ca. 14 Ma), and the mid-Pliocene warm period (ca. 3.5 Ma). The aim is to understand the interplay between Antarctic ice sheet dynamics, subglacial landscape evolution and climate.

In our topographic reconstructions the land area of Antarctica situated above sea level was ~25% larger at the Eocene-Oligocene boundary than at the present-day. During the Oligocene and Miocene, deep near-coastal topographic troughs formed around the margin of East Antarctica, with up to 3 km of material removed by erosion, which in turn drove up to 1.5 km of flexural uplift of adjacent highlands. Contemporaneously, large areas of West Antarctica were experiencing thermal subsidence associated with the West Antarctic Rift System. By the mid-Miocene, the topography of East Antarctica began to closely resemble that of the present-day, and much of West Antarctica had subsided below sea level. Offshore sediment records and terrestrial constraints indicate that after the mid-Miocene, erosion and sedimentation rates in West Antarctica increased by ~50%, whereas rates in East Antarctica decreased by ~50%, with large areas experiencing relatively little modification after ca. 14 Ma.

We use an ice sheet model to simulate steady-state Antarctic ice volume and extent on this range of palaeotopographies, with sensitivity tests applying low, medium and high CO_2 conditions. We find that the Antarctic Ice Sheet has become progressively more sensitive to climate as a result of landscape evolution processes. The modelled sensitivity is particularly large in the vicinity of deep near-coastal subglacial basins around the margin of East Antarctica where the marine ice sheet and ice cliff instabilities become increasingly important processes towards present day.

Ocean-driven non-linear glacier retreat during the Holocene: southwestern Ross Sea, Antarctica

Richard Selwyn Jones, *Hilmar Gudmundsson, Andrew Mackintosh and Ross Whitmore*

Recent grounding-line retreat, dynamic thinning and mass loss in Antarctica has been attributed to oceanic warming. Episodic grounding-line retreat and rapid thinning also occurred in the southwestern Ross Sea during the Holocene, despite relatively cold ocean temperatures. We applied 2D mesh-based ice-flow modelling, constrained by geological data, to investigate the role of ocean temperature in the deglaciation of this region. Firstly, our experiments demonstrate that the bed geometry controlled the spatial pattern of grounding-line retreat. Topographic pinning points limited the rate of ice loss until retreat progressed beyond a bathymetric threshold. Secondly, ocean forcing determined the timing of this ice loss. In order to replicate the geological data, enhanced ocean-driven melt is required during the early-mid Holocene. Such oceanic changes are possibly linked to the production of High Salinity Shelf Water, and could explain similar episodes of ice loss that are recorded elsewhere in Antarctica at this time.

The velocity response of Cook Glacier, East Antarctica, to past and future large scale calving events and grounding line migration

***Jim Jordan**, Hilmar Gudmundsson, Chris Stokes, Stewart Jamieson, Bertie Miles and Adrian Jenkins*

The Wilkes Subglacial Basin in East Antarctica contains ice equivalent to 2-4 m of global mean sea level rise, draining through Cook Glacier. Recent observations show an acceleration in ice-speed over the grounding line for Cook Glacier, with the change in calving front position and a thinning of the ice shelf suggested as causes for the Western and Eastern sections, respectively. We use the ice model Ua to simulate the effects of changing ice geometry on the instantaneous ice velocity. Simulations show that the acceleration of Cook West was caused by a retreat in calving front position, whilst Cook Easts acceleration was caused by a combination of ice thinning and grounding line retreat. Simulations show that ice discharge at Cook East would increase by ~75% if it ungrounds from a pinning point. Simulations also show that if Cook Wests grounding line retreated by 10 km the ice discharge would increase by ~300%

Glacial lake expansion exacerbates Himalayan glacier mass loss

Owen King, *Atanu Bhattacharya, Rakesh Bhambri and Tobias Bolch*

Heterogeneous glacier mass loss has occurred across High Mountain Asia on a multi-decadal timescale. Contrasting climatic settings influence glacier behaviour at the regional scale, but high intra-regional variability in mass loss rates points to factors capable of amplifying glacier recession in addition to climatic change along the Himalaya. Here we examine the influence of surface debris cover and glacial lake expansion on glacier mass loss rates across the Himalaya since the 1970s. We find no substantial difference in the mass loss rate of debris-covered and clean ice glaciers over our study period, but substantially more negative (41-48%) mass balance for lake-terminating glaciers, in comparison to land-terminating glaciers. Despite representing a minor portion of the total glacier population (~10%), the recession of lake-terminating glaciers accounted for up to 32% of mass loss in different sub-regions. The continued expansion of established glacial lakes, and the preconditioning of land-terminating glaciers for new lake development increases the likelihood of enhanced ice mass loss from the region in coming decades; a scenario not currently considered in regional ice mass loss projections.

Airborne and ground-based geophysical evaluation of the surface hydrological system of the Sarsdal Glacier, East Antarctica

Bernd Kulessa, *Sarah Thompson, Sue Cook, Glenn Jones, Christopher Watson, Christian Schoof, Ben Galton-Fenzi, Hannes Hollmann, Matt King and Richard Coleman*

Large swathes of the margin of the East Antarctic Ice Sheet experience surface melting during the austral summer. The nature and temporal evolution of the surface hydrological system is poorly known, however, as are its potential connections with englacial and subglacial water systems and their effects on ice dynamics. We have acquired helicopter-based ground-penetrating radar (GPR), passive seismic and electrical self-potential (SP) geophysical data to delineate the geometry and monitor the temporal evolution of the surface hydrological system of the marine-terminating Sarsdal Glacier, Princess Elizabeth Land, East Antarctica, between the austral summers of 2017-18 and 2018-19. Our data reveal the presence of a shallow englacial hydrological system that is connected to surface lakes upstream of the grounding line and, surprisingly, is active not only in the austral summer but also through the Antarctic winter. Here we discuss the spatial and temporal characteristics of the surface hydrological system and its potential connection with tidally-forced ice dynamics.

Mapping supraglacial lakes over the entire Greenland Ice Sheet using Google Earth Engine, from 1984-present

James Lea *and Stephen Brough*

The filling and drainage of supraglacial lakes on the Greenland Ice Sheet has a significant impact on seasonal ice dynamics and represents a key component of overall mass balance. However, even with automated methods, the mapping of these on catchment scales can be extremely time consuming due to the requirement to download and process large volumes of imagery.

In this study we leverage the cloud computing capabilities of the Google Earth Engine (GEE) platform to rapidly execute established supraglacial lake detection methods. By utilising GEE we are able to circumvent previous requirements to download each image to be analysed, allowing the time series and geographical coverage of supraglacial lake monitoring to be substantially extended compared to previous studies. In this study we present initial results from combining available imagery acquired by Landsat 4-8 satellites (1984-2019). This comprises analysis of several tens of thousands of images with a typical execution time of 1-2 days on Google Earth Engine's servers, dramatically improving processing time compared to previous studies. Results show that the elevation and distance inland of lakes has been increasing during the last 10 years, achieving the greatest elevations/distances in 2012 and 2016.

These findings have significant implications for the monitoring of the Greenland Ice Sheet and understanding its response to contemporary climate change, providing the opportunity to interrogate the impact of supraglacial lakes on ice sheet scale behaviour for the first time.

<u>Quantifying post-Little Ice Age mass change in the Himalaya</u>

***Ethan Lee**, Duncan J. Quincey, Jonathan J. Carrivick and Simon J. Cook*

Himalayan glaciers store the greatest volume of ice beyond the Polar ice sheets, but their response to Holocene climate change is not very well documented in the literature. Recent work has focussed on modern glacier dynamics and on reconstructing Last Glacial Maximum extents, while glacier extent during the Little Ice Age (LIA) is relatively poorly understood. The limited research undertaken so far on LIA Himalayan glacier extent has demonstrated asynchronous retreat due to local topographic controls, and suggests that the LIA glacial advancement in this region peaked around 1500 AD with widespread retreat since 1850 AD. Here, we present an inventory of LIA extents across the entire Himalayan region, and provide a first-order estimate of the mass loss since the LIA. We take the Randolph Glacier Inventory (RGI) version 6.0 to represent present day glacial extents and use these data overlaid on recently released High Mountain Asia (HMA) 8m Digital Elevation Models (DEM) and remotely sensed images to digitise interpreted LIA glacial extents. By interpolating an estimated LIA glacier surface, we can then quantify areal and volumetric changes between the two epochs. In a final step, the results of their volumetric change are used to quantify the contribution of Himalayan glaciers to sea-level rise (SLR) since the LIA.

Evolution of Supraglacial lakes on Larsen B in the decades before it collapsed

Amber Leeson, *Elliott Foster, Aimee Rice, Noel Gourmelen and Melchior van Wessem*

Supraglacial lakes have been implicated in the disintegration of Larsen B Ice Shelf due to their ability to cause hydrofracture and thus structural weakening. Despite this, a detailed quantitative analysis of lake evolution in the decades prior to shelf failure has yet to be undertaken, largely due to a data gap in the optical (Landsat) record spanning most of the 1990s. Here, we combine the available optical satellite imagery with SAR data to produce the first multi-decadal analysis of lake evolution on Larsen B prior to its collapse. 13,850 lake occurrences were mapped over eight images between 1988 and 2002. We found that there is a high degree of inter-annual variability in lake area and number, which can be correlated with variability in climate. We also reveal a southerly spreading of the lake populated area at a rate of around 3 km a year between 1979 and 2002. Lake depth is calculated by applying a radiative transfer model to the Landsat imagery. We find that lakes get deeper year-on-year in a pattern which is statistically independent of changing melt amounts. This suggests that lakes on Antarctic ice shelves deepen either by melting out at their base or as a result of successive fill-drain cycles as opposed to climate forcing. The collapse of Larsen B Ice Shelf was the last catastrophic shelf disintegration event; therefore, it is vital to attempt to understand the mechanisms contributing to its failure. Such knowledge can then support more informed predictions of the future of Larsen C and other Antarctic ice shelves.

Reconstructing the geochronological context of the former Patagonian Ice-Sheet in under-studied northern Patagonian valleys (43°S) using cosmogenic radionuclide dating

***Tancrede Leger**, Hein, A. S., Bingham. R. G and Rode, A.*

The former Patagonian Ice Sheet (PIS) was the most extensive Quaternary ice sheet of the southern hemisphere outside of Antarctica, with a latitudinal extent of approximately 2000 km stretching along the Patagonian Andes (Davies et al., 2018). Against the background of global, Northern Hemisphere-dominated ice volumes, it is essential to document how the PIS and its sensitive outlet glaciers fluctuated throughout the Quaternary. This information can help us investigate the climate forcing mechanisms responsible for ice sheet fluctuations and provide insight on the causes of Quaternary glacial cycles at the southern mid-latitudes. Although the PIS has been subject to an increasing number of geochronological glacial reconstructions, there are a general lack of published data for glacial deposits from the north-eastern part of the former PIS, between latitudes 41 and 46Â° S. Glacier reconstructions in this region are required to better understand the latitudinal variation in the timing of glacial advance and retreat throughout Patagonia, and the complex atmospheric and oceanic circulation systems responsible for millennial-scale interhemispheric coupling of climate change throughout the last glacial cycle. This study presents an effort to reconstruct the glacial geomorphology and geochronology in a valley of northern Patagonia previously occupied by the Rio Huemul and Rio Corcovado (43°S, 71°W) outlet glaciers. Forty-five glacio-marginal cosmogenic samples and four glacio-lacustrine OSL samples collected in 2019 from those valleys are currently under analysis. With this dataset, we aim to constrain the timing of the local LGM through the dating of six well-preserved glacier expansion events. We also aim at dating the formation of two pro-glacial lake phases in those valleys, and reconstruct the timing of the local LGT and its associated Pacific/Atlantic drainage reversal. By comparing our findings with results from other palaeoclimate studies, this research aims at improving our understanding of atmospheric systems and energy re-distribution mechanisms responsible for climate variability in northern Patagonia. Such palaeoclimatic information is vital to parameterize climate models and better assess the significance of current and predicted global environmental change in the southern mid-latitudes.

Mapping Antarctic grounding lines from ICESat-1 and ICESat-2 repeat tracks

***Tian Li**, Geoffrey Dawson, Stephen Chuter and Jonathan Bamber*

Knowledge of the grounding line is critical in ice sheet numerical modelling, mass budget assessment and monitoring ice sheet stability. The grounding line position can be mapped from the limits of tidal flexure of the grounding zone from repeat track analysis of ICESat-1 laser altimeter data. Satellite laser altimetry has the potential to provide better sampling in both space and time compared with the differential satellite synthetic-aperture radar interferometry (DInSAR) and has a higher accuracy compared to CryoSat-2 radar altimetry. As a continuation of the ICESat-1 satellite mission, the satellite ICESat-2 was launched on 15 September 2018. ICESat-2 can achieve higher spatial resolution as well as an order of magnitude denser spatial coverage than ICESat-1. Previous mapping of Antarctic grounding lines from ICESat-1 repeat tracks was based on visual interpretation, which was computationally inefficient and could not be directly applied to ICESat-2. Therefore, a robust and efficient technique to automatically and repeatedly detect the grounding line for both ICESat-1 and ICESat-2 repeat tracks has been developed. Various proxies have been used to infer the grounding line location such as the break in slope and the point of hydrostatic equilibrium. Here we present a new method for extracting the grounding line position by detecting the landward limit of tidal flexure from ICESat-1 repeat tracks, which is tested on the Filchner-Ronne Ice Shelf. The estimated grounding line position is in good agreement with the previous grounding line products from DInSAR and ICESat-1. The mean absolute separations between our results and previous measurements from DInSAR and ICESat-1 are 1.03 km and 1.3 km, while the standard deviations are 0.83 km and 0.95 km, respectively. The method developed in this study is now being applied to ICESat-2 repeat tracks.

Ice shelf rifts: a three-dimensional linear elastic fracture mechanical analysis

Bradley Lipovsky

Understanding the processes that govern ice shelf stability are of fundamental importance to improved estimates of future sea level rise. The propagation of through-cutting fractures called rifts is the dominant control on the extent of modern ice shelves. I present the first ever three-dimensional fracture mechanical analysis of ice shelf rift propagation. I account for buoyancy, advection of pre stress, and the partial contact of rift walls. The results of these calculations illustrate the importance of ice shelf margins in the stability of ice shelf rifts. In particular, marginal weakening may cause rift propagation. This result is consistent with previous observations of marginal thinning prior to rift propagation on the Pine Island and Larsen Ice Shelves. This study provides a description of ice shelf calving that is based in fracture mechanics and that can be feasibly coupled to typical ice shelf flow models.

The retreat history of the Seno Skyring lobe of the Patagonian Ice Sheet following the Last Glacial Maximum

Maria Paz Lira*, Juan-Luis Garcia, Michael Bentley, Stewart Jamieson, Andrew Hein and Steven Binnie*

Patagonia hosts an exceptional opportunity to study past glacial activity due to its unique position in the Southernmost latitudes (between 47° to 56°S) and the exceptional preservation of the glacial features due the arid conditions that prevail on the lee side of the Andes. A series of dating studies in eastern Patagonia show an asynchrony during the Last Glacial Maximum (LGM) along Patagonia. In central Patagonia (45-48°S) the LGM took place between 27 to 23 ka ago, being contemporary with the global LGM. In Southernmost Patagonia (49-53°S) this signal is different, where the local LGM occurs at different times during MIS 3. Moreover, there are former ice outlets that still lack dating for the last glaciation. We aim to determine the extent and retreat chronology of the Seno Skyring lobe (52°, 71°W), located in Southernmost Patagonia.

We present a geomorphological map that distinguishes a series of landforms associated with the advance and retreat of the Skyring lobe. In particular, two sets of moraines, which are observed to have different morphological characteristics, characterise the form of the palaeo Skyring glacier. Finally, we show preliminary results of cosmogenic exposure age dating (9 of 32 samples) that constrain the outer advance as a local LGM during late MIS 3 and the inner one contemporary to the global LGM.

Structural evolution during a High-Arctic tidewater glacier surge

Harold Lovell *and Edward Fleming*

We present an investigation of glaciological structures at the front of the Paulabreen glacier system (PGS), Svalbard. The most recent surge within PGS was initiated in the tributary Skobreen in 2003. The surge propagated into the main flow-unit, Paulabreen, in 2005, activating the tidewater front and resulting in a ~2 km advance. We mapped surface glaciological structures (e.g. foliation, crevasses) from aerial photographs captured in 2003, before the surge had activated Paulabreen, and in 2011, six years after surge termination. Three-dimensional structural measurements of medial moraines, foliation, and debris bands exposed in the tidewater front were collected during fieldwork in 2013. These datasets document the physical changes experienced by PGS during (1) downglacier propagation of the surge; (2) activation of the main glacier trunk by the surging tributary, and (3) frontal advance. Large displacement (~1.5 km) of frontal moraine loops and medial moraines is evident, indicating simple shear as the surge propagated both laterally and downglacier. Changing crevasse patterns record the passage of the surge front and the associated change in tectonic regimes. The surge failed to propagate laterally into Bakaninbreen, the other main flow-unit within PGS that last surged in 1985-1995. The independent surge behaviour of flow-units within PGS means a total collapse of the tidewater glacier system has been avoided thus far in the 20th/21st centuries. Such collapses have recently occurred elsewhere in Svalbard (Nathorstbreen glacier system, Austfonna ice cap) and in the Russian High Arctic (Vavilov ice cap, Severnaya Zemlya), resulting in large and rapid ice mass losses.

Greenland Ice Sheet Elevation and Elevation Change: How do the Sentinel-3 missions compare to CryoSat-2?

Jennifer Maddalena, *Geoffrey Dawson, Jack Landy, Stephen Chuter and Jonathan Bamber*

Since 1992, satellite-borne radar altimetry has been used to record surface elevation change over the Greenland ice sheet (GrIS). Until the launch of CryoSat-2 in 2010, conventional radar altimeters performed poorly over high sloping terrain with heterogenous topography. The novel synthetic aperture radar interferometric (SARIn) mode of CryoSat-2 is used over the margins of the GrIS, which have been experiencing the largest mass loss, and has improved capability in these regions of high sloping terrain. ESA's Sentinel-3 missions are the latest radar-altimeters to be launched. The first satellite, Sentinel-3A, was launched in February 2016 followed by Sentinel-3B April 2018.

Sentinel-3A is the first satellite to use synthetic aperture radar (SAR) across the interior of the GrIS. This has improved the along-track resolution (sampling) to approximately 300 m compared to CryoSat-2 Low Resolution Mode (LRM) footprint which has a diameter of ~1.65 km. Here, we establish the capacity of Sentinel-3's SAR altimeter to monitor the GrIS and identify any mission biases that may occur in continuing the elevation change record. Through crossover analysis and a point-to-point comparison, we assess the performance of Sentinel SAR mode compared to the LRM mode of CryoSat-2 over the interior of the ice sheet and the SARIn mode over the margins of the GrIS. We then assess the implications of this comparison for monitoring glaciology processes over the ice sheet.

Calving at lacustrine ice-margins: an integrated SfM time-lapse analysis of processes, mechanisms and drivers in west Greenland

***Joe Mallalieu**, Jonathan Carrivick, Duncan Quincey and Mark Smith*

Ice-marginal lakes can exert considerable control over ice-margin dynamics, frequently accelerating rates of mass loss and ice-margin recession. Such lakes are a common feature along the western margin of the Greenland ice-sheet, where they have increased in both number and volume over recent decades. Consequently, an understanding of the capacity of ice-marginal lakes to regulate ice-margin dynamics in Greenland is of growing importance. However, the inaccessibility and highly-dynamic nature of lacustrine ice-margins, coupled with the climatic and financial constraints of field-based investigations, have limited existing studies of lacustrine ice-margin dynamics to melt seasons in predominately mid-latitude alpine environments.

Fine spatio-temporal resolution records of ice-margin dynamics over extended durations (i.e. > 1 yr) are now achievable through the integration of time-lapse photography and Structure-from-Motion (SfM) techniques (Mallalieu et al. 2017). Here we present the results of a continuous 15 month SfM time-lapse camera survey of a lacustrine ice-margin in west Greenland. Analysis of 56 successive ice-margin point clouds yields a comprehensive database of calving losses throughout the study period, including the areas, volumes and mechanisms of >300 calving events. Our dataset also documents the effects of two lake drainage events on ice-margin stability. Coupled with records of lake volume and weather, our approach reveals the key relationships between ice-marginal lake properties and ice-margin dynamics over two successive melt seasons at a high-latitude ice sheet margin, with potential implications for modelling the future response of the Greenland ice sheet to anticipated increases in meltwater production and ice-marginal lake growth."

Effects of canopy structure and snow cover fraction on wintertime land surface albedo of forested environments

Johanna Malle, *Nick Rutter, Clare Webster and Tobias Jonas*

Land surface albedo (LSA) is strongly affected by seasonal snow cover and the presence of forest canopy. In forested environments, LSA is the result of downwelling and upwelling shortwave radiation fluxes through the canopy; spatial and temporal variation of solar radiation transmission to the snow surface is a function of the 3D canopy structure. The amount of solar radiation that is subsequently reflected at the forest floor is controlled by snow cover fraction, the albedo of the snow on the ground as well as canopy shading of the snow surface. Canopy density further modulates the absorption of upwelling solar radiation but also affects snow interception entailing enhanced backscatter of solar radiation in the upper canopy. Accurately representing these fluxes in land surface models is challenging and poorly constrained due to a general lack of suitable measurements.

In this study we compare above-canopy drone-based LSA measurements to simultaneous sub-canopy measurements along the same horizontal transects. Respective data were acquired at five sub-alpine discontinuous forest locations in Switzerland as well at three boreal forest locations in northern Finland, capturing a wide range of forest structures and species found in seasonally snow covered environments. A total of 130 UAV flights captured daily and seasonal ranges of solar zenith and azimuth angles, snow cover extents, cloud cover conditions, and interception loads. Our analysis showed the ratio of tree-shaded area per ground surface area to be a primary control on effective LSA on clear sky days. Results of this study emphasize a need for improved representation of canopy structural shading of the snow surface in land surface models.

A Multi-Proxy Sediment Provenance Record of Antarctic Ice Sheet Change in the Early to Middle Miocene: Preliminary Results from IODP Site U1521 (Ross Sea)

James Marschalek, *T. van de Flierdt, A. Carter, P. Vermeesch, M. Siegert, K. Licht, R.M. McKay, L. De Santis, D. Kulhanek, and the Expedition 374 Scientists*

An accurate record of past ice sheet change is critical for constraining models that predict future mass loss from Antarctica. During January to March 2018, International Ocean Discovery Program (IODP) Expedition 374 conducted a latitudinal/depth transect involving five drill sites from the outer continental shelf and rise in the eastern Ross Sea. The drilling was designed for optimal data-model integration, enabling an improved understanding of the sensitivity of Antarctic Ice Sheet mass balance during warmer-than-present climates (e.g. the early Pliocene and middle Miocene).

411.5 m of early Miocene to recent sediments were recovered from site U1521 (75°41.0351S, 179°40.3108W, 562 m water depth), located in the Pennell Basin on the middle-outer continental shelf. The primary objective of this site was to sample and date strata above and below Ross Sea Unconformity 4 (RSU4), which had been previously identified in seismic stratigraphic studies.

To elucidate the erosional behaviour and extent of Miocene-to-recent ice sheets in the Ross Sea, we applied a multi-proxy geochemical approach including detrital zircon U-Pb dating and the measurement of fine grained (<63 Î¼m) neodymium and strontium isotope ratios. Preliminary data on 30 samples with depositional ages spanning from the present to ~18 Ma show epsilon neodymium values ranging from approximately -5 to -10. Intervals with lower values appear to correlate with maxima in magnetic susceptibility. Uranium-Pb age spectra on ten select samples deposited between ~3 and 18 Ma are dominated by zircons with ages spanning 500 to 600 Ma. Other age populations vary substantially in their downcore abundance and include grains dating to approximately 90-120 Ma and 180-220 Ma, as well as many grains older than 600 Myr. Future work will complement these existing data sets with other provenance indicators to unravel changes to ice sheet form and flow in the Miocene.

Crevasse and rift detection from satellite-based SAR backscatter

Oliver Marsh

Crevassing and rifting strongly impact the flow of ice, effectively softening key regions of glaciers and ice sheets and leading to the formation of icebergs and ice shelf instabilities. In addition, they can be a hazard for field operations which, in Antarctica, are increasingly moving towards overland traverses. Sub-surface features hidden by snow bridges up to several metres thick have historically been identified using ground-penetrating radar. Here we discuss the application of satellite-borne synthetic aperture radar systems including L-band ALOS PALSAR, C-band Sentinel-1, and X-band TerraSAR-X, for a broader mapping of sub-surface features, their formation and their evolution. The effectiveness of these sensors at identifying sub-surface features is strongly dependent on their individual imaging geometries, ground-resolution, wavelength and polarisation. Satellite data is compared directly with coincident ground-based observations from within a crevasse field on the Beardmore Glacier, Antarctica and across rifts on the Brunt Ice Shelf. A strong agreement is shown between crevasse locations identified from ground-penetrating radar and SAR imagery. Mapping of crevasse location and orientation in this way can be applied to assist with route finding through crevassed terrain; to identify areas of active crevasse formation, rate of burial in inactive areas and damage criteria for ice sheet models; and to understand ice fracture processes and ice rheology.

New insights into polar ice crystal fabrics from radar polarimetry

Carlos Martin Garcia, *Alex Brisbourne, Jonnathan Kingslake, Robert Mulvaney, Julius Rix and Catherine Ritz*

Ice is one of the most anisotropic natural materials but it is common knowledge in our community that anisotropy in ice is: a) a second order factor that can be ignored, b) easily assimilated into isotropic models by tuning certain parameters or c) so complicated that it is better to ignore. Interestingly, any measurement of anisotropy in polar ice shows that ice develops crystalline preferred-orientation fabrics that produce strong mechanical, optical and dielectric anisotropic properties. Here, we look in detail at polarimetric radar measurements in different regions of East and West Antarctica. We use a ground-based phase-sensitive frequency-modulated continuous-wave radar (ApRES) and a matrix-based model to study the radio-waves depolarization and anisotropic scattering (Fujita et al, 2006). We find that anisotropy is widespread and an excellent archive of past ice flow conditions. We use it here to extract details of the recent deglaciation of the Ross and Ronny ice shelves over the last thousands of years. Also, we use our method to show that a candidate ice core location near Dome C for the Beyond Epica Oldest Ice Core project, has been under steady ice-flow conditions over the last million years or so.

The Role of Ice-Bed Interface Conditions on Basal Slipperiness and Instability

Rebecca McCerery, *John Woodward, Glen McHale and Kate Winter*

Controls on fast ice flow are key to understanding the behaviour of glaciers and ice sheets and discerning mechanisms of glacier instability such as surging. Current theories suggest sliding controlled by subglacial hydrology or the deformation of subglacial sediment are the dominant mechanisms that generate fast flow. However, the importance of subglacial deformation as a driving mechanism has been contested due to the lack of pervasive, thick deforming layers in the sedimentary record of palaeo-ice streams. Recent advances in material physics have highlighted the role of micron- and nano-scale roughness for creating super hydrophobicity. Furthermore, bio-inspired slippery liquid infused porous surfaces (SLIPS) and lubricant impregnated surfaces (LIS) can produce super slippery surfaces with excellent water shedding properties. This study aims to understand how the chemical, biological and structural properties of basal sediment may induce hydrophobicity and SLIPS/LIS at the glacier bed with the hypothesis that they can create fast flow in glaciers and ice sheets. Using monolayers of different sand particle sizes treated with a commercial hydrophobising agent (Granger's Solution) and 20cSt silicone oil, model hydrophobic and oil impregnated basal environments were created. Using a KRUSS Droplet shape Analyzer (DSA) the degrees of hydrophobicity and water mobility were classified per sediment size. Our results show that increasing micron-scale roughness leads to an increase in contact angle and droplet mobility on a hydrophobic sediment surface. We also found that droplet motion is enhanced with oil impregnation of the surface. The implications of these experiments support our hypothesis that hydrophobic sediments and SLIPS concepts are important for glacier flow dynamics, in particular in areas of hydrocarbon release to the ice-bed interface.

Links between calving dynamics, ice velocity and grounding line retreat of Denman Glacier, East Antarctica 1962-2018

Bertie Miles, *Jim Jordan, Chris Stokes, Stewart Jamieson, Hilmar Gudmundsson and Adrian Jenkins*

Over the past two decades outlet glaciers in Wilkes Land, East Antarctica, have been thinning, losing mass and retreating. This has raised concerns over the future stability of some of its major outlets that drain the Aurora Subglacial Basin, such as Totten, Denman, Moscow University and Vanderford Glaciers. Their present-day grounding lines are close to retrograde bed-slopes and, furthermore, geological evidence indicates that they may have experienced substantial retreat under past warm climates, which are similar to those predicted in the near-future. After Totten, Denman Glacier, is thought to be the largest contributor to global sea level rise in East Antarctica. However, despite its importance there are few detailed observations of its recent dynamics. In this study, we use remote sensing observations to report on the changes in glacier velocity (1962-2018), calving dynamics (1962-2018) and groundling line position (1996-2018). This reveals a ~17% increase in velocity between 1972-74 and 2018, and a retreat of the grounding line between 1996 and 2018. We also observe significant differences between Denman's present-day calving regime (1985-present) compared to past calving activity (1940's-1985). In addition, Denman's ice shelf has shifted a few kilometres westward and now makes significantly less contact with an eastern pinning point that may have previously exerted a buttressing effect. Using a numerical ice flow model (Ua), we simulate these observed changes to explore the drivers of the recent acceleration.

Incorporating dh/dt measurements into ice flow model inversions: a case study on the Larsen C ice shelf

***Tom Mitcham**, Hilmar Gudmundsson and Jonathan Bamber*

To model ice dynamics in real-world settings, inverse methods are often used to estimate the free parameters in the governing equations. Within the Ua ice flow model, used here, these parameters are the rate factor in Glen's flow law, A, and the basal slipperiness coefficient, C, in a `Weertman' type sliding law. Typically, the inverse problem is solved by iteratively adjusting these parameters to minimise the mismatch between observations of ice velocity and modelled ice velocity. However, discrepancies between the velocity measurements and other data sets used in the model, such as ice thickness or bedrock topography, can result in unphysical, large amplitude, short wavelength dh/dt (rate of change of ice thickness) values in the subsequent forward runs. Existing techniques to combat this behaviour, and to provide initial model conditions close to a steady state, include model spin-up or relaxation runs and applying synthetic mass balances. Here, in a case study on the Larsen C ice shelf and its tributaries, dh/dt measurements are incorporated into the inversions such that the model output is tuned to fit both velocity and dh/dt observations. The resulting A and C fields, and the initial transient model behaviour, are compared with those from inversions using velocity observations alone. The suitability of the resulting initial conditions for subsequent perturbation experiments are compared with those from other commonly used model initialisation techniques.

Using fluctuations in borehole water pressure to infer sediment properties beneath Rutford Ice Stream, West Antarctica

Tavi Murray *and BEAMISH Project members including: Paul Anker, Alex Brisbourne, Dominic Hodgson, Keith Makinson, Keith Nicholls, Samu Rios Costas, Rebecca Schlegel and Andy Smith (PI).*

Fast flowing ice streams and outlet glaciers act as volume regulators for the polar ice sheets of Greenland and Antarctica. Thus, ice stream flow speed is one of the key controls on the ice sheet's contribution to sea level rise. The fast flow of these ice masses is controlled and facilitated at their base, making it key to understand basal processes and conditions. The Rutford Ice Stream is a fast-flowing glacier that drains ice from the West Antarctic Ice Sheet into the Ronne Ice Shelf. In January 2019 for the first time we drilled three holes to the bed of the Rutford Ice Stream using a hot water drill. Two holes were drilled close together at a site where the sediments at the bed are actively deforming and the third was drilled ~2.5 km downstream at a site where the ice is sliding over the basal sediments. Ice thickness in this area is ~2200m and borehole radii were ~0.18m.
Drilling the first hole we did not know the exact depth at which it would connect to the basal water system. The hole was therefore overpressurised on connection, and it drained rapidly with the water pressure dropping ~23.5m over ~1 minute. No sediments were collected from this borehole and it is likely that the bed was flushed by the arrival of the borehole water. Water level in the subsequent boreholes was manipulated close to completion to ensure it was balanced with the expected water pressure at the ice stream base in order to minimise disturbance to the bed. In the second borehole the water level at connection rose by ~0.9m and began oscillating. Oscillations were reinitiated periodically until the pressure sensor was removed ~18 hours later. The period of these oscillations was ~4-8 minutes. This borehole successfully reached the bed, and sediment samples were retrieved. The third hole did not any show any pressure response on completion. Although sediments were collected on the drill stem, these are interpreted as being of englacial origin. Water was subsequently pumped into this borehole and it drained progressively ~35 hours later, with water pressure dropping ~69m over ~30 minutes. Each borehole shows different drainage characteristics and we interpret the responses using analyses designed for slug testing. Drainage events in boreholes 1 and 3 are interpreted using Cooper-Bredhoeft-Papadopulos and Hvorslev methods. The oscillations seen in borehole 2 are interpreted using the Van der Kamp method for underdamped slug tests. Using these methods we estimate the hydraulic conductivity of the basal sediments in regions of basal sliding and bed deformation.

The subglacial hydrology of the Ellsworth-Whitmore Mountains West Antarctica: newly identified subglacial lakes and the stability of water flow since the Mid-Pleistocene.

Felipe Napoleoni, *Jamieson, S.S.R., Bentley, M.J., Ross, N., Rivera, A., Smith, A., Gacitua, G., Paxman, G., Uribe, J.A., Zamora, R., Brisbourne, A., Siegert, M and Vaughan, D.G.*

There is a well-developed subglacial hydrological network across the Antarctic continent (Wright et al., 2012; Fricker et al., 2014) and in places it is highly dynamic (Fricker et al., 2007). This is important because the subglacial water plays a fundamental role in controlling ice flow.

We aim to characterize the subglacial hydrology system in the Ellsworth subglacial highlands, West Antarctica, and assess the sensitivity of the flow routing under different ice sheet configurations. We are doing this so that we can better understand the regional setting of the various subglacial lakes in this area, including the recently discovered Lago Subglacial CECS (SLC; Rivera et al., 2015). Knowledge of the source area for water in the lake as well as any potential drainage directions will help us determine the stability of the lake over recent and glacial-interglacial timescales. To understand the modern hydrological system, we use a range of available data (e.g., radar, Cryosat-2 ice surface DEM data); firstly, for calculating the hydropotential; and secondly, for determining the flow routing within Ellsworth-Whitmore Mountains (EWM) terrain. We then extend this approach to assess how the subglacial hydrological system responds to changing ice conditions (e.g., during glacial-interglacial cycles) where the ice extent, thickness, surface slopes and divides all evolve. To do this we use ice sheet model output (Pollard and DeConto, 2012) for snapshots of ice geometry relating to the last 150 k yr within which time period significant changes in ice conditions have been experienced.

We also conduct a broader analysis of the presence of subglacial water bodies in the region surrounding Lago Subglacial CECs. We identify ca. 23 new subglacial lakes by means of Radio Echo Sounding in the head of the subglacial basins underneath the ice divide of Pine Island Glacier (PIG), Rutford Ice Stream (RIS) and Institute Ice Stream (IIS) near Subglacial Lake Ellsworth and CECS. Analysis of present subglacial hydrological conditions suggest many of these subglacial lakes are connected in a bigger subglacial hydrological network, but some are not. Modelling of the past configurations of subglacial hydrological conditions (e.g. during the Mid-Pleistocene), using hydropotential from simulations, shows both spatial and temporal evolution of this subglacial hydrological network and indicates that in some areas water flow has reversed (e.g., RIS from Weddell Sea toward Amundsen Sea sector) but in other areas with isolated subglacial lakes, e.g. SLC, water conditions have remained largely static since the Mid-Pleistocene.

The findings of this work will improve our understanding of the subglacial hydrology of the EWM, and will be used to inform future subglacial lake access experiments in the EWM and in particular to Lago Subglacial CECS.

Dynamic discharge variability and mass balance of the Academy of Sciences Ice Cap, Severnaya Zemlya, Russian Arctic

Pablo Sanchez-Gamez, ***Francisco J. Navarro,*** *Toby J. Benham, Andrey F. Glazovsky, Robin P. Bassford Julian A. Dowdeswell and Jamie Otero*

We analyse, using feature tracking, 54 pairs of Sentinel-1 synthetic-aperture radar (SAR) images of the Academy of Sciences Ice Cap, Severnaya Zemlya, Russian Arctic, from the period November 2016-November 2017. Seasonal velocity variations up to 20% (peak-to-peak) of the yearly-averaged velocity are observed. Shorter-term intra-annual velocity variations have average deviations up to 32% and maximum up to 64% (peak-to-peak). This provides an order-of-magnitude of the errors that could be incurred when extrapolating to the whole year discharge values determined using a single pair of SAR images. Average ice discharge for 2016-2017 was 1.93±0.12 Gt/yr. We attribute the difference from an earlier estimate of 1.4 Gt/yr for 2003-2009 to the initiation of ice stream flow at Basin BC. The total geodetic mass balance for the ice cap over 2012-2016 was -1.72±0.67 Gt/yr (-0.31±0.12 m w.e./yr). The climatic mass balance is not significantly different from zero, at 0.21±0.68 Gt/yr (0.04±0.12 m w.e./yr), and seems to have remained at this level for the last four decades Therefore, the total mass balance is governed by the variations in ice discharge, whose long-term changes do not appear to respond to environmental changes but to intrinsic characteristics of the ice cap.

Assessing the accuracy of a deglacial history of Antarctica

***Mark Pittard**, Pippa Whitehouse and Michael Bentley*

Understanding the evolution of the Antarctic Ice Sheet throughout the last glacial cycle has important implications for understanding its present-day contribution to sea-level change. Satellite-based measurements of the present-day mass balance of Antarctica must be corrected for a signal associated with deformation of the solid earth beneath the ice sheet. However, this rate of deformation is dependent on a number of factors, including the viscosity of the mantle and the deglaciation history of the ice sheet. The estimated maximum volume of the ice sheet at the last glacial maximum ranges from ~5m of sea level equivalent to up to ~30m of sea level equivalent depending on the methodology used. While there are observations of the present-day rates of deformation, these are point measurements which are both spatially and temporally sparse requiring models to incorporate all of Antarctica. The response of the solid earth can be predicted using a deglaciation model of Antarctica in conjunction with an isostatic adjustment model. Outputs can be validated with the existing observations, however uncertainty in the rheology of the solid earth allows for different deglaciation models to match these similarly. There is a growing database of observations of the past configuration of the ice sheet which can be used to quantitatively assess the accuracy of existing and new deglaciation models of Antarctica. Here we develop a scoring methodology which focuses on using observations of ice thickness, ice extent and ice thinning rates in addition to comparing the output to present day uplift rates. The uncertainty in the dating of palaeo-observations and the asynchronous nature of the deglaciation is taken into account. We test our scoring methodology on three widely used ice loading models, ICE-5G/6G and W12 in addition to a small ensemble of simulations using the Parallel Ice Sheet Model.

Assimilation of geophysical data in snow hydrology modelling

Alex Priestley

Modelling and monitoring seasonal snow is critical for water resource management, flood forecasting and avalanche risk prediction. Snowmelt processes are of particular importance. The behaviour of liquid water in snow has a big influence on melting processes, but the ways we monitor this in the field are expensive and often require human observers. This project attempts to apply geophysical measurement techniques in a novel fashion to snow, to create an in situ automatic monitoring system to monitor liquid water behaviour as the snow melts. Following laboratory tests using artificial snow during summer 2018, a prototype system was installed at a French alpine site in autumn 2018. Techniques to measure small electrical currents generated by water in the snow, and differences in electrical resistivity between dry and wet snow were used. Standard meteorological and hydrological observations were also taken. Alongside field measurements, modelling experiments were conducted using a snow hydrology model. Some data from last winter's field season are discussed here, along with proposed modifications and improvements for next winter's fieldwork.

Cryoegg - field trials of a wireless subglacial sensor platform for deep, fast moving ice

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Much of our knowledge about the englacial and subglacial environment comes from sensors deployed in boreholes on rugged cables that return data to a logger unit on the surface. Glacier motion often has a detrimental effect on the cables, especially in fast-moving glaciers and ice streams, which results in data loss. Since it is desirable to obtain these data year-round, there have been several attempts to develop wireless subglacial sensor platforms, notably Glacsweb (Hart et al. 2006 etc.) and WiSE (Smeets et al.) and previous iterations of our Cryoegg (Bagshaw et al. 2014). Wireless sensors also have the advantage that they could be more conveniently deployed. In this paper, we present the latest trials of a new version of the sensor platform, carried out on fast flowing ice at two locations in Greenland during July 2019 (EGRIP and RESPONDER). We demonstrate that the radio link can operate through more than 1km of ice, and that it can also work in the very hostile environment of a large moulin on a Greenlandic glacier. The current electronics can measure conductivity, temperature and water pressure to interpret englacial and subglacial dynamics, and can easily be modified to accept other types of sensors.

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SNOWFALL: a new way to measure an important water resource

Hamish Pritchard

Snowfall is important. Each winter, snow covers 45 million km2 of the northern hemisphere, shrinking to 2 million km2 each summer, a substantial water resource stored and released with the seasons. The water content of snow is hard to model though and estimates are uncertain and often likely to be biased, being underestimated by a factor of up to 3 in some Asian mountain ranges.

The models struggle in part because snowfall is difficult to observe, and is very variable across mountain landscapes. Numerous measurement techniques have been developed over the last 800 years but all have limitations in spatial and temporal sampling or functionality that mean that they are not widely used: in most of the world's mountain river catchments there are no snowfall observations. This lack of data means that it is often not possible even to check the estimates of models, let alone refine model skill at predicting snow.

I have developed a novel measurement technique that provides low-cost, autonomous, near-real-time, direct observations of the mass of water falling as snow (the Snow Water Equivalent, SWE) on spatial scales of thousands to millions of square metres, scales that are large enough to be directly comparable to the resolution of weather models. Tests of this new technique in Arctic and Alpine settings show that it is highly sensitive to falling snow, and they highlight the biases present in conventional instruments and operational weather forecast models."

Evolution of Supraglacial Channels on the Greenland Ice Sheet

Lauren Rawlins, *David Rippin, Andrew Sole and Stephen Livingstone*

Throughout the satellite era, an increasingly positive trend in the extent and duration of seasonal surface melt across the Greenland Ice Sheet (GrIS) has been observed, with meltwater runoff now accounting for over 68% of Greenland's annual mass loss [1-2]. As a consequence, a vast expanse of supraglacial channels and lakes form across the ablation zone during the melt season, transporting and storing large volumes of meltwater over the ice surface. Intersecting systems such as crevasses and moulins provide internal pathways for such meltwater to penetrate at depth to the ice-bed interface, influencing ice flow rates and expelling meltwater directly into the ocean [3]. This generation, routing, storage and evacuation of increasingly large volumes of seasonal meltwater is of critical importance for projecting Greenland's future mass balance and its ongoing contribution to global sea level rise [4].

Over recent years, the increased availability and resolution of satellite imagery, as well as the use of unmanned aerial vehicles (UAVs) in the field, have driven considerable advances in the field of ice sheet hydrology [5]. However, as one of the least studied hydrologic systems on Earth [6], the understanding of certain drainage components, particularly within the warming climate, remains unknown. This project uses a combination of remote sensing techniques and UAV photogrammetry to investigate the evolution and transport efficiency of supraglacial channels across the Greenland Ice Sheet at both high spatial and temporal scales. Controlling mechanisms behind such changes are also explored, including meteorological, albedo and topographical influences.

We present some preliminary results of channel evolution derived from innovative automatic river detection methods [7] applied to remotely sensed imagery and early-state results from recently acquired structure-from-motion imagery from a first field season in Greenland.

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Identifying Antarctic Ice Sheet tipping points caused by ice shelf basal melting

Bradley Reed, Hilmar Gudmundsson and Adrian Jenkins

The Antarctic Ice Sheet holds enough fresh water to raise global sea level by over 50 m if it all melted. In the last four decades warmer atmospheric and oceanic temperatures have led to a six fold increase in mass loss from the region. It is difficult to predict how the ice sheet will respond to future warming as it is subject to a number of positive feedback mechanisms which could destabilise the system. Observational and modelling work has shown that ice streams in West Antarctica may be undergoing unstable and possibly irreversible retreat due to increased basal melting beneath their ice shelves. Being able to identify and predict these stability thresholds in ice streams draining the Antarctic Ice Sheet could help establish early warning indicators of near-future abrupt changes in sea level. Here we use the shallow-ice flow model Ua to investigate the impact of ice shelf basal melting on an idealised ice stream from the third Marine Ice Sheet Model Intercomparison Project (MISMIP+). The rate of grounding line migration is used to identify the onset of unstable retreat. Initial results show that uniform melt rate across the ice shelf causes a faster retreat than melt concentrated close to the grounding line. Further, whilst the level of basal melting is the main control for rate of retreat, the bedrock topography is also important, with a more rapid retreat occurring over retrograde sloping bed.

The role of particles in coupling solar radiation into ice

Katie Reeves, *Jennie Gilbert, Stephen Lane, Amber Leeson and Jeremy Everest*

The presence of debris on an ice surface can modify the thermodynamic behaviour of the environmental system due to changes in the absorption rate of solar radiation. This can impact heat transfer and ablation rates of ice. A `dirty' debris-covered ice surface is found on more than 60% of continental glaciers and this value is predicted to increase (Reid et al., 2012; Zhen and Shiyn, 2012). It is, therefore, crucial to understand the physical mechanisms behind these systems to aid future ice ablation modelling in the face of climate change.

Our laboratory experimental study investigates the physical coupling between water-ice and analogue contaminant particles that interact strongly with visible light; a review of the literature having indicated limited laboratory-based studies in this field of research. Experiments involve illuminating a transparent block of ice under temperature-controlled conditions with a white Light-Emitting Diode (LED) radiation source. Minimal infrared radiation (IR) is required because a significant amount of this is naturally removed by the Earth's atmosphere. Limited IR also prevents ice-radiation interaction that could mask ice-particle interaction. Foreign particles are placed on the surface of the ice block in the center of the LED beam. Time-lapse imagery and visual observations capture the response of the particle and ice block to the radiation source and allow melt rates to be calculated.

The behaviours of single particles with a variety of properties (e.g. albedo, thermal conductivity, density and size) have been investigated. Two single-particle behavioural modes have been identified, in which a particle responds to radiation by (1) sinking into the ice by melting, and (2) creating a meltwater pond on the surface of the ice. These modes vary depending on particle properties; for example, the ice melt rate caused by a low albedo particle (2.36 x 10-6 m s-1) is higher than that caused by a high albedo particle (2.39 x 10-7 m s-1). Sinking particles can create channels within the ice which, when drainage is possible, can remain open even when they are no longer in contact with the particles. We have found that the sphere of influence (i.e. the volume of ice which is impacted by a single particle) is larger for low density and low thermally conductive particles relative to high density and high thermally conductive particles. Experiments suggest that the size of the particle has an impact on high thermally conductive particle-ice interaction.

Our experiments have shown that sublimation cooling can lower the ice surface temperature relative to the rest of the ice, consequently restricting the effects of heat coupling from the foreign particle into the underlying ice. In high humidity environments (i.e. those in which sublimation cannot take place), the surface particle couples heat into the ice body with greater effect than in low humidity environments. We estimate that sublimation cools the ice surface by approximately 1°C. This is sufficient to stabilize ice above an ambient environmental temperature of 0°C and to `armor' the ice surface against ablation. Future experiments will use these single-particle results to inform the behaviour of natural single particles, a sub-monolayer of particles and a monolayer of particles.

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North American ice sheet controls on West Antarctic climate variability.

William Roberts, *TR Jones, EJ Steig, K Cuffey, BJ Markle and JM White*

Ultra high resolution ice core records show that climate variability over West Antarctica was markedly different during the last glacial period. Using a series of climate model simulations we can show that the increased variability seen in West Antarctica can be explained by the evolving size of North American ice sheets. The ice sheets influence the atmospheric flow over the North Pacific, which in turn alters the flow in the Tropical Pacific. Changes in the Tropical Pacific then modulate the teleconnection to the South Pacific, altering the variability that is seen over West Antarctica.

Identifying tipping points of the marine ice sheet instability

Sebastian Rosier, *Ricarda Winkelmann, Jonathan Donges, Ronja Reese and Hilmar Gudmundsson*

The marine ice sheet instability (MISI) is an example of a fold bifurcation. In this type of bifurcation, a small forcing can be applied such that a system (for example the volume of an individual glacier) crosses the border of a basin of attraction into a new and distinct state. Whether a glacier has (1) undergone a tipping point or (2) simply been retreating rapidly is an important distinction to make since, in the first scenario, restoring the glacier to its previous state would require reversing the forcing beyond the point at which the tipping point was crossed. In some cases, the area of this hysteresis loop may be very large, meaning that the forcing (e.g. temperature) might need to be reversed so far from its previous value that the retreat is effectively irreversible. Many of the Antarctic Ice Sheet's major drainage basins are believed to be vulnerable to this instability and indeed it may already be underway in some areas. Despite the importance of making the distinction between these two kinds of retreat, very few studies attempt to rigorously identify when a retreat is a result of the MISI or not. Here, we use techniques not previously applied in ice sheet modelling to pick out tipping points in simulations of glacier collapse through analysis of model time series via identification of `critical slowing' as a bifurcation is approached.

Near-margin ice thickness and subglacial water routing, Leverett and Russell glaciers, Greenland

***Neil Ross**, Andrew Sole, Ben Davison, Adam Igneczi and Mathieu*

Ice thickness measurements near the margin of the Greenland Ice Sheet (GrIS) are relatively sparse, presenting issues for modelling ice-flow dynamics, ice-sheet change, and subglacial hydrology. In April 2015 and October 2018, we acquired near-margin ice thickness data at Leverett and Russell Glaciers, west Greenland, using human-hauled low-frequency (10 and 40 MHz) ground- and ice-penetrating radars. Radar-derived ice thickness measurements from 2015 were incorporated into the BedMachine model of ice thickness, created using mass conservation methods. Data from this initial field season significantly modified the modelled ice thickness, and hence bed elevation and routing of subglacial water, in both the Leverett and adjacent Russell Glacier catchments. Although the revised modelled basal topography and subglacial hydrology were more consistent with observations, our 2015 data unrealistically reduced the overall size of the Leverett Glacier hydrological catchment. We therefore acquired additional extensive ice-thickness measurements in 2018 to better constrain subglacial topography and subglacial hydrological routing in the study area. Here, we summarise the findings of the 2015 field season, and report preliminary results from the 2018 survey. We integrate our observations with Center for the Remote Sensing of Ice Sheets (CReSIS) UAV radar ice thickness measurements from Russell Glacier. Our work improves understanding of the basal topography and the subglacial hydrology of Leverett and Russell Glaciers, with implications for glacier dynamics, assessments of water piracy between catchments in the marginal zone of the GrIS, and for the interpolation of ice-thickness grids using mass conservation methods.

Geomorphological and sedimentary signatures of transient subglacial hydraulics during the November 1996 jakulhlaup, Skeiarjarjakull, Iceland.

Andy Russell, *Mandy J. Munro-Stasiuk, Andrew R. Gregory and David Blauvelt*

The landform and sedimentary record of former glacial meltwater systems provides valuable information about the dynamics of former ice-sheets. Although it is well known that ice-sheet plumbing systems can respond rapidly to transient processes such as the drainage of stored meltwater and glacier surging, the identification of such process within the Quaternary record is difficult due to the paucity of accessible modern process analogues. This study presents evidence of the sedimentary and landform signature of extreme hydraulic transience during a well-studied glacier outburst flood (jakulhlaup).

A volcanic eruption beneath Vatnajokull ice cap generated 3.8 km3 of meltwater which travelled into Gramsvotn subglacial lake until it reached a critical level for drainage. The resulting jakulhlaup reached a peak discharge of 45-53 x 103 m3s-1 within 14 hours. After its release from Gramsvotn, the jakulhlaup propagated as a high pressure subglacial flood wave taking 10.5 hours to reach the glacier snout. Negative effective pressure during passage of the subglacial flood wave induced hydraulic jacking of the glacier by 2â€"5 m. As the jakulhlaup progressed, discharge from the glacier became progressively focussed on major conduit outlets. To exit the glacier, floodwaters had to ascend ~300 m to the sandur surface bursting from multiple englacial vents and fractures, spreading progressively, along the entire 23 km wide ice margin over a 6-hour period.

Recession of the margin of Skeiararjakull, by ~ 2 km since 1996, reveals corridors of subglacial meltwater activity which are inset with the drumlinised landscape occupying areas of low elevation and on the ice-distal sides of drumlins. Parallel depressions, subglacial cavity fills, hydrofracture-fills and eskers within these corridors can be linked directly to known November 1996 jakulhlaup outlets. The internal sedimentary architecture of the hydrofractures and cavities is entirely conformable with the surrounding glacier ice and indicates deposition from jakulhlaup flow ascending from beneath the drumlinised surfaces (glacier bed). Hydrofracture and cavity-fills are interbedded with englacial eskers demonstrating synchronous deposition. Rectilinear ridges composed of glacifluvial sediment coalesce into single-crested esker ridges feeding directly to November 1996 jakulhlaup conduit portals. Rectilinear gravel ridges comprise clastic dykes which reflect the upward injection of fluidised sand and gravel from an over pressured aquifer towards the former ice-bed interface. Substrate disruption/evacuation and ridge formation occurred simultaneously during the passage of the high pressure subglacial wave during the early stages of the 1996 jakulhlaup.

This study demonstrates the ability of highly pressurised jakulhlaup flow to produce distinctive assemblages of subglacial landforms and deposits. Such assemblages are associated with large englacial eskers, giant supraglacial ice-walled channels and distinctive pitted ice-contact proglacial jakulhlaup outwash fans."

Modelling sub-canopy longwave radiation in snow-covered deciduous and needleleaf boreal forests

Nick Rutter, *Richard Essery, Robert Baxter, Maya Horton, Brian Huntley and Tim Reid*

In-situ meteorological, tree temperature and forest canopy structure measurements from Arctic European snow-covered boreal forests, were made March through April in Abisko, Sweden (2011) and Sodankya, Finland (2012). Data were collected to evaluate methods that simulate longwave radiation to sub-canopy snow; an important component of the land surface energy balance influencing the timing and magnitude of snowmelt.

Simple models of sub-canopy longwave radiation to snow worked very well. In continuous forest canopies away from forest edges, although tree trunks receiving direct solar radiation got hot, trunks made a small contribution to total sub-canopy longwave emission because trunk view fraction was small. Other parts of the forest canopy (especially the down-facing elements) were often well ventilated and in equilibrium with sub-canopy air temperature. Although canopies, especially sky-facing elements of canopies, can absorb shortwave radiation, the strength of the modelled fit suggests these elements are not strongly contributing to subcanopy snow. Consequently, the vertical location of air temperature measurements (i.e. above or below canopy) used to drive models and the representation of canopy structure becomes critical.

Sub-canopy air temperature provided the best meteorological forcing for accurate longwave modelling. At Sodankyla there was a decoupling of air temperatures above and below forest canopy when less than -5°C, which was enhanced during night-time (above canopy air temperatures staying warmer than below canopy). Where air temperature does not adequately describe the radiometric temperature of an emitting canopy towards the snow surface, improved knowledge of vertical temperature profiles within canopies that have more complex vertical structures may help improve models of sub-canopy longwave radiation. In addition, measured sub-canopy longwave enhancement was very strongly controlled by the proportion of canopy closure as described by sky view fraction, assessed from upward-looking hemispherical photography, rather than plant functional type or sky emissivity.

Representation of 3D Microstructure of Snow for Microwave Scattering

***Mel Sandells**, H. Lowe, G. Picard, M. Dumont, R. Essery, A. Kontu, J. Lemmetyinen, W. Maslanka, C. Matzler, S. Morin and A. Wiesmann*

Snow is important as a water resource, affects the atmosphere through boundary-layer processes and impacts the energy balance of the Earth's surface due to thermodynamic processes and radiation scattering properties. Scattering at microwave frequencies is used to monitor changes in snow mass, but this is very sensitive to the microstructure of the snow. The Snow Microwave Radiative Transfer (SMRT) model was developed to explore different microstructural models and implications for satellite monitoring of snow. 3-D information of snow microstructure can be obtained from microtomography scans, and 2-D information from thin section images. Data from three field campaigns were used to evaluate SMRT (i) scattering and absorption coefficients for different microstructure models, (ii) brightness temperature for a layered snowpack over simple lower boundary and (iii) brightness temperature and backscatter for a layered snowpack over a complex lower boundary. The results highlight the importance of the microstructure model and indicate that microstructure models with more than one length scale may be required depending on the type of snow.

Changes in topography and reflectivity over 8 years beneath the Rutford Ice Stream, West Antarctica

Rebecca Schlegel, *Andy M. Smith, Tavi Murray, Edward C. King, Alex M. Brisbourne, Adam D. Booth, Roger A. Clark and Stephen L. Cornford*

The Rutford Ice Stream, a fast flowing ice stream in West Antarctica, has been subject of ongoing research over the past three decades. The main aim of the past and present research is to understand bed properties, glacier dynamics and the resulting bedforms. Both drumlins and mega-scale glacier lineations (MSGL) have been mapped beneath the Rutford Ice Stream. Topography changes over time have been identified in previous studies using seismic and radio-echo sounding (RES) techniques, showing that the basal sediments are highly mobile. These studies have also identified a transition from upstream deforming sediment to downstream basal sliding.

We used repeated RES surveys in 2008/09 and 2016/17 to calculate the basal topography and bed reflection power (BRP) over an 18 by 18 km grid over this transition zone. The resolution is comparable to that of typical marine swath bathymetry data. Data in both seasons were acquired with the same RES system, allowing direct comparison. The topography data show 16 areas of erosion, including the upstream migration of a cross-cutting trough feature, no areas of deposition were identified. Patterns in BRP are elongated along flow and are often correlated to bedforms. Temporal changes in reflectivity around bedforms are identified and help contribute to the understanding of their formation. The transition zone between deformation and sliding correlates with spatial and temporal changes in BRP, which help understanding of the stability of this zone. Furthermore, we combine the BRP with the locations of bedforms as well as temporal topographical changes to investigate the link between the processes of erosion and deposition. The speed of ice streams is known to be strongly modulated by the interactions of ice and the underlying sediment. Direct observations of the bed conditions and the link between fast ice flow speed and the shape of the bed, can be used to improve the basal boundary conditions in ice-dynamic models.

Using passive seismology to investigate the hydrological conditions of fast glacier flow in West Greenland

Charlotte Schoonman, *Poul Christoffersen, Samuel H. Doyle and Bryn Hubbard*

The acceleration of fast-flowing, marine-terminating glaciers and the steady increase in surface run-off are the two most influential factors affecting present-day ice loss from the Greenland Ice Sheet. Because almost all surface (melt)water is transported to the glacier bed, basal hydrological conditions are directly influenced by surface processes. Studying the relationships between surface run-off, basal hydrology, and ice velocity is therefore essential to understanding the effects of climate change on the contribution of marine-terminating glaciers to global sea-level rise.

Passive seismology enables the continuous observation of a range of glacio-hydrological phenomena, including icequakes, hydrofractures, and tremors associated with water transport. To investigate the effects of variations in water input over the course of several melt seasons, a network of 12 near-surface and 3 deep borehole geophones was deployed on Store Glacier, a fast-flowing, marine-terminating glacier in West Greenland. The network, part of the multidisciplinary RESPONDER project, recorded continuously throughout May-October 2018 and May-July 2019. Here, we present results in the form of spectrograms, RMS amplitude, and microseismic event locations, capturing a variety of phenomena including rapid supraglacial lake drainage events, crevassing, rainfall, the onset and termination of the summer melt season, and impulsive basal microseismic activity. In particular, Seismic and GPS recordings of a partial lake drainage event place constraints on the magnitude (~0.1 m) and extent (3-4 km) of ice sheet uplift and fracturing downstream of the drainage site. We also observe changes in seismic amplitude and frequency content consistent with increased surface water transport and meteorological events such as rainfall throughout the recording period. Our dataset is therefore uniquely suited to studying the links between surface meltwater input and glacier hydrology.

Atmosphere doubles the impact of the ocean on the Greenland Ice Sheet

Donald Slater *and Fiamma Straneo*

Submarine melting of tidewater glacier calving fronts is a key driver of Greenland Ice Sheet mass loss and sea level rise. Submarine melting is most rapid where buoyant subglacial runoff, deriving from ice sheet surface melting, drives vigorous ice-marginal plumes that increase the transfer of ocean heat into the ice. Thus submarine melting has both atmospheric and oceanic influences, yet their relative importance has yet to be quantified. Here we estimate the role of atmospheric versus oceanic variability in driving changes in submarine melt rates around Greenland from 1900 to present. We use regional climate models to estimate subglacial runoff, and regional ocean reanalyses combined with a novel method of extrapolation into fjords to reconstruct ocean properties adjacent to the ice sheet. These time series are used to force a simple plume model that estimates submarine melt rate.

We find that over the past century, subglacial runoff and ocean temperature co-vary, so that when tidewater glaciers are subject to high subglacial runoff they also experience warm ocean waters. While subglacial runoff is three times more variable than ocean temperature, the dynamics of plumes are such that subglacial runoff and ocean temperature contribute equally to variability in submarine melting. In particular, the recent rapid retreat of tidewater glaciers - often attributed to ocean warming - should really be attributed to atmospheric and ocean warming in equal parts. More broadly, the atmosphere plays an equal and amplifying role in ocean forcing of tidewater glaciers, doubling the impact of ocean variability on the Greenland ice sheet."

Automatic identification of supraglacial debris expansion using Google Earth Engine: A new tool for glacier monitoring

Will Smith *and Stuart Dunning*

As glacial environments lose ice mass due to increasing atmospheric temperatures, more bedrock is exposed with decreasing binding permafrost. Debris supply rates increase and large failures (debatably) become more commonplace. This suite of increased subaerial supply, along with thinning and frontal retreat allowing englacial debris emergence, results in expanding extents of supraglacial debris cover. These debris additions affect glacial dynamics through melt regime modification, and potential chemical and physical changes to supraglacial, englacial and subglacial hydrology. Here we present a first tool that identifies supraglacial debris additions and debris cover expansion through efficient cloud based processing. We use the Google Earth Engine platform to quantify supraglacial debris expansion, utilising the large collection of optical satellite imagery from Landsat 4, 5, 7, and 8. This array of data allows investigation of debris expansion and its slope's glaciological causes from 1982 until the present day to be undertaken.

Bathymetry, sedimentary environment and joint UK-Chile access plans for Lago Subglacial CECs (SLC), West Antarctica

Andy Smith, *Alex Brisbourne, Andreas Rivera, Rodrigo Zamora and Felipe Napoleoni*

Hundreds of lakes lie hidden beneath the Antarctic Ice Sheet. Despite being remote and difficult to access, these lakes are of considerable scientific interest: as archives of ice sheet history, as habitats for unique life forms, as sources of water to lubricate ice flow, and as terrestrial analogues in the search for extra-terrestrial life. Although a number of subglacial lakes from the deep ice sheet interior have been identified as possible choices for access and further investigation, no attempts to enter and sample them have yet been successful.

Lago Subglacial CECs (SLC) was discovered in 2014 from ground-based radar surveys. It lies beneath ~2600-2700 m of ice, in a deep, steep-sided subglacial valley west of the Ellsworth Mountains. During subsequent years, further surveys mapped the lake outline in more detail and acquired seismic data to determine the lake's bathymetry and sedimentary environment.

The seismic data indicate a maximum water column thickness of more than 300 m. The lake-bed reflection strength can be used to indicate the likely bed material, allowing interpretation of the lake's sedimentary environment. The lake bed is formed predominantly of very soft, fine-grained sediments with no signs of disturbance, implying a long-lived, low-energy environment. Despite the steep valley sides, the bed topography shows no evidence of slumps or slides, also suggesting that an undisturbed lake environment has persisted for a long time.

All the seismic lines shows a discrete sediment package deposited in the deepest part of the lake. The low signal-to-noise ratio on some of the lines limits comprehensive interpretation of this. However, there are indications that it becomes finer-grained and smoother downstream, perhaps reflecting the sedimentation characteristics of an underflow formed where sediment-bearing water enters the lake at the upstream end.

All the characteristics of SLC determined so far suggest it is an excellent candidate for further exploration. On the basis of this, a new UK-Chile collaboration has been initiated to access the lake and recover both sediment and water samples.

Sudden and substantial late winter speed-up of Nordenskiold Glacier, west Greenland, forced by subglacial hydrology

Andrew Sole, *Stephen J Livingstone, Ben J Davison, Felix S Ng, Jeremy Ely, Malcolm McMillan and Helen E Lankester*

Ice motion in the ablation zone of west Greenland over inter-annual timescales is relatively insensitive to changes in surface melt because faster flow in warmer summers is offset by slower flow the following winter. This `self-regulation' of ice flow is thought to have a subglacial hydrological origin: larger and more extensive subglacial channels (created by enhanced summer melt) more effectively drain water from higher pressure parts of the subglacial drainage system, leading to a net increase in basal effective pressure and reduced winter ice flow. We present new observations, derived from the Sentinel 1 satellite, of an abrupt acceleration of Nordenskiold Glacier, west Greenland over several weeks in March-April 2018. The positive flow-speed anomaly, which originated ~100 km from the glacier terminus and increased flow-speed by up to 100 % of mean winter values, propagated as a coherent packet at ~0.1 m/s (comparable to the speed of inefficient subglacial water flow) along the axis of a computed subglacial hydraulic-potential low. A plume of turbid water was observed in the fjord adjacent to the glacier when the speed-up front reached the terminus. Although the trigger of this speed-up is yet to be determined, the evidence points towards a spike in basal sliding rate related to a large flux of water along the ice-bed interface. Potential sources of this water include: drainage to the bed of an ice-topped supraglacial lake, evacuation of a subglacial lake, and the inter-catchment piracy of subglacial water related to the recent thickening of Jakobshavn Isbrae, which lies immediately to the north of Nordenskiold Glacier. The speed-up began following a period of several days at the beginning of March when mean hourly atmospheric temperatures at Ilulissat (~100 km to the north) remained above zero (with an absolute maximum value of 3.9C) and ice flow within 20 km of the Nordenskiold terminus accelerated by up to 10 %. This acceleration may have caused an up-glacier transfer of tensile stresses, leading to the release of stored water that triggered the speed-up. This mechanism may enable future winter warming to disrupt the current self-regulation of inter-annual ice motion.

Comparing the use of reanalysis data with automatic weather station data within debris thickness modelling

Rebecca Stewart, *Matt Westoby, Francesca Pellicciotti, Ann Rowan, Darrel Swift and John Woodward*

Debris thickness is a key control on a debris-covered glacier's (DCG) ablation rate, yet most observations of supraglacial debris thickness layers consist of point-based measurements, which are limited in their spatial resolution. Remote sensing-based approaches have been demonstrated to be effective for deriving distributed maps of debris thicknesses below 0.5 m, with recent studies focusing on resolving a surface energy balance, or an inversion of a sub-debris melt model. However, such approaches require AWS data, or costly, high-resolution satellite data. We present a low-cost, remote sensing based method for debris thickness estimation using the high-resolution, freely available ERA-5 reanalysis dataset, and compare our results with those derived from NCEP/NCAR reanalysis data. Utilising these reanalysis data, alongside Landsat-7 ETM thermal imagery, ASTER DEM's, and the RM14 debris thickness model (Rounce and McKinney, 2014), we generated distributed debris thickness maps for the Miage (Italy) and Khumbu (Nepal) glaciers. Our ERA-5-derived debris thickness maps suggest a breakdown of the relationship between debris thickness and surface temperature where debris thicknesses exceed 0.5 m. When combined with the coarse (30 x 30 m) resolution of our satellite imagery, this means that it is likely that our method underestimates the absolute magnitude of debris thickness. Despite these limitations, RM14 performs well over areas of thin debris which are the most significant for exacerbating melt rates. ERA-5 reanalysis data estimates debris thickness to within 0.01 ± 0.05 m and 0.01 ± 0.02 m of AWS-derived estimates for the Miage and Khumbu glaciers respectively, whereas NCEP/NCAR reanalysis data estimates debris thickness to within 0.02 ± 0.05 m and 0.02 ± 0.02 m, respectively. Our results show that reanalysis-derived debris thickness estimations cause an over-estimation of debris thickness relative to AWS-derived debris thicknesses. Our method can be used to derive distributed debris thickness estimations at remote glaciers, negating the need for fieldwork, and ultimately improving ablation modelling for DCGs globally.

Widespread development of supraglacial lakes around the margin of the East Antarctic Ice Sheet

Chris Stokes, *Jack E. Sanderson, Bertie W.J. Miles, Stewart S.R. Jamieson and Amber A. Leeson*

Supraglacial lakes (SGLs) are important to ice sheet mass balance because their development and subsequent drainage has been linked to changes in flow velocity and ice shelf disintegration. However, little is known about their distribution on the world's largest ice sheet in East Antarctica. In this paper, we apply an automated method (Normalised Difference Water Index) to ~5 million km2 of high-resolution satellite imagery (Landsat 8 and Sentinel 2A) and identify >65,000 lakes around the peak of a single melt season (January 2017). We find that SGLs are far more widespread than previously recognized and occur in most peripheral regions of the ice sheet. In some regions, lake area densities are similar to values reported for well-studied regions of the Greenland Ice Sheet. We also discover SGLs in several regions where their widespread development has not been previously documented. The cumulative area of SGLs amounts to 1,383.5 ± 13.8 km2 and individual lakes range in area from 0.0002 km2 (our minimum threshold for lake detection) to a maximum of 71.6 ± 0.7 km2. Our analysis indicates that SGLs typically develop at low elevations (<100 m) on low surface slopes (< 1º), but exist 500 km inland and at elevations >1500 m, where they are typically found in close proximity to nunataks. Significantly, SGLs are clustered near grounding lines and ~60% (>80% by area) develop on ice shelves, including several that are thought to be vulnerable to hydro-fracturing. This suggests that some parts of the ice sheet may be more sensitive to future climate warming than previously thought.

<u>The impact of large proglacial lakes on past outlet glacier dynamics during the Last Glacial Maximum in New Zealand</u>

Jenna Sutherland, *Dr Jonathan Carrivick, Dr Duncan Quincey and Prof. James Shulmesiter*

Proglacial lakes are known to affect the stability of mountain glaciers and can partly disengage glacier behaviour from climatic perturbations. Ice-contact proglacial lakes are pervasive across New Zealand and 33 % of the country's perennial ice terminates within lake-calving glaciers. Proglacial lakes have been recognised as an integral part of the onset and progression of ice sheet deglaciation. It has been widely suggested that the retreat of glaciers in the Southern Alps immediately after the Last Glacial Maximum (LGM, c. 30--20 ka BP) could have been relatively rapid, not only because of climate forcing, but in addition to the widespread formation of large proglacial lakes. Ice-contact proglacial lakes formed during deglaciation from LGM ice advance limits, infilling their overdeepenings. These lakes would have caused a shift from land-terminating to lacustrine-calving glacier termini, and that would have accelerated ice margin recession in many valleys and consequently ice mass loss. Despite the importance of glacier-lake interactions in influencing deglaciation, these mechanisms are generally ignored by ice sheet model simulations. The importance of this omission has not been quantified.

We use a simple calving parameterization in the Open Global Glacier Model (OGGM) to study the impacts of a proglacial lake on ice dynamics. The lake boundary is treated in a similar way to a marine calving margin. We perform idealised experiments using a transient climate forcing for the last glacial cycle to present a simulation of the Tasman Glacier at the LGM and beyond, in an attempt to constrain the effect of proglacial lakes on glacier retreat. The Tasman Glacier has abundant empirical data and is well chronologically constrained at the LGM, which is used to inform, validate and analyse our numerical modelling simulations in this study. We look at the effect on the glacier margin by running two simulations, once with, and once without the presence of a lake. Results highlight the importance of including ice-contact proglacial lakes in palaeo-ice sheet modelling, as well as the need for a coherent regional model of ice-lobe and palaeo-lake evolution that reconciles all dating evidence in order to elucidate the pattern of retreat following the LGM in New Zealand."

Proglacial observations at Findelengletscher, Switzerland indicate ice-bed stabilising feedbacks and rapid basal slip by ploughing

Darrell Swift*, Simon J. Cook, William J. Higson, Guy D. Tallentire, Daniel Farinotti, Mauro A. Werder, Robert G. Bryant, Nick Rutter, Kaylee McHale and Alice Witherick*

Ongoing retreat of Findelengletscher, Switzerland, is exposing an overdeepened basin in a location where Iken and Bindschadler (1986) previously obtained measurements of ice motion and borehole water levels. The exceptional dataset obtained by Iken and Bindschadler (1986) demonstrated an increase in ice speed with water pressure even at low borehole water levels that was interpreted to provide important evidence of sliding motivated by growth of subglacial cavities. However, observation of the recently deglaciated area demonstrates the presence of a thick fine-grained till layer within the overdeepening that, where exposed, exhibits a fluted surface. Further, borehole water-pressure sensors and their cables, presumed to have been installed by Iken and Bindschadler (1986), were found on this surface. Calculation of the ratio between the ice surface slope and the overdeepening adverse slope gradients, informed using data from Iken and Bindschadler (1986), indicate conditions suitable for glaciohydraulic supercooling. We infer that the till has been deposited as a consequence of ice-bed stabilising feedbacks, associated with the erosion of an adverse slope, that limit the efficiency of the subglacial drainage system, and further conclude that the till layer and its associated fluting is likely contemporaneous with measurements of motion and water pressure made by Iken and Bindschadler (1986). This indicates that the slip relation observed by Iken and Bindschadler (1986) reflects widespread slip at the ice-till interface (i.e. ploughing), which is associated with little deformational resistance. Preliminary calculations using a ploughing model (Iverson et al. 2007) support our interpretation. Further, observation of basal ice facies consistent with glaciohydraulic supercooling and weak increases in suspended sediment concentration with discharge in the proglacial stream indicates maintenance of adverse slope morphology close to the stabilising threshold during recent retreat. Our findings indicate that overdeepening formation can lead to ice flow dominated by rapid slip by ploughing even for glaciers with steep beds characteristic of alpine environments.

Comparison of glaciers of Himalayan region with artic region in respect to the climate change using remote sensing and GIS techniques

Swati Tak and Ashok Keshari

Glaciers in Himalayan region shows its effects on hydrology, water resources and climatic view. Water in the stream of sub basins originating from glacial part of Himalayan region provide water for various domestic and drinking purpose for the millions of people. Mass loss and distribution of glaciers leads to the various sources of melt water over the region. Thus, Glaciers Inventory adopted to measure the scenario of Himalayan region of India in respect to Glaciers indicating the climate change due to advance and retreat of glaciers which is compared with artic region. Results shows that the sub basin glaciers of the Ganga basin have become dirty and which indicate the climate sensitivity that is compared with climatic sen of artic region from the past records. Due to higher percentage of ablation, retreating exposed debris resulting in the non--uniform heterogeneous heaps of snow mass and debris which is identified by the remote sensing techniques which leads to hydrological concern and, water availability in the basin of Ganga Himalayan region.

Spatial and temporal patterns of supraglacial pond evolution in the Bhutan-China border region of the Himalayas.

***Caroline Taylor**, J. Rachel Carr and Stuart Dunning*

The importance of supraglacial ponds and ice cliffs for glacier scale ablation on debris-covered glaciers is now widely recognised. Supraglacial ponds have the potential to coalesce to form larger moraine dammed lakes, representing a risk of outburst floods which can have catastrophic downstream consequences. However, with the exception of the well-studied Lunana region, there remains a significant lack of data for the majority of glaciers spanning the Bhutan-China border, despite the prevailing negative mass balance of the regions glaciers. Here, we use fine resolution (3 m) Planet Labs satellite imagery to provide the first short-term spatiotemporal dataset of supraglacial pond and ice cliff evolution for three glaciers situated centrally along the Bhutan-China border, 2016-2018. A total of 5867 ponds and 2118 ice cliffs were identified. Large intra-annual changes were observed, with the increases and decreases in ponded area as well as the number and frequency of pond drainage events appearing to be coupled to the seasonality of the Indian Summer Monsoon. On average, ~ 19 % of ponds were found to have a coincident ice cliff, which is comparatively lower than that of studies from neighbouring regions (e.g. Thompson et al., 2016; Watson et al., 2017), however cliff aspect, length and backwasting rates all follow trends reported by similar studies across the wider Himalaya. Both ponds and ice cliffs were found to be influenced by ice-surface velocities and surface gradient, with higher numbers of both found in areas of low velocity (< 8 m/a-1) and lower gradients (< 10°). We anticipate our study to be a starting point for more detailed monitoring, providing much needed qualitative data for what is an understudied, yet important region of the Himalayas.

Calving style and environmental sensitivity of a Greenland outlet glacier from discrete & finite element modelling

Joe Todd, *Doug Benn, Tom Cowton, Thomas Zwinger and Jan Atram*

Calving from outlet glaciers and ice shelves remains poorly represented in numerical models, hampering predictions of future sea level contributions from both Greenland and Antarctica. Recent developments in process scale observations and modelling provide new insight into the complex interactions between calving, ice dynamics and external climate. Here, we present results from a modelling study of Store Glacier, west Greenland. Using the 3D finite element glaciological model Elmer/Ice, and the 3D particle-based model HiDEM, we reproduce the predominant observed calving styles of the glacier, and demonstrate the influence of 1) undercutting by submarine melting, 2) buttressing by ice melange, and 3) the advance of the glacier into the fjord. We find that melt undercutting of the front quickly leads to typical 'top-first' calving events, while glacier advance produces 'toe-first' calving events due to buoyant forces. We generate realistic melange by repeatedly restarting HiDEM simulations, allowing the fjord to fill with icebergs. We find the iceberg size distribution matches closely with observations & theory, and that the melange is readily able to transfer buttressing stress from the valley sidewalls to the glacier terminus. Comparing HiDEM calving results with the stress field from Elmer/Ice reveals exciting new possibilities for the representation of calving in continuum models.

Simulated single-layer forest canopies delay Northern Hemisphere snowmelt

Markus Todt, *Nick Rutter, Christopher G. Fletcher, Leanne M. Wake and Michael M. Loranty*

Boreal forests cover about a fifth of annual maximum snow cover extent over the Northern Hemisphere. Enhancement of longwave radiation beneath coniferous forest canopies has been shown to impact the surface energy balance and rates of snowmelt. However, single-layer vegetation schemes in modern land surface models have been found to overestimate diurnal cycles in sub-canopy longwave radiation. This study introduces an empirical correction, based on forest stand-scale simulations, which reduces diurnal cycles of sub-canopy longwave radiation. The correction is subsequently implemented in land-only simulations of the Community Land Model version 4.5 (CLM4.5) in order to assess the impact on snow cover. Nighttime underestimations of sub-canopy longwave radiation outweigh daytime overestimations, which leads to underestimated averages over the snow cover season. As a result, snow temperatures are underestimated and snowmelt is delayed in CLM4.5 across evergreen boreal forests. Comparison with global observations confirms this delay and its reduction by correction of sub-canopy longwave radiation. Increasing insolation and day length change the impact of overestimated diurnal cycles on daily average sub-canopy longwave radiation throughout the snowmelt season. Consequently, delay of snowmelt in land-only simulations is more substantial where snowmelt occurs early.

Bayesian optimisation of firn densification models

Vincent Verjans, *Amber A. Leeson, Christopher Nemeth and C. Max Stevens*

Accurate firn densification modelling serves several glaciological applications such as conversion of measured surface elevation changes to mass changes, ice sheet surface mass balance modelling and ice-core dating. Many firn densification models have been developed over the years, with no governing formulation being unanimously accepted. These models are based on simplified formulations consistent with the underlying physics, but all rely on a certain degree to parameter calibration against observed data. Data typically consists of firn cores or sparse strain rate measurements and is usually site-specific, focussed on regions of either Greenland or Antarctica. Such model calibration is an inverse problem for which we adopt a Bayesian approach. In this procedure, model parameters are considered as random variables for which we seek a probability distribution.

We focus on three benchmark firn densification models from the literature and investigate their updated parameterisation in this Bayesian framework. We use a dataset of 91 firn cores, spanning a wide range of climatic conditions in Greenland and Antarctica and separated in a training set for calibration and a test set for model evaluation.

Our method yields parameter values significantly different from the ones originally proposed and applicable for both Greenland and Antarctic firn. This points to potential improvements for firn models and to implications for their inherent assumptions about densification physics. Based on the independent test set, we show a significant decrease (-10 to -30 %) in data-model discrepancies and we highlight the differences in performance between the three models investigated. Additionally, Bayesian calibration provides an effective quantification of the remaining uncertainty in model parameters. As such, our parameterisation method can enhance firn models by improving their fit to real data and by providing robust uncertainty quantification of model output. Both aspects will be crucial in our future measurements and predictions of ice sheet mass balance."

Retrieval of soil relative permittivity for snow radiative transfer modelling using passive microwave brightness temperatures

Leanne Wake, *Melody Sandells, Nick Rutter, Juha Lemmetyinen, Richard Esser and Anna Kontu*

Accurate determination of the relative permittivity of frozen soil is required in order to account for emission of thermal microwave radiation from soil when producing estimates of snow depth from satellite passive microwave measurements. On a global scale, observations of the spatial variability of the relative permittivity of the underlying frozen soil are very limited.

A new retrieval method aimed at estimating the relative permittivity of soil was developed by forcing a radiative transfer model, DMRT-ML, with a snow microstructure evolution framework from the JIM snow evolution model and an ensemble of soil dielectric configurations. The ensemble of simulated brightness temperatures (TBs) were then compared to TB observations collected from an area of intensive observation in Sodankyla, Finland.

A radiometer configuration consisting of a 10 GHz H-pol receiver retrieved soil permittivity to within 10% of the observed value for all incidence angles between 30 - 60 degrees. The use of a 10 GHz V-pol configuration produced less accurate and less precise retrievals of soil relative permittivity. Accurate retrieval of soil relative permittivity is only weakly dependent on assumed snow density. Relative permittivity values obtained using this procedure were then input into DMRT- ML to estimate snow depth from TBs differenced at 19 GHz and 37 GHz. Snow depth errors as a proportion of total snow depth were largest (up to 45%) during December for all soil dielectric parameterisations considered; reducing to <13% in the following January to April.

This demonstrates the importance of accurately retrieving permittivity at the onset of the snow season, immediately after ground freezing and before the first significant snowfall. When this is not taken into account, errors in estimation of snow depth from passive microwave sensors persist through peak annual snow depth the following spring.

A new ice triaxial test system and method for studying the effect of freezing pressure

Baosheng Wang, *Weihao Yang, Peixin Sun and Dongliang Bo*

Triaxial test as a crucial method in studying ice mechanical properties has been extensively employed for revealing the impacts of loading rate, confining pressure, and ambient temperature. However, previous researches only focus on the impacts of loading conditions of solid ice, the conditions of phase transformation, the freezing pressure in particular, has not been received much attention.

To fill in this gap, this study proposes a new triaxial test system and method which could freeze pressured liquid water to standard ice samples in triaxial cell. The purpose-built servo-controlled triaxial test system is developed from rock-testing apparatus, with axial load up to 400kN, confining pressure up to 64 MPa, and temperature down to -60ƒ. The triaxial cell with top, lateral, and bottom circulating channels can apply not only uniform temperature but also gradient temperature and other temperature fields. During freezing, the radial deformation of the cylinder sample is constrained by the constant volume of confining medium, and the frost heave is controlled in the axial direction by axial pressure servo system. The key to ensuring the dimensional accuracy of the ice sample is to minimize the variation of the average temperature of confining medium. Thus the finite element numerical calculation was used to simulate temperature field of triaxial cell, and the fluctuate of confining medium average temperature can be limited in 0.5ƒ. Consequently, the lateral surface of ice cylinder is smooth, free of abrupt irregularities and straight to within 0.3 mm over the full length of the sample, which meets the International Society for Rock Mechanics and Rock Engineering (ISRM) suggested methods for rock testing (within 0.5 mm).

The new test system and method achieves the whole process stress control from liquid water pressured, freezing to triaxial test. Therefore, it is appropriate for studying the effect of freezing pressure on ice mechanical properties. Also, the research results of this method provide the basic data for artificial freezing engineering in the pressured situation. Overall, the new test system and method extends the study of ice mechanical properties to the impacts of phase transformation conditions.

Tidal Grounding Line Migration Modulated by Subglacial Hydrology

Katarzyna Warburton, *Jerome Neufeld and Duncan Hewitt*

The position of the grounding line is of key importance in determining the dynamics of ice sheets, as highlighted by numerous studies. Over long timescales, their position is determined by the viscous flow of ice, while over short timescales, the ice sheet responds elastically to tidal forcing.

To date, while many models of the tidal migration of grounding lines of marine ice sheets have been proposed, the induced fluid motion has been neglected. Yet the large pressure gradients required to drive water across the grounding line on a daily cycle would be expected to influence the water pressure beneath the grounded ice sheet, on which glacier velocity sensitively depends.

Here we present a mathematical model of the hydrology of grounding line migration, in which the ice acts as an elastic beam, lying on a poro-elastic till, with the ocean tides modelled by an oscillating far-field fluid height. The upstream grounding line migration is driven by a fluid pressure drop across the grounding line, while the downstream migration is limited by fluid drainage through the till. The two processes are described via separate travelling wave solutions, using results from the theory of fluid flow under elastic sheets.

This asymmetry between the up- and downstream motion allows the grounding line to act as a filter on the tidal forcing as the pressure signal propagates upstream, and this frequency modulation is discussed in the context of velocity data from the Rutford Ice Stream which shows a distinct fortnightly variation in sliding velocities consistent with forcing not at the tidal timescale, but on the timescale of the fortnightly tidal modulation.

Multi-annual geomorphological evolution of debris-covered glacier surfaces

Matt Westoby, *David Rounce, Thomas Shaw, Rebecca Stewart, Peter Moore, Catriona Fyffe and Ben Brock*

There exists a need to advance our understanding of debris-covered glacier surfaces over relatively short timescales due to rapid, climatically induced areal expansion of debris cover at the global scale, and the impact that debris has on mass balance. We applied UAV-SfM and DEM differencing, alongside debris thickness and debris stability modelling to unravel the evolution of a 0.15 km2 region of the debris-covered Miage Glacier, Italy, between June 2015 and July 2018. Following corrections for glacier flow, DEM differencing revealed widespread surface lowering (mean 4.1 ± 1.0 m a-1; maximum 13.3 m a-1). We combined DEMs of difference with local meteorological data and assumptions about debris properties to derive surface lowering-debris thickness relationships through inversion of a sub-debris melt model, and used these relationships to produce high resolution, spatially distributed maps of debris thickness. These maps were differenced to explore patterns and mechanisms of debris redistribution. Median debris thicknesses ranged from 0.12 - 0.17 m and were highly spatially variable. We observed localised debris thinning across ice cliff faces, except those which were decaying, where debris thickened. We observed pervasive debris thinning across larger, backwasting slopes, including those bordered by supraglacial streams, as well as ingestion of debris by a newly exposed englacial conduit. Debris stability mapping showed that 18.2 - 26.4% of the survey area was theoretically subject to debris remobilisation in a given period. By linking changes in stability to changes in debris thickness, we observed a net debris thinning signal across slopes which become newly unstable, and a net thickening signal across those which stabilise. Our data provide quantifiable insights into mechanisms of debris remobilisation on glacier surfaces over sub-decadal timescales, and open avenues for future research to explore glacier-scale spatiotemporal patterns of debris remobilisation.

Sustained retreat of South Georgia tidewater glaciers in response to atmospheric forcing, 2000-2019

George White, *James M Lea and Dominik Fahrner*

Marine terminating glaciers are known to exhibit potential for rapid retreat, contributing to significant sea level and local landscape and ecosystem change. However, previous investigations into tidewater glacier stability demonstrate that there are multivariate controls on their behaviour. In this study we use the Google Earth Engine Digitisation Tool (GEEDiT) to access all available Landsat and Sentinel 2 optical satellite imagery, providing a detailed record of all 39 tidewater glaciers on the South Georgia archipelago for the period 2000-2019 (terminus observations, n = 2736). The overall response of these glaciers was quantified using the Margin Change Quantification Tool (MaQiT), and is compared to both seasonal air temperature records from Grytviken (the only meteorological station on the island), and annually averaged sea surface temperatures from the HadISSTv2 dataset. Rather than analyse the response of each glacier individually, we sought to identify trends in the responses of South Georgiaâ€™s marine terminating glaciers overall. The normalisation of terminus changes to a common scale allows glaciers that have retreated several kilometres to be compared directly with those that have retreated significantly less, permitting overall trends to be identified. In this study, we show that overall terminus response is highly likely to be driven by sustained positive air temperature anomalies rather than synoptic changes in oceanic forcing. Where sufficient temporal detail allows (2016-2019) the relative importance of seasonal air temperatures on seasonal terminus response is also evaluated, qualitatively showing the importance of summer (DJF) air temperatures on driving retreat at larger glaciers, while the magnitude of response of smaller glaciers is relatively less. Overall this demonstrates that continued warming in this region is likely to drive further retreat and major ecosystem and landscape change on South Georgia, with significant implications for conservation efforts on the archipelago.

Radar-detected englacial debris

Kate Winter, *John Woodward, Neil Ross, Stuart Dunning, Andy Hein, Matt Westoby, Riley Culberg, Shasta Marrero, Dusty Schroeder, David Sugden and Martin Siegert*

Glaciers can entrain and transport sediments rich in essential nutrients, like silica and iron, from continental sources to the ocean, where deposition could enhance marine primary productivity. A lack of data from geophysical instruments capable of detecting englacial sediment has led to limited knowledge on the acquisition, transfer and distribution of debris-rich ice in Antarctica. Here, we use ground penetrating radar and airborne radio-echo sounding to detect, and assess the controls on, sediment entrainment and transfer in Antarctic ice flows. We identify sediment reflectors near the glacial surface in katabatic-wind-scoured blue ice areas, and further down the ice column, along partially buried mountain ranges and subglacial bedrock bumps. These sediments are entrained at the thermal boundary between cold- and warm-based ice and transported through the ice by compression towards the mountain front, and regional ice flow towards the coast. Our radargrams highlight the sensitivity of debris entrainment processes and transportation mechanisms to internal and external forcings – related to sediment availability, ice flow and ice temperature. As these controls vary spatially and temporally, changes in the climate and/or internal instabilities in the glacial system could modify sediment sources, alter debris entrainment mechanisms and revise englacial transportation routes – with resultant implications for patterns of continental-sediment-derived nutrient deposition in the Southern Ocean.