International Glaciological Society

British Branch Meeting 2018

Abstract Volume Draft 20/08/18

4th & 5th September

Geography

University of Exeter

Seismic acoustic impedance, effective pressure, and basal drag

Robert Arthern[1], Alex Brisbourne[1], Andrew Smith[1]

[1]British Antarctic Survey, High Cross, Madingley Road, Cambridge, CB3 0ET

Acoustic impedance is a measurable quantity that can be recovered using active seismic surveys. Its value depends on the speed of sound in the sediment and the sediment density. For granular sediments there are theories that relate the speed of sound to the effective pressure, the difference between ice overburden and subglacial water pressure. This provides a link between the seismic observable and a key control on basal sliding. For sediments that follow a Coulomb friction law, the higher the effective pressure the higher the shear stress supported by the sediments. In this poster we investigate the links between acoustic impedance, effective pressure and basal drag that are predicted by theories of the speed of sound in granular materials. We use results for basal drag from an ice flow model inversion in Antarctica to predict how acoustic impedance would vary under the hypothesis that sliding is controlled by a Coulomb sliding law.

High elevation firn conditions assessed by wireless sensors

Liz Bagshaw[1,*], Nanna Karlsson[2], Ben Lishman[3], Lai Bun Lok[4], Steve Burrow[5], Jemma Wadham[5], Lindsay Clare[5], Keith Nicholls[6], Olaf Eisen[2], Hugh Corr[6], Paul Brennan[4], Dorthe Dahl-Jensen[7]

[*] BagshawE@cardiff.ac.uk; [1]School of Earth and Ocean Sciences, Cardiff University, Cardiff, UK;
[2] Geological Survey of Denmark (GEUS), Copenhagen, Denmark;
[3] Mechanical Engineering and Design, London South Bank University, London, UK;
[4] Electronic and Electrical Engineering, University College London, UK;
[5] Queens School of Engineering and Bristol Glaciology Centre, University of Bristol, UK;
[6] British Antarctic Survey, NERC, Cambridge, UK;
[7] Centre for Ice and Climate, Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark

Wireless sensors can be used to reveal subsurface processes in a variety of glacial environments. As the technology matures, so does the range of applications and their potential to reveal important processes out of the range of cabled monitoring solutions. We present results from a firn monitoring experiment at the East Greenland Ice Core Project, and proof of concept trials for a deep borehole experiment. Small wireless sensors were deployed in the upper 15 cm snow layer, beneath environmental control chambers which altered surface conditions. We aimed to mimic the impacts of climate warming and surface darkening using open top chambers and the addition of dust to the snow surface. Temperature, pressure and electrical conductivity (as a proxy for melt) were measured by the sensors and transmitted to a local receiving station. The sensors revealed subsurface conditions within the firn that differed substantially from the surface, and highlighted the importance of solar radiation and surface reflectivity to the firnpack. The sensors have potential for wider scale monitoring, since they are low cost and require no connection to the surface, and can be combined with a variety of complementary instruments. Finally, we introduce a new 'Cryoegg' project, which will deploy a wireless sensor to the bed of the Greenland ice sheet.

Helheim and Kangerdlugssuaq Glaciers in retreat

Suzanne Bevan[1], Adrian Luckman[1], Doug Benn[2],Tom Cowton[2], Joe Todd[2]

[1] Geography Department, College of Science, Swansea University, Singleton Park, Swansea SA2 8PP

[2] Environmental Change Research Group, Department of Geography and Sustainable Development, University of St Andrews, St Andrews KY16 9AJ

Two of the largest glaciers in Greenland, Helheim and Kangerdlugssuaq, underwent synchronous retreat and acceleration in the early 2000s. During the last two years both glaciers have again retreated to positions further upstream than at any other time within the satellite record.
The retreat of Helheim Glacier in summer 2017 was accompanied by an acceleration of 8 m/day compared with the previous year. A 2011-2017 series of high temporal and spatial resolution TanDEM-X DEMs reveals also that the surface elevation of Helheim has dropped by 30 m, superimposing a thinning trend on the annual cycle of elevation change. Using an improved bed DEM based on mass continuity we are able to show where flotation accompanies thinning and calculate temporal changes in mass discharge.
Kangerdlugssuaq Glacier failed to make its normal seasonal advance during the first half of 2017 and has continued to retreat into 2018. This glacier also appears to be thinning.
With both these major glaciers undergoing significant change we investigate how ocean temperatures have influenced this latest phase of retreat.

Towards automatic grounding-line detection from optical satellite imagery

Rosie R. Bisset[1], Robert G. Bingham[1], Noel Gourmelen[1], Daniel N. Goldberg[1], Frazer D.W. Christie[1]

[1]School of Geosciences, University of Edinburgh, UK

Monitoring and modelling ice-ocean interactions over large spatial and temporal scales is critical for effective global sea-level prediction. Changes in grounding-line position provide an important indication of ice-sheet response to atmospheric and oceanic forcing. The position of the grounding line can be detected using a range of satellite remote sensing techniques, including the use of optical imagery, which takes advantage of a break-in-surface-slope that typically occurs as ice transitions from a grounded to a floating state. Optical satellites cover the longest operational time period, providing the opportunity to expand considerably our current records of grounding-line change. However, current imaging of grounding lines from optical imagery is manual and time-consuming, limiting the ability to upscale records through space and time. Here, we aim to develop an automatic technique for grounding-line detection from optical satellite imagery. Using this technique, we aim to subsequently develop a high-resolution record of grounding-line change around Antarctica over the entire 45-year Landsat optical satellite era. Producing this record will help to constrain ice-ocean models, ultimately contributing towards more accurate future sea-level predictions.

Energy balance on the South Patagonia Icefield: First results from meteorological observations

Claudio Bravo[1], Duncan Quincey[1], Andrew Ross[2]

[1]School of Geography, University of Leeds, Leeds, United Kingdom.
[2]School of Earth and Environment, University of Leeds, Leeds, United Kingdom.

Empirically-based studies that characterise the fundamental glacier conditions needed for surface mass balance models are extremely limited in the South Patagonia Icefield (SPI) and hence great uncertainty exists in both past glacier reconstructions as well as future projections. In this work, we present the first estimations of an energy balance model with a strong observational basis in the northern sector of the SPI. The observational network consists of five Automatic Weather Stations (AWS) installed in proglacial zones and nunataks on the plateau of the SPI along a west-east transect around 48°S. Also, three air temperature sensors were installed over the glacier surface. This network allows us to describe the spatial and temporal variability in meteorological conditions, as well as to calculate an energy balance. The first results suggest that conditions are dryer, clearer and colder in the east than the west. In addition, the air temperature lapse rate is steeper and the cooling effect is higher in the east when comparing with the west. Energy balance modelling suggests that the main source of energy in the west is incoming longwave radiation, while in the east, incoming longwave and shortwave radiation are of similar magnitude. Mean turbulent heat fluxes are a source of energy in the west and a sink of energy in the east. In ablation terms, point-scale energy balance analysis reveals that melt is overestimated and sublimation is underestimated if the glacier cooling effect is not included in the air temperature data. Considering this, the sublimation under certain conditions could reach 12% of the total ablation in the east at an elevation of 1234 m asl. Ongoing work is focussing on distributing the input data to calculate a glacier-scale energy balance to analyse the controls and the spatial differences in the ablation between both sides of the SPI. This work is financed by CONICYT, Doctoral Fellowship (CB).

Monitoring of east Greenland marine-terminating glaciers, 2013-2017

Stephen Brough[1*], Rachel Carr[1], Neil Ross[1] and James Lea[2]

[1]School of Geography, Politics and Sociology, Newcastle University, NE1 7RU, UK
[2]Department of Geography and Planning, Liverpool University, L69 3BX, UK

[*]Corresponding author: stephen.brough@ncl.ac.uk

Numerous studies have documented rapid mass loss from the Greenland ice sheet (GrIS) during the last decade. A key component of this mass loss is attributed to thinning, acceleration and retreat of fast-flowing, marine-terminating outlet glaciers. Crucially, these outlet glaciers allow the GrIS to respond very rapidly to climatic change. Understanding these glaciers is therefore essential for accurately predicting near-future mass loss and sea-level rise from the GrIS, but large uncertainties remain over their behaviour and controlling factors (e.g. air and ocean temperatures, sea ice, basal topography, fjord geometry, glacier velocity, width and catchment area).

Glaciers on Greenland's east coast provide a particularly marked example of differing responses to climatic change, with some glaciers retreating rapidly and others demonstrating decades of limited change (e.g. Stearns et al., 2005; Seal et al., 2011; Carr et al., 2017). East Greenland therefore affords an excellent opportunity to investigate glaciers displaying end-member responses to climatic change and may allow us to determine which factor(s) promote rapid dynamic change and which encourage stability. This project utilises a variety of recently acquired remote sensing and/or publically available data to assess changes in the dynamics of east Greenland (~67 – 76^{o}) outlet glaciers for the period 2013-2017. Here, we use a combination of optical (Landsat-8) and radar (Sentinel-1) data to assess seasonal and inter-annual terminus change for all marine-terminating outlet glaciers (>1.5 km) along Greenland's east coast. This data is supplemented by publically-available velocity measurements (e.g. MEaSUREs/GoLIVE) where available. Changes in glacier dynamics will be assessed with respect to external (e.g. atmospheric and oceanic temperatures) and glacier-specific (e.g. basal topography) controls in the next phases of the project.

Quantifying ice thickness, sub-surface characteristics and surface topography of a large debris-covered glacier: Annapurna South Glacier, Nepal

J.R. Carr and N. Ross

Himalayan glaciers represent a key water resource for large populations, and feed some of the largest river systems in the world. In recent decades, they have shrunk rapidly and forecasting their ice loss in the future is essential for predicting changes in water supply. Many of these glaciers have substantial debris-covered tongues, which alter their mass balance characteristics: they primarily lose ice by melting downwards in-situ, rather than undergoing terminus retreat, as observed on clean-ice glaciers. As such, it is imperative to quantify changes in ice thickness, in order to accurately quantify ice loss and forecast the future longevity of these glaciers. However, very little data are available on ice thickness from debris covered glaciers in the Himalaya, not least due to the logistical challenges of data collection. Here we present Ground Penetrating Radar (GPR) data from Annapurna South Glacier (ASG), Nepal, acquired between October and November 2017. ASG has a large debris covered tongue (~5km long) and is cut off from its high-elevation accumulation areas, and is therefore broadly representative of debris-covered glaciers in the region. During the field season, we collected ten cross profiles and one long profile over the lowermost 3.5 km of the glacier. Our data show an intermittent bed reflection of variable strength that is apparent in both cross and along glacier profiles, with ice as thick as 200 m sounded. Data also indicate that glacier ice (~ 50 m thick) persists ~ 1km further down valley than previously inferred from surface morphology. Based on the GPR data and surface observations, we identify three distinct layers with different radar characteristics: 1) an upper layer of continuous debris, although the thickness cannot be resolved at this GPR frequency; 2) a layer characterised by a series of strong englacial reflections, which are often dipping; and 3) Comparatively clean ice, above a deep reflection, which we interpret as the glacier bed. We suggest that the reflections in Layer 2 may be debris layers and/or reflections from englacial water. The former is consistent with up-thrusted debris layers exposed in several ice cliffs. In addition to our GPR data, we also surveyed the surface topography of the lower ice tongue, using a combination of an Unmanned Aerial Vehicle and ground-based photography from the surrounding ice moraine.

Glacial aerodynamic roughness (z_0): methodological sensitivities, precision and uncertainty

Joshua Chambers[1], Mark Smith[1], Duncan Quincey[1], Mike James[2]

[1]A School of Geography, University of Leeds, Leeds, LS2 9JT
[2]Lancaster Environment Centre, Lancaster University, Lancaster, LA1 4YQ

Accurate estimation of the aerodynamic roughness length (z_0), defined as the height above a surface at which wind velocity reaches zero, is one of the main challenges in measuring glacier turbulent fluxes using the bulk aerodynamic method. z_0 is usually in the order of millimetres, and thus difficult to measure directly. Many energy balance studies assume spatially and temporally uniform z_0, contradicting empirical evidence and having a knock-on effect for turbulent fluxes; therefore, parameterisation of this term is a source of considerable uncertainty in surface energy balances. Here, we review the more widely used traditional aerodynamic and 2D microtopographic methods as well as newer 3D methods, and demonstrate their sensitivities and uncertainties with new field data gathered from the Tarfala Valley, Arctic Sweden. In addition to several field considerations and processing assumptions, we show that slight variations in thresholds used to filter aerodynamic data can substantially alter z_0, as can the scale and resolution of microtopographic data. 3D microtopographic z_0 is shown to be relatively precise, and quite insensitive to aspects of uncertainty within Structure-from-Motion methods. This represents the first systematic review to address the effect on z_0 of these methods, providing a reference point for studies that employ them or incorporate z_0 into turbulent flux calculations, and highlighting the key areas for improvement in future.

Glacier change along the Central Pacific-facing margin of West Antarctica driven by spatial and inter-decadal atmosphere-ocean variability

Frazer D.W. Christie[1], Robert G. Bingham1, Eric J. Steig[2], Noel Gourmelen[1] & Simon Tett[1]

[1]School of GeoSciences, University of Edinburgh, UK
[2]Department of Earth & Space Sciences, University of Washington, Seattle, USA.

It is well known that glaciers are retreating in West Antarctica, particularly along the rapidly-deteriorating Amundsen Sea Sector. Within this region, the importance of local-scale atmospheric, oceanic and topographic influences to this glaciological drawdown is now well resolved. However, recent research has made it clear that glaciers all over West and parts of East Antarctica are also undergoing recession, suggestive of a higher-order forcing divorced from stochastic glacier variability. Here, we present a new, spatially complete synthesis of glaciological change across the Central Pacific-facing margin of West Antarctica for the period c.2003-2015, and compare this dataset to contemporaneous estimates of the state of the Southern Ocean and its atmosphere. We find a spatially coherent gradient in the magnitude and nature of glaciological change along this coastline, consistent with the Rossby radius scale of atmospheric forcing across coastal West Antarctica. Signifying an intimate relationship between West Antarctic glacier change and regionally-contrasting atmosphere-ocean variability across inter-decadal timescales, our findings yield important implications for predicting the future evolution of the West Antarctic Ice Sheet.

Using GNSS-assisted aerial triangulation and UAV photogrammetry to study short-term dynamics of the Greenland Ice Sheet

Thomas R. Chudley[1]*, Poul Christoffersen[1], Antonio Abellan[2], Samuel H. Doyle[3], and Neal Snooke[4]

[1]Scott Polar Research Institute, University of Cambridge, Cambridge CB2 1ER, United Kingdom.

[2]Institute of Applied Geoscience, University of Leeds, Leeds LS2 9JT, United Kingdom

[3]Centre for Glaciology, Department of Geography and Earth Sciences, Aberystwyth University, Aberystwyth SY23 3DB, United Kingdom

[4]Department of Computer Science, Aberystwyth University, Aberystwyth SY23 3DB, United Kingdom

Unmanned Aerial Vehicles (UAVs) and Structure from Motion (SfM) photogrammetry are commonly used to produce terrain elevation models for environmental studies. A conventional photogrammetric approach to geolocation requires a dense network of ground control points (GCPs), and in the absence of this control, accuracy can be significantly affected. This is problematic in environments where stable GCPs are difficult to implement and access – including crevassed glaciers and ice sheets. To overcome this challenge in a research programme investigating hydrological networks and flow of the Greenland Ice Sheet, we employ an alternative geolocation approach known as GNSS-supported aerial triangulation. Using an on-board carrier-phase GNSS system to geolocate imagery acquired during a preplanned UAV mission, we can reduce and potentially eliminate the dependency on GCPs during the SfM photogrammetry process. The imagery we used in our test were captured from a fixed-wing Skywalker X8 UAV with an Emlid Reach L1 GPS receiver. Data from the GPS were post-processed kinematically using differential carrier-phase processing, and were used to geolocate photos used as input to the AgiSoft Photoscan photogrammetry software. The resulting point clouds were processed into high-resolution velocity datasets which provide a new and unique opportunity to investigate day-to-day variability of glacier dynamics, which is not captured by satellites. The method was tested at Store Glacier, a large marine-terminating outlet glacier flowing into the Ummannaq Fjord system in West Greenland. Tests show the method is well-suited to revealing heterogeneity in ice-sheet dynamics over scales of hundreds of metres and tens of hours, and is able to detect diurnal variation in ice velocity at an inland study site where the ice flows at a rate of 2 m day^{-1}. Given the increasing use of UAVs in glaciological applications, GNSS-supported aerial triangulation will be of interest to those wishing to use UAVs to obtain high-precision measurements of glacier change in regions where GCP collection is logistically constrained.

Annual Greenland mass trends from 2003-2015 from a Bayesian hierarchical modelling approach

Stephen Chuter[1], J. Rougier[2], Zhe Sha[1], Andrew Zammit-Mangion[3], J.L. Bamber[1]

[1]School of Geographical Sciences, University of Bristol, UK
[2]School of Mathematics, University of Bristol, UK
[3]Centre for Environmental Informatics, NIASRA, School of Mathematics and Applied Statistics, University of Wollongong, Australia

The Greenland Ice Sheet has seen increases in mass loss over the course of the satellite altimetry era and is currently the largest single contributor to global mean sea level rise. Being able to accurately quantify the magnitude of this mass loss is imperative for providing closure to the sea level budget and providing initial conditions for future projections. Existing approaches to determining ice sheet mass trends (altimetry, gravimetry and mass budget approach) all require corrections derived from the output of geophysical models to resolve for unobserved processes. The use of these model outputs can introduce common sources of error and bias to the results. Additionally, the differences in spatio-temporal resolution of each approach makes it challenging to combine results in a statistically rigorous manner. Here we present a Bayesian Hierarchical Model (BHM) approach to determine the total annual mass trend and its constituent component parts. The approach is similar to that developed for the Resolving Antarctic ice mass TrEndS (RATES) project over Antarctica and aims to provide complementary results for the Greenland Ice Sheet. The framework combines the following observations: satellite altimetry (ENVISAT, ICESat and CryoSat-2), Gravity Recovery and Climate Experiment (GRACE), InSAR and GPS uplift rates using statistical source separation to accommodate the different spatio-temporal length scales of each observational dataset. Prior information from geophysical models (e.g. surface mass balance) regarding the spatial and temporal smoothness of the processes governing mass changes are only used to aid source separation, making the solution predominantly data-driven. Therefore, results from this approach can be a useful independent validation of forward geophysical models. We will present an overview of the methodological approach taken for determining Greenland Ice Sheet mass trends between 2003-2015. Additionally, preliminary results for total annual ice sheet mass changes and the relative contribution of ice dynamics and surface processes will be shown. The results from this statistical approach will also be compared and discussed in context with mass trends from other methods.
Finally, we will present an update of results from the RATES project, where the time series of annual ice sheet mass trends has been extended to cover the 2003-2015 period.

This work is part of the wider GlobalMass (www.globalmass.eu) European Research Council five-year project, based at the University of Bristol.

Storage and release of anthropogenic pollutants from glaciers: a future problem for environmental quality?

Caroline Clason[1], Will Blake[1], Nick Selmes[2], Geoff Millward[1], Alex Taylor[1] & Stephanie Mills[1]

[1] School of Geography, Earth and Environmental Sciences, University of Plymouth, Plymouth, PL4 8AA, UK
[2] Plymouth Marine Laboratory, Plymouth, PL1 3DH, UK

Glaciers act as stores for external products that fall onto their surface, ranging from rock and ash to black carbon and environmental pollutants. Falling snow is an efficient scavenger of trace elements from the atmosphere, and glacial ice can subsequently act as a reservoir capable of storing and releasing pollutants into waterways or onto the land surface during glacial retreat. Increased temperatures are accelerating the melt of glaciers worldwide, introducing a risk of augmented contaminant release. Snowmelt has been shown to increase contaminant release in alpine freshwater systems, indicating that similar processes can be anticipated due to ice melt. Fine-grained glacial sediments also act as a sink for fallout radionuclides (FRNs) and other elements that are stored on and within ice then released through melting, with the high ice-to-particulate ratio resulting in increased concentrations of contaminants within sediments. The transport of contaminant-enriched sediments through glacial meltwater streams, or direct deposition onto the land surface through glacier down-wasting, could have detrimental effects on the ecology and water quality of proglacial environments as well as the downstream reaches of glacier-fed rivers.

The presence of FRNs (originating from sources including the Chernobyl nuclear accident and nuclear weapons testing) in glacial catchments has been investigated by only a handful of studies to date. Geochemical analysis of cryoconite and glacial sediments from the Isfallsglaciären catchment in Arctic Sweden has revealed high activity concentrations of FRNs in ice surface sediments, at levels substantially greater than the surrounding proglacial environment. The concentration of fallout caesium-137 in a number of cryoconite samples retrieved from Isfallsglaciären exceeds 4000 Bq/kg^{-1}, some two orders of magnitude greater than the surrounding landscape. This is well in excess of the legal level of caesium set by Sweden's Food Standards Agency (1500 Bq/kg^{-1}), and may present a risk to grazing animals and traditional Sami reindeer husbandry as glaciers retreat and down-waste in this region, depositing FRN-enriched cryoconite within the proglacial environment. Other studies of FRNs in cryoconite thus far span the European Alps, Canada, Svalbard and Iceland. The development of a new spatial database of FRN concentrations offers an opportunity to synthesise existing datasets and assess the prevalence of FRNs in glacier catchments worldwide, in addition to better understanding the processes controlling their accumulation. Improved understanding of the storage, release and fate of FRNs and other anthropogenic contaminants in glacial catchments is imperative to better predict future changes to environmental quality and assess the ecological and socio-economic impacts of this emerging challenge.

Modelling subglacial hydrology at a large Greenland outlet glacier

Samuel J. Cook[1], Poul Christoffersen[1], Joe Todd[2]

[1]Scott Polar Research Institute, University of Cambridge
[2]Department of Geography and Sustainable Development, University of St Andrews

The structure of subglacial hydrological drainage systems beneath large Greenlandic tidewater glaciers influences ice velocity due to its effect on basal traction, and it may also influence calving by its control on melting at the ice-ocean interface. 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 use numerical modelling and observations of Store Glacier in West Greenland to determine the morphology and dynamics tied to different types of basal hydrology, and we specifically investigate the latter's effect on calving, of which little is known.
Store Glacier in Uummannaq Fjord is the second-largest outlet glacier on the west coast of Greenland, and has been the subject of investigation under the auspices of the RESPONDER project (www.erc-responder.eu), as well as several other studies. As such, its seasonal dynamics are well-characterised and several high-quality datasets exist, making it a suitable target for numerical modelling studies. Its terminus position is currently stable, except a seasonal advance/retreat cycle of a few hundred metres, and has remained so for at least several decades. This means it is possible to examine the natural behaviour of its subglacial hydrological system and its calving dynamics without having to disentangle the effects from perturbations tied to frontal retreat and acceleration, which have become widespread in Greenland over the last several decades.
Here we investigate the evolution of Store Glacier's subglacial hydrology between winter and summer seasons using the open-source, full-Stokes model Elmer/Ice and its GlaDS hydrological module. Results suggest that a network of small channels (<1 m^2 in area) can extend up to 25-30 km inland beneath Store Glacier during the melt season, with larger channels (>1 m^2 in area) restricted to within 10 km of the terminus. Meltwater preferentially exits from two extensive, plume-forming regions of the terminus with major outlets having radii of 5-10 m. The small size and limited extent of the summer channel network, combined with the existence of higher modelled water pressures in summer, indicate that Store Glacier largely maintains an inefficient, distributed drainage system year-round. This is hypothesised to be due to the constant high ice velocity hindering the formation and preservation of channels, except where meltwater is concentrated in the terminal region. Instead, water seems to be mainly evacuated in a sheet at the ice-bed interface. This finding is hypothesised to be valid for other, similar Greenlandic glaciers and suggests that, in the short-to-medium term, these glaciers will respond to greater melt by speeding up, as water pressures in the distributed system continue to rise.

Further work will look to improve the coupling between flow and hydrology, and explicitly link this to calving processes, with the ultimate objective of comparing modelled magnitude-frequency distributions of icebergs to observations as a way of validating the model.

Results of the third marine ice sheet model intercomparison project (MISMIP+)

S L Cornford[1], H Seroussi[2], X S Asay-Davis[3]

[1]Swansea University
[2]Jet Propulsion Laboratory, California Institute of Technology
[3]Potsdam Institute for Climate Impact Research

The Third Marine Ice Sheet Model Inter-comparison Project (MISMIP+) builds on the earlier MISMIP and MISMIP3d projects by considering an idealized ice sheet geometry that includes substantial lateral stresses in its ice shelf. The experiment is designed around an idealized bedrock featuring a steep-walled channel, resulting in an ice shelf that buttresses the upstream ice to the extent that the stable equilibrium state features a grounding line crossing a retrograde slope. In contrast to the earlier experiments, the MISMIP+ ice sheet is sensitive to the ablation of its ice shelf, allowing us to define a set of experiments intended to test ice sheet models that are used to study ice shelf melting and its impact on ice flow in Antarctica an Greenland. We present results submitted by 12 modelling groups.

Contrasting seasonal speed-ups of neighbouring Greenlandic tidewater glaciers

Ben Davison[1], Andrew Sole[2]

[1]Department of Geography and Sustainable Development, University of St Andrews, St Andrews
[2]Department of Geography, University of Sheffield, Sheffield

The response of the Greenland's tidewater glaciers to environmental forcing remains one of the largest uncertainties in projections of future sea level rise. The new sentinel satellite constellation has revolutionised our ability to monitor these glaciers; enabling high spatial and temporal resolution estimation of ice flow speeds, regardless of cloud cover and throughout the dark of the arctic winter. Here, we present contrasting ice velocity estimates of several tidewater glaciers in Southwest Greenland. We observe speed up of Kangiata Nunaata Sermia during the 2017 melt season that was much larger and more sustained than during 2016, as well as ice flow sensitivity to supraglacial lake drainage events. In contrast, the neighbouring Akullersuup Sermia was characterised by an early-summer speed-up followed by compensatory slow-down and gradual ice flow recovery over winter, much like in land-terminating sectors of the ice sheet. We use observations and modelling of environmental conditions to investigate the causes of these contrasting ice flow patterns.

Coupled ice shelf-ocean modelling for glaciers in the Amundsen Sea

Jan De Rydt[1], Hilmar Gudmundsson[1]

[1]Geography and Environmental Sciences, Northumbria University, Newcastle-upon-Tyne, UK (jan.rydt@northumbria.ac.uk)

We explore the sensitivity of ice-shelf buttressing and associated grounding line flux to changes in ambient ocean conditions for glaciers that drain into the Amundsen Sea. We use an asynchronous coupling between a regional setup of the eddy-resolving ocean model MITgcm, and Úa, an SSA ice flow model with grounding line resolving capabilities. The ocean model is forced by varying conditions at the boundaries, characterized by extreme scenarios ('cold' and 'warm') for the thermocline depth. The response of the ice shelf geometry and changes in ice volume of the upstream grounded ice sheet are assessed for different scenarios, providing constraints on the future contribution of the Amundsen Sea glaciers to sea level rise.

Applying semi-automated methods to investigate the changing surface hydrology of the Nivlisen Ice Shelf, Dronning Maud Land, East Antarctica

Rebecca Dell[1], Ian Willis[1], Neil Arnold[1], Alison Banwell[2,1], Hamish Pritchard[3]

[1] Scott Polar Research Institute, Lensfield Road, Cambridge, United Kingdom, CB2 1ER
[2] CIRES/NSIDC, University of Colorado Boulder, Boulder, United States, 80309
[3] British Antarctic Survey, High Cross, Madingley Road, Cambridge, CB3 0ET

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, has highlighted the need for a greater understanding of ice shelf instability drivers under current climate warming trends. Surface and basal melting, firn densification, ponding, vertical hydrofracturing, horizontal fracture propagation, and ice shelf edge retreat are all factors that have been identified as potential contributors to previous ice shelf collapse events. In order to further investigate the potential precursors to ice shelf instability, remotely-sensed data from several Antarctic ice shelves will be analysed. The data will include optical imagery from Sentinel-2 and Landsat, and Synthetic Aperture Radar (SAR) imagery from Sentinel-1 and ERS 1 and 2, together with DEMs derived from Worldview and IKONOS imagery, where available. Preliminary investigations have been conducted on the Nivlisen Ice Shelf, which is characterised by extensive surface water features. Until now, this ice shelf has been understudied compared with other ice shelves, despite its proximity to better studied ice shelves, including several that have shown recent signs of instability. Using the available data, a semi-automated method for tracking spatial and temporal changes in the development and demise of surface meltwater features has been developed. This method builds upon an existing algorithm which identifies lake drainage events on the Greenland Ice Sheet. Preliminary results from surface meltwater analysis on the Nivlisen Ice Shelf reveal marked inter- and intra- annual variations in the number, area, and depth of meltwater features between 2013 and 2017. In February 2017, the extent of surface melt peaked at 541 km^2, which was 46 % greater than the next greatest surface melt extent identified throughout the study period (2013-2017). Water propagates towards the ice shelf edge during the summer melt season though a series of interconnected melt ponds and well-defined channels, advancing by a maximum of 24 km in 2017.

Cold ice in a warm bath: Observations of high proglacial lake temperatures across Arctic Sweden from ASTER thermal infrared satellite imagery and thermistor surveys

Adrian Dye[1], Dr. David Rippin[1], Dr. Rob Bryant[2]

[1] Environment Department, Wentworth Way, University of York, Heslington, York.
[2] Department of Geography, University of Sheffield, Sheffield.

It has been shown that where glaciers terminate in proglacial lakes, this contact accelerates glacier mass loss through mechanical and thermal processes, particularly through the formation of thermal notches in the ice front (Carrivick and Tweed, 2013). Despite this, there are limited studies into the thermal regime of proglacial lakes and very limited observations of temperatures near to the ice-water contact point. The abundance and temperature of these proglacial lakes in Arctic glacier systems has received relatively little attention despite proglacial lakes becoming more common as glaciers retreat from their Little Ice Age maxima (~100 years ago).
Here, for the first time, we present the results of the application of the ASTER surface kinetic temperature product (with atmospheric correction) to investigate the surface skin temperature of proglacial lakes across Arctic Sweden. We report maximum daytime surface skin temperatures of ~11^{o}C from proglacial lakes in contact with glaciers. These temperature observations (validated by robust thermistor data from within lakes) are an order of magnitude higher than previously assumed. We also present data that captures diurnal temperature cycles from a proglacial lake in the study area. This data provides important insights into how temperatures recorded during the daytime (e.g. from ASTER thermal imagery) relate to ambient lake temperatures (following night time cooling); and allow us to work towards a coupled heat balance model for subaqueous melt rates at the front of lacustrine terminating glaciers.
These investigations are some of the first to be reported from Arctic proglacial lakes and provide vital data for assessing the influence of warming proglacial lakes on glacier melt rates, and likely future changes alongside projected increases in air temperature (IPCC, 2013).

Quantifying bed roughness beneath contemporary and palaeo-ice streams

Francesca A.M. Falcini[1*], David M. Rippin[1], Maarten Krabbendam[2], Katherine A. Selby[1]

[1] Environment Department, Wentworth Way, University of York, Heslington, York, YO10 5NG
[2] British Geological Survey, The Lyell Centre, Research Avenue South, Edinburgh, EH14 4AP
**Email address: famf500@york.ac.uk*

Bed roughness is an important control on ice stream location and dynamics. Previous bed roughness studies have mostly 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. 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 Möller Ice Streams (Antarctica). We then investigated how data-resolution, transect orientation and spacing, affected roughness measurements. Our results showed that fast palaeo-ice flow can occur over a rough, hard bed. This differs from the majority of previous studies, which found that fast ice flow occurred over smooth, soft beds. Smooth sections of the bed are found over areas of both bedrock and sediment cover. We propose that the spacing of RES transects is often too wide to measure the bed roughness of landform assemblages, and that transect orientation impacts bed roughness measurements of contemporary and palaeo-ice streams.

Evidence from ice-keel landforms for rapid retreat of the ancestral Dotson-Getz ice stream by ice-cliff failure mechanisms

Alastair G.C. Graham[1], Robert D. Larter[2], James A. Smith[2], Claus-Dieter Hillenbrand[2], Karsten Gohl[3], Frank Nitsche[4]

[1]College of Life and Environmental Science, University of Exeter, EX4 4RJ, UK.
[2]British Antarctic Survey, Cambridge, CB3 0ET, UK.
[3]Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven, Germany.
[4]Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY, USA.

Theoretical studies and some modern observations have shown that when marine-terminating ice cliffs reach a critical threshold thickness (c. 900 m, with ~90 m high cliffs above the water line) stresses from an unopposed overburden in the ice margin may exceed the yield strength of ice, causing ice cliffs to fail. On retrograde slopes, such failure may propagate in a runaway fashion as ever-greater ice thicknesses are exposed at the retreating ice edge. This process, termed Marine Ice Cliff Instability (MICI) has been proposed as a key mechanism in the retreat of the past Antarctic ice sheets, as well as a process that might compound future retreat in ice streams whose present-day grounding lines rest on deep reverse beds. One study of sea-floor iceberg ploughmarks in the submarine trough extending seaward of Pine Island Glacier has provided observational evidence inferring MICI during major phases of past grounding line retreat. However it is not yet known how influential the process was in the wider deglaciation of Antarctica through the last glacial cycle. Here, we investigate the geomorphological signature of iceberg scouring on the sea bed in the Dotson-Getz trough, West Antarctica, using multibeam bathymetry data. We document 5033 iceberg ploughmarks over an area >20,000 km^2 in size, ranging in depth from 290 to 881 m below sea level. Such ploughmarks record the depth of scour, directionality, and iceberg type from both modern and palaeo-scouring episodes. A sub-set of strongly-aligned corrugated ploughmarks exists over a narrow range of modern water depths, down to ~797 mbsl, which we interpret as formed by tidally-modulated intermittently-grounded icebergs, scoured during an ice-shelf breakout. Spatially, the ploughmarks occur immediately downstream of retrograde marine basins with depths >800 m. We calculate minimum ice cliff heights above the water line of up to 95 m to create such features, many exceeding the threshold by which MICI is theorised to take hold. The main population of non-corrugated ploughmarks also comprises of deep iceberg ploughmarks that can only have formed at unstable ice fronts ~1 km thick. Furthermore, we show that the corrugated scouring event was associated with a potential phase of rapid retreat from a large wedge-like deposit with a continually-deepening backslope. From these results, we interpret that ice-cliff failure was an important process of marine ice retreat from the outer Dotson-Getz basin. Our results suggest that rather than being isolated to one ice-stream system, ice-cliff failure was a widespread mechanism that enhanced ice-margin retreat in the Amundsen Sea sector through the last deglaciation.

Is the Antarctic Peninsula getting warmer or colder?

G. Hilmar Gudmundsson[1]

[1]Geography and Environmental Sciences, Northumbria University, Newcastle-upon-Tyne, UK (hilmar.gudmundsson@northumbria.ac.uk)

In the recent literature, two apparently divergent views on warming trends of the Antarctic Peninsula (AP) have been presented: It has been claimed that:

a. From 1951-2001, rates of warming over the Antarctic Peninsula were exceptionally high or around 0.57 deg/decade.

b. There has been no significant warming in the 21st century.

We discuss the reasons for these apparently different viewpoints, both of which are derived from the same data sets, and suggest how these can be reconciled.

While we are able to reproduce previous findings, we suggest that some aspect of the error analysis may need closer attention. When fitting linear trends to AP temperatures, residuals are strongly auto- correlated. While this does not affect linear trends, previous errors estimates need to be revised. This we do using both first-order autoregressive models and blockwise cyclical Monte-Carlo methods. The previously reported change in trend at 1997 in stacked temperature anomalies from the Antarctic Peninsula does not appear to be statistically robust. Using discontinuous picewise-linear regression models, as done in some previous work, appears physically questionable. We suggest using instead continuous picewise regression. Using this methodology we find warming trends over the Antarctic Peninsula to be similar and consistent with global trends.

Greenland Ice Sheet mass balance and climate interactions

Prof. Edward Hanna FRMetS Professor of Climate Science and Meteorology, School of Geography, College of Science, University of Lincoln

The rate of mass loss from the Greenland Ice Sheet (GrIS) has tripled over the last 20 years, reflecting strong climate warming over the region. Here I will present a review of some of the Greenland mass-balance evaluations that I have been involved with over the last 15 years. We will also review other recent estimates of GrIS mass change, including some very recent observational updates from satellite data, noting the impacts on global sea-level rise. I will then focus on some current key challenges in modelling the meteorologically-driven surface mass balance component (SMB, = snow accumulation minus surface melt-water runoff), and highlight what future work is needed to address remaining gaps in our knowledge and understanding of GrIS mass balance changes and climate interactions.

High-resolution digital elevation models for studying the martian cryosphere

Adam J. Hepburn[1], Bryn Hubbard[1], Thomas Holt[1], Felix S. L. Ng[2]

[1]*Department of Geography and Earth Sciences, Aberystwyth University, Llandinam Building, Penglais Campus, Aberystwyth SY23 3DB, UK*
[2]*Department of Geography, University of Sheffield, Sheffield S10 2TN, UK*

Sub-decametre digital elevation models (DEMs) are becoming increasingly available for the study of Earth's cryosphere. For Mars, however, widely-available DEMs are limited in coverage and resolution (often 50-500 m/pixel). These restraints currently limit their contribution to the study of Mars's cryosphere, and specifically that of smaller-scale features such as ice-rich 'glacier-like forms'. Glacier-like forms are important indicators of environmental change on Mars, hinting at recent episodic phases of glaciation, but they are rarely >5 km long and so their surface features are not well-resolved by available DEMs. While it is possible to generate high-resolution DEMs (~1-2 m/pixel) from stereo pairs of HiRISE images, the process is intricate and correspondingly esoteric. Here, in order to expand the catalogue of published HiRISE DEMs to include more glacier-like forms, we present a largely automatic photogrammetric method—based on the Ames Stereo Pipeline—for rapidly crating 1-2 m/pixel DEMs from HiRISE stereo pairs. We describe several case-studies where such fine-resolution DEMs enable a detailed study of the surface morphology and roughness that furthers our understanding of processes on glacier-like forms. Finally, as repeat stereo pairs of HiRISE imagery are available for some locations, we also take the opportunity of using orthorectified time-separated images for precise tracking of surface changes on glacier like forms.

The instantaneous velocity response of Petermann Glacier, northern Greenland to future ice tongue loss

Emily A. Hill[1], J. Rachel Carr[1], G. Hilmar Gudmundsson[2], Chris R. Stokes[3]

[1] School of Geography, Politics and Sociology, Newcastle University, Newcastle upon Tyne, UK
[2] Department of Geography and Environmental Sciences, Northumbria University, UK
[3] Department of Geography, Durham University, UK

Dynamic ice discharge from marine-terminating outlet glaciers is an important component of recent mass loss from the Greenland Ice Sheet (GrIS). The rapidly-flowing (~1000 m a^{-1}) Petermann Glacier in north-west Greenland has a catchment area representing 6% of the GrIS, suggesting that future dynamic changes could contribute substantially to sea level rise. In recent years, Petermann Glacier lost large sections of its floating ice tongue, including two major calving events in 2010 and 2012, which were the largest recorded from Greenland in the past two decades. However, the glacier has shown limited dynamic response to these major calving events, and it is unclear how sensitive it is to future ice tongue losses. We aim to assess this sensitivity using a state-of-the-art, finite element numerical ice flow model (Úa). Specifically, we use remotely sensed data to initialise the model and replicate the limited change in ice velocities observed after the 2010 and 2012 calving events. We then assess the instantaneous velocity response of Petermann Glacier to the calving of further sections of its floating ice tongue, which may occur in the future. Initial estimates suggest inland ice flow is insensitive to the removal of floating ice up until ~12 km seaward from the grounding line, after which large calving events (8 km) contribute to an instantaneous velocity increase of ~700 m a^{-1} at the grounding line. Future work will incorporate transient simulations estimating the future ice discharge contribution of Petermann Glacier once its entire ice tongue is lost.

Production and preservation of the smallest drumlins

J. K. Hillier[1], Í.Ö. Benediktsson[2], TPF Dowling[3], A Schomacker[4]

[1]Department of Geography, Loughborough University, UK.
[2]Institute of Earth Sciences, University of Iceland, Iceland.
[3]Geospatial Insight Ltd., Coleshill, B46 3AD, UK.
[4]Department of Geosciences, UiT The Arctic University of Norway, Norway.

Few very small drumlins (e.g. H < 4 m) are typically mapped in previously glaciated landscapes, which might be an important signature of sub-glacial processes or an observational artefact. 143 newly emergent drumlins, recently created by the Múlajökull glacier, have been mapped using high-resolution LiDAR and aerial photographs in addition to field surveying. In this note, these are used as evidence that few small drumlins are produced; at least, few survive to pass outside the ice margin in the only known drumlin field that has both an exposed zone and one that is probably geomorphically active. Specifically, the lack of a multitude of small features seen in other landforms (e.g. volcanoes) is argued not to be due to i) Digital Elevation Model (DEM) resolution or quality, ii) mapper ability in complex (i.e. anthropogenically cluttered or vegetated) landscapes, or iii) post-glacial degradation at this site. So, whilst detection ability must still be at least acknowledged in drumlin mapping, and ideally corrected for in quantitative analyses, this observation can now be firmly taken as a constraint upon drumlin formation models (i.e. statistical, conceptual, or numerical ice flow). Our preferred explanation for the scarcity of small drumlins in apparently immature zones (i.e. elongation ratio <2.0), at least at sites similar to Múlajökull (i.e. ice lobes with near-margin drumlin genesis), is that drumlins form by streamlining pre-existing landforms (e.g. moraines, debris fans) rather than through progressive growth from small perturbations to full-size features.

Linking the recent retreat of Kronebreen, western Svalbard to glacial proximal water temperatures in Kongsfjorden

Felicity Holmes[1], Nina Kirchner[1,2,3], Riko Noormets[4], Jakob Kuttenkeuler[3], Jari Kruetzfeldt[3]

[1] Dept. of Physical Geography, Stockholm University
[2] Bolin Centre for Climate Research, Stockholm University
[3] Dept. of Naval Architecture, KTH Royal Institute of Technology, Stockholm
[4] Dept. of Arctic Geology, University Centre in Svalbard UNIS

Recent studies have shown that calving rates of fjord terminating glaciers vary strongly with ocean temperature (Luckman et al. 2015), but there remains a paucity of observations of ocean temperatures taken in close proximity to fjord terminating glaciers in Svalbard.

Here, we present results from the Long Term Underwater Sensing (LoTUS) program at Kronebreen, western Svalbard. The first generation of LoTUS buoys are small, lightweight thermometers which acquire temperatures at a specified water depth and predefined sampling frequency, and which surface at a user-defined date to transmit collected data to an on-shore recipient. The Kronebreen LoTUS campaign was a pilot study, sampling water temperature at 10 minute intervals starting in Aug 2016 and ending in Sept 2017 at a water depth of ca 67 meter, 1200 m from the calving front of Kronebreen.

The LoTUS timeseries from Kongsfjorden is used to study the relative importance of water temperatures at depth for frontal ablation rates of Kronebreen 2016-2017, in comparison to other climatic drivers such as atmospheric temperature, sea surface temperature, precipitation and sea ice cover. Both multivariate and univariate regression are employed to this end. The frontal ablation of Kronebreen is derived from high resolution ground range detected Sentinel 1 images. A physically based parametrization of submarine melt, adopted from Beckman and Goosse (2003), is calculated using in situ measurements of water temperature and salinity from Kongsfjorden. This time series of submarine melt rates is compared to the frontal ablation time series and shows submarine melt to be of considerable significance, accounting for around 26% of the frontal ablation rate on average but with this being seasonally variable. Sound velocity profiles collected at the beginning of the LoTUS sampling period are used to reconstruct the water masses present within the fjord. Dynamical processes linking submarine melt and frontal ablation cannot be quantified based on the available datasets, but will be targeted in future numerical experiments.

Reconstructing palaeo jökulhlaup magnitude and frequency on the western and north western flanks of Bárðarbunga volcano, Iceland.

Sigurdís Björg Jónasdóttir[1],
Andrew J. Russell[1], Neil Ross[1], Matthew Perks[1]

[1]School of Geography, Politics & Sociology, Newcastle University, Newcastle upon Tyne, NE1 7RU

Iceland is a natural laboratory for jökulhlaup (glacier outburst flood) research, due to the high frequency of subglacial drainage from volcanic eruptions. Bárðarbunga is one of Iceland's largest subglacial volcanoes and has been in a state of unrest since September 2014 when a large-scale fissure eruption occurred in harmony with collapse (65m) of the 10 km diameter Bárðarbunga subglacial caldera. Previous fissure eruptions have preceded enormous subglacial eruptions within the main subglacial caldera generating massive jökulhlaups. Despite this knowledge there has been no systematic assessment of the occurrence and magnitude of jökulhlaups in the glacier-proximal sectors of the Þjórsá, Kaldakvísl and Skjálfandafljót river systems draining the south-western to north-western flanks of Bárðarbunga. As such, there is an urgent need for knowledge of past jökulhlaup hazard processes which can be used to assess and mitigate risk in event of a future eruption. The aims of this project are therefore: (1) to identify the inundation areas of palaeo jökulhlaups within proglacial rivers draining the western and north-western flanks of Bárðarbunga; (2) provide a relative jökulhlaup chronology; (3) reconstruct palaeo-jökulhlaup magnitude; and (4) to evaluate the relationship between specific jökulhlaup route ways and the local glacial and volcanic history.
To achieve the above aims, geomorphological evidence of palaeo-jokulhlaup channels was mapped using aerial photography and DEM's (LiDAR and ArcticDEM). Fieldwork edentailed identification of 'washed-surfaces' ; systematic surveying of jökulhlaup channel extents and cross-sections using dGPS units ; measurement of channel surface grain size ; logging and sampling of available sedimentary sections ; GPR surveys using an Utsi Groundvue GV7 system ; and dGPS surveying of volcanic landform and glacier margin positions .

The Anticipated outcome of the research is a development of a new model assessing the controls in palaeo jökulhlaup characteristics and impacts for the proglacial river systems of Bárðarbunga volcano, and a production of a series of inundation maps based on knowledge of modern glacial margin positions, proglacial topography and possible drainage ways to the west and northwest into Skjálfandafljót.

How stable is the East Antarctic Ice Sheet?

Jim Jordan[1], Hilmar Gudmundsson[1], Chris Stokes[2], Bertie Miles[2], Stewart Jamieson[2] and Adrian Jenkins[3]

[1]Northumbria University, Newcastle
[2]Durham University
[3]British Antarctic Survey

The East Antarctic Ice Sheet contains within it water equivalent to a sea level rise of ~53m, an order of magnitude greater than the Western Antarctic Sheet. Whilst East Antarctica is thought to be comparatively stable when compared to West Antarctica, some recent studies suggest that parts of East Antarctica are thinning and may be vulnerable to ocean induced retreat. We present here preliminary work looking at this previously understudied area.

Synchronous Ice-Ocean Coupling using MITgcm

Jim Jordan[1], Paul Holland[2], Dan Goldberg[3], Kate Snow[3] and Adrian Jenkins[2]

[1]Northumbria University, Newcastle
[2]University of Edinburgh
[3]British Antarctic Survey

The first fully synchronous, coupled ice shelf-ocean model with a moving grounding line has been developed using the MITgcm (Massachusetts Institute of Technology general circulation model). Unlike previous, asynchronous, approaches to coupled modelling our approach is fully conservative of heat, salt, and mass. Example result of this new method are show from ISOMIP.

Subglacial Sediment Characterisation using Analysis of Seismic Surface Waves and Time Domain Electromagnetics

Siobhan Killingbeck[1], Dr Adam Booth[1], Dr Phil Livermore[1], Dr Jared West[1]

[1]School of Earth and Environment, University of Leeds, Woodhouse Lane, Leeds, LS6 9JT

Subglacial hydrology exerts a substantial control on the flow dynamics of glaciers and ice masses. Subglacial water influences ice flow by modulating basal friction, the strength of subglacial sediments and their potential to deform. A range of glacio-geophyscial methods has developed for investigating the character of subglacial drainage systems: seismic reflection, refraction and ground penetrating radar (GPR). However these conventional techniques can often experience problems for measuring material properties beyond the immediate vicinity (~2 m) of the glacier bed.

This study applies the seismic technique 'Multichannel Analysis of Surface Waves' (MASW) and time domain electromagnetics (TEM) for the exploration and characterisation of subglacial sediment, to a greater depth into the subglacial environment than is often practical with conventional methods. MASW is sensitive to changes in the velocity, Vs, of seismic shear waves; a small amount of unfrozen water in sediment pores can lead to large decreases in Vs. Therefore the Vs profile provides useful information on water content and degree of freezing in sediment pores. Additionally water has a very low resistivity compared to ice and frozen sediments. Electrical resistivity values decrease by several orders of magnitude when ice melts or liquid water is present in sediment pores. This allows resistivity to be used as an indicator of moisture content and temperature of subsurface materials.

A combined analysis, using a joint inversion technique, of MASW and TEM can quantify the groundwater contents of subglacial sedimentary basins exploiting the fact both data types are sensitive to porosity, permeability and liquid water content.

Active source seismic, TEM and GPR lines were acquired around the frontal margin of the glacier Midtdalsbreen, an outlet of the Hardangerjøkulen ice cap, in spring 2018. A 200 MHz GPR survey was used to constrain ice thickness of the glacier (to a maximum of ~70 m) to support the MASW and TEM analysis and inversions. A Vs and resistivity profile of the glacier and its subglacial sediments, extending to ~40 m depth, was obtained from this analysis. The profiles showed low Vs and low resistivity zones directly underlying the glacier bed, suggesting unfrozen and unconsolidated till within the sediment package. These data match well synthetic MASW and TEM responses for ice overlying unfrozen/wet subglacial sediments.

The presentation will include: preliminary GPR, MASW and TEM results from the 2018 field campaign at Midtdalsbreen and potential strategies for the joint inversion technique to be applied between the MASW and TEM datasets.

The Snow_blow model: Data/model comparison of snow drift in the Ellsworth Mountains, Antarctica.

Anne M. Le Brocq[2,] Stephanie C. Mills[1*], Kate Winter[3], Ekaterina Ardakova[?], Clare Boston[5], John Hillier[6], Michael Smith[?], David Sugden[7] and John Woodward[3].

[1] Geography, College of Life and Environmental Sciences, University of Exeter, Exeter, EX4 4RJ, UK
[2] School of Geography, Earth and Environmental Sciences, Plymouth University, Drake Circus, Plymouth, PL4 8AA. UK.
[3] Department of Geography, Faculty of Engineering and Environment, Northumbria University, Newcastle upon Tyne, NE1 8ST, UK.
[?] Department of Geography and Geology, Kingston University London, Penrhyn Road, Kingston upon Thames, KT1 2EE, UK
[5] Department of Geography, University of Portsmouth, Buckingham Building, Lion Terrace, Portsmouth, PO1 3HE
[6] Department of Geography, Loughborough University, Leicestershire, LE11 3TU, UK
[7] School of GeoSciences, University of Edinburgh, Edinburgh, EH8 9XP, UK

Wind-driven snow redistribution can increase the spatial heterogeneity of snow accumulation on ice caps and ice sheets, and may prove crucial for the initiation and survival of glaciers in areas of marginal glaciation. We present an enhanced snowdrift model (*Snow_Blow*) based upon Purves (1999), which calculates spatial variations in relative snow accumulation that result from variations in topography, using a Digital Elevation Model (DEM) and wind direction as inputs. Improvements include snow redistribution using a flux routing algorithm and DEM resolution independence. Results will be presented from a data/model comparison on the Blue Ice Areas of the Ellsworth Mountains, Antarctica. Once validated, the model has the potential to determine whether redistribution of snow by wind is significant in explaining variations in estimated equilibrium line altitudes (ELAs) of glaciers and formerly glaciated areas of the UK, in both marginal and plateau icefield settings.

Purves, R.S., Mackaness, W.A. and Sugden, D.E. 1999. An approach to modelling the impact of snow drift on glaciation in the Cairngorm Mountains, Scotland. *Journal of Quaternary Science,* 14, 4 313-321

Investigating the sedimentary architecture and morphology of the Brampton kame belt using ground-penetrating radar (GPR) and high-resolution LiDAR data

Harold Lovell[1], Clare Boston[1], Stephen Livingstone[2], Adam Booth[3]

[1]University of Portsmouth
[2]University of Sheffield
[3] University of Leeds

Kames constitute a diverse range of glaciofluvial and glaciolacustrine landform-sediment assemblages that provide information on the style and pattern of deglaciation. The Brampton kame belt is one of the largest (>40 km^2) glacio-depositional complexes in the UK and is located at the centre of the former British-Irish Ice Sheet. A large-scale survey of the kame belt subsurface sedimentary architecture was conducted using ground-penetrating radar (GPR). Using a 100 MHz Mala Geosciences 'Rough Terrain Antenna' system allowed us to test the application of GPR in investigating complex glaciofluvial landform-sediment assemblages and to provide insight into the formation of the kame belt. The full range of geomorphic features were targeted, including ridges, flat-topped hills, channels and depressions. Where possible, GPR survey lines were collected both along and across features in order to provide an insight into their 3D architecture. At two locations survey lines were collected above man-made sediment exposures, which were logged in order to tie the radar data to the sedimentary facies. Initial analysis of the data demonstrates it is possible to identify large-scale sedimentary architecture, including bedding, changes in sediment type, and deformation structures (e.g. faulting and folding). It is also possible to tie radar facies to sediment facies exposed in section. Our analysis builds on existing models of kame formation by providing a better understanding of individual landform-sediment assemblages, transitions between them and spatial variations in the pattern, style and volume of kame sediments in the region.

Investigating surging and calving in Svalbard glaciers with long time-series of satellite radar images

Adrian Luckman1, Doug Benn2

1 Department of Geography, College of Science, Swansea University, SA2 8PP 2 School of Geography & Sustainable Development, University of St Andrews KY16 9AL

Dynamic processes in ice can be difficult to understand when observations are limited to fieldwork opportunities or cloud-free summer months. The recent availability of high resolution satellite Synthetic Aperture Radar (SAR) data at unprecedented temporal frequency provides a significantly improved opportunity to investigate time-varying processes in polar regions. Here, using time-series of data at weekly intervals over five years from the TerraSAR-X and Sentinel-1 satellites, we explore calving and surging at several glaciers in Svalbard and elsewhere. Velocity maps and time-series animations reveal a variety of behaviours and insights previously hidden from view.

A horizontally integrated model of rotational meltwater plume flow beneath ice shelves

Christopher MacMackin[1], Andrew Wells[1]

[1]Atmospheric, Oceanic, and Planetary Physics, University of Oxford

Though small in volume compared to the entire ice sheet, Antarctic ice shelves control the flow of mass from the continent into the ocean. This makes them disproportionately important to the climate system and when making predictions of future sea level rise. Most melting on ice shelves is driven by uptake of heat from the ocean. Ice-ocean interactions have typically been analysed using a vertically-integrated plume model. Though computationally cheaper than a full 3-D ocean model, solving for the plume in 2-D remains challenging. While they can provide certain insights, 1-D versions of plume models are unable to capture transverse plume flow or rotational effects. For this reason, a "horizontally integrated" version of the plume model has been developed which averages plume flow over some transverse width, starting at the sidewall of the subglacial cavity. This model predicts that, after a narrow region of transient behaviour, the plume reaches an asymptotic state where forcing is balanced by lateral outflow from the modelled region. The asymptotic values of plume thickness, velocity, temeprature, and salinity can be analytically predicted for a given ice shelf slope, Coriolis parameter, drag coefficient, and plume width. While only strictly valid for a constant ice slope, the analytic results also approximately hold in the more usual setting where the slope varies gradually. Examining the behaviour of the plume variables with different values of integration width gives insight into the transverse structure of the plume. This reveals that, in the asymptotic region, there is a narrow boundary layer near the sidewall where longitudinal flow occurs, beyond which the Coriolis force has caused the flow to rotate into the transverse direction. This horizontally integrated model provides a tool to aid understanding of 2-D flow of the plume and predict the resulting basal melt rate of the ice shelf, without the expense of a fully 2-D model.

Sentinel-3A's SAR altimetry for the Greenland Ice Sheet

Jennifer Maddalena[1], Geoffrey Dawson[1], Stephen Chuter[1], Jonathan Bamber[1]

[1]School of Geographical Sciences, University of Bristol, UK

In order to measure fluctuations in the mass of the Greenland Ice Sheet (GrIS), satellite radar and laser altimetry measurements have provided accurate quantification of ice sheet elevation change since 1992. Whilst CryoSat-2's novel synthetic aperture radar interferometric (SARIn) mode has improved spatial coverage over the ice sheet margins and outlet regions compared to traditional instrumentation (which suffered in regions in steep topography); the low resolution mode (LRM) used in the ice sheet interior fails to depict small scale spatial and temporal changes. When Sentinel-3 was launched in 2016 it became the first satellite to use SAR over the interior of the GrIS, improving the along track resolution to ~250 m, a higher spatial resolution than that of the LRM mode of CryoSat-2.

Here we investigate the performance of the Sentinel-3A SAR altimetry mission and present a new elevation product using a threshold first maximum re-tracker. Using a robust approach for observing elevation changes over the interior of the GrIS, we produce a preliminary dh/dt time series crossover analysis for Sentinel-3A's first year in operation. The analysis includes consideration of appropriate spatio-temporal statistical interpolation methods to allow for an inter-comparison with CryoSat-2's LRM over the ice sheet interior.

The Impact of Extratropical Cyclones on the Greenland Ice Sheet

Maffezzoni L.[1], Edward L. A.[1], Matthews T.[2], Lane T. P.[1], Mottram R. H.[3]

[1]School of Natural Sciences & Psychology, Liverpool John Moores University, Byrom Street, Liverpool, L3 3AF
[2]Loughborough University, Epinal Way, Leicestershire, UK
[3]Danish Meteorological Institute, Lyngbyvej 100, Copenhagen, 2200, Denmark

With a volume representing a potential sea level rise of 7.3 m, the Greenland Ice Sheet (GrIS) is the largest source of fresh water in the Northern Hemisphere. Mass is lost from the ice sheet primarily due to changes surface mass balance (SMB) and ice dynamics and over the past few decades, under the influence of Global Warming, the GrIS has experienced enhanced melt, run-off and ice calving. Despite extratropical cyclones' direct impact on SMB and surface energy budget (SEB) via snowfall, rainfall, incident longwave radiation and turbulent heat flux and recent work suggesting that their passage during summer can initiate intense melting and local ice flow acceleration, there is limited research on their role in forcing variations in SMB and ice dynamics. Our research aims to expand knowledge in the field of cyclones and their influence on GrIS SMB and dynamics.

Initial work is presented on a study of cyclones within a distance of 550 km (the mean radius of cyclones) from the GrIS boundaries extracted using the daily, 58-year record (1958 to 2016) of extratropical cyclones in the Northern Hemisphere of Serreze (2009). Two models, Model Atmospherique Regional (MAR) and HIRHAM, were used to produce climatological parameters, identify the 20 most extreme events during the period and extract a variety of SMB variables and related meteorological patterns for these events. Results show a recent decline in summer cyclones over GrIS as well as a steep decline in summer snowfall consistent with the decreasing frequency of cyclones.

Integrating Structure-from-Motion and time-lapse imagery to investigate ice-margin dynamics

Joseph Mallalieu[1], Jonathan Carrivick[1], Duncan Quincey[1], Mark Smith[1], and William James[1]

[1]School of Geography, University of Leeds, UK

Recent advances in Structure-from-Motion (SfM) and Multi-View Stereo (MVS) techniques have driven a dramatic increase in the use of high-resolution topographic datasets to investigate a wide variety of geomorphological processes and landforms. However, to date, many SfM-MVS based studies have been typified by low temporal resolution and discontinuous data collection, which can make the processes behind any changes difficult to disaggregate. The limitations of intermittent data collection are further compounded where processes themselves are unpredictable or require prolonged monitoring. In such cases, time-lapse photography has been widely employed to facilitate the generation of continuous datasets at fine-temporal resolutions. Consequently, the integration of SfM-MVS techniques with time-lapse imagery has remarkable potential for revealing mechanistic drivers and triggers of geomorphological change. Here we demonstrate the use of a novel SfM-MVS and time-lapse setup to investigate ice-margin dynamics under hostile environmental conditions in western Greenland.

Fifteen trail cameras were installed around a lacustrine-terminating margin of the Greenland ice-sheet between July 2014 and September 2015. Cameras acquired imagery 3 times a day over a continuous 426 day period, yielding a dataset of ~19 000 images. SfM-MVS analysis of the image dataset demonstrated the viability of the setup for generating high-resolution point clouds of ice-margin topography throughout a seasonal cycle. Differencing of successive point clouds identified calving events ranging from 234 to 1475 m^2 in area and 815 to 8725 m^3 in volume, induced by ice cliff undercutting at the waterline and the collapse of spalling flakes. The density of the dataset also facilitated an analysis of ice-margin dynamics at multiple temporal scales (from sub-daily to annual), thus permitting investigation of calving event magnitudes and frequencies. Analysis of smaller scale ice-margin dynamics was hindered by factors including low ambient light levels, locally reflective surfaces and a large survey range.

This study demonstrates that an integrated SfM-MVS and time-lapse setup can be employed to generate continuous topographic datasets and thus quantify ice-margin dynamics at a fine spatio-temporal scale. This approach provides a template for future studies of geomorphological change.

Influences of shading and fractional snow cover on sub-canopy effective albedo

Johanna Malle 1,2 , Nick Rutter 1 , Tobias Jonas 2

1 Department of Geography, School for Engineering and Environment, Northumbria University, Newcastle upon Tyne, UK
2 WSL Institute for Snow and Avalanche Research SLF, Flüelastrasse 11, CH-7260 Davos Dorf, Switzerland

The presence of forest canopy alters the energy balance of the land surface which, during winter-time, further affects snow cover dynamics. Accounting for these spatial and temporal differences between open and forested areas is essential for snow modelling in land surface models as well as hydrological models. In this study we investigated temporal radiation patterns along a 48m long transect in a discontinuous Norwegian Spruce forest in the Swiss Alps from January through May 2018. Forest structure metrics of the site were computed from up-looking hemispherical images as well as from airborne laser scanning (ALS) data. A cable car system with up- and down-looking pyrgeometers and pyranometers allowed us to capture both incoming and upwelling radiation in a continuous manner. An attached down-looking hemispherical camera further allowed us to quantify the influence of a shaded/sun-lit snow surface on effective sub-canopy albedo. Both fractional snow cover and shading were shown to have substantial impact on the sub-canopy effective albedo, indicating the importance of partitioning between areas of sun-lit and shaded snow when aiming to model sub-canopy snowpack dynamics.

InVEnTA: Interactive Virtual Environments for Teaching and Assessment – applications for virtual fieldtrips in the cryosphere

Damien Mansell[1], Steven Palmer[1], Anne Le Brocq[1]

[1]College of Life and Environmental Sciences, University of Exeter, EX4 4RJ, UK.

The InVEnTA project embraces the recent advances in geospatial and visualisation technologies to develop a software tool for efficiently producing ‘free roaming’ immersive Interactive Virtual Environments (IVEs). Environments can simply be created from freely available digital elevation data and satellite/airborne imagery, from new datasets collected by Unmanned Aerial Vehicles (UAVs) or kite-based photography, or even from a handheld camera (for smaller areas) or smartphone (for simpler objects). There is enormous potential for using these 3D data to form the basis for interactive, immersive virtual representations of real-world environments for teaching and learning, not just in the Geosciences, but in many other disciplines.
As part of the project, we are developing ‘case study’ examples, to demonstrate the tool and to explore the use of IVEs in existing and planned undergraduate teaching activities. The focus of one of these case studies will be Russell Glacier on the western margin of the Greenland Ice Sheet, for which high resolution imagery was acquired using a fixed-wing UAV in August 2017. These IVEs primarily lend themselves to the ‘engaged knowledge acquisition’ approach to learning. In addition, an alternative approach is to enable learners to create the educational beneficial material in the environments for themselves, allowing an ‘active knowledge construction’ approach, either from their own observations or from pre-existing datasets.

Utilising Esri's Collector App for Learning & Assessment on an Undergraduate Fieldtrip in Iceland

Damien Mansell[1],

[1]College of Life and Environmental Science, University of Exeter, EX4 4RJ, UK.

Recent advances in mobile technologies, integrated GPS, imaging sensors and processing techniques are revolutionizing spatial data. GIS (Geographical Information Systems) is the tool we use to store, manage, manipulate, analyse and present this geographically referenced data. Advances in functionality and access is changing the way in which we learn; utilising GIS to learn discover and increase engagement through Geographical inquiry. Students are taught using the latest functionality of ArcGIS including the collector app which allows field data to be collected using the inbuilt GPS of mobile devices. An example of this work and how it is changing the way in which our students plan and collect field data is on the Iceland fieldtrip. Students are tasked with reconstructing glacier retreat in one of four areas of interest. Using GPS to help navigate, collect and share the data has revolutionised not just how we teach the course but how the students are collecting data for their research.

Characterising the subsurface hydrology of a Himalayan debris-covered glacier using dye-tracing

Katie E. Miles[1], Bryn Hubbard[1], Duncan J. Quincey[2], Evan S. Miles[2], Ann V. Rowan[3], Tristam D. L. Irvine-Fynn[1]

1. Centre for Glaciology, Department of Geography and Earth Sciences, Aberystwyth University, Aberystwyth, UK
2. School of Geography, University of Leeds, Leeds, UK
3. Department of Geography, University of Sheffield, Sheffield, UK

Meltwater from Himalayan glaciers provides a vital resource for irrigation, sanitation and hydropower for millions of people in the Hindu-Kush Himalaya. Despite a recent increase in investigations into supraglacial hydrological features and processes of debris-covered glaciers, very little is known about how water is conveyed or stored beneath the glacier surface. Here, we report the results of fluorescent dye-tracing to investigate the englacial and subglacial drainage of the high-elevation, debris-covered Khumbu Glacier, Nepal, during the 2018 pre-monsoon season. We carried out six preliminary dye tests near the terminus, and a further ten long-range tests across the 9 km long ablation zone (ranging from 80 m to 7 km upglacier from the fluorometers located at the glacier terminus). Resulting dye breakthrough curves show that a subsurface hydrological network drains water to the terminus from up to 7 km upglacier, although the water does not appear to route through the linked supraglacial pond chain system. Water transport was slow (dye transit velocities varied between ~0.01 – 0.07 m s^{-1}), indicating an inefficient and convoluted drainage system, perhaps associated with the early pre-monsoon timing of the dye-tests. Close to the terminus, meltwater was stored in near-surface englacial reservoirs located between supraglacial ponds, providing transit delays of several hours. Such characteristics differentiate the hydrological features of debris-covered glaciers from those of clean-ice glaciers, indicating a need for further research into their distinct subsurface hydrology.

Modelling the instantaneous response of the Larsen C ice shelf and its tributary glaciers to shelf thinning

Tom Mitcham[1], G. Hilmar Gudmundsson[2], Jonathan Bamber[1]

[1] Bristol Glaciology Centre, School of Geographical Sciences, University of Bristol, Bristol, UK
[2] Department of Geography and Environmental Sciences, Northumbria University, Newcastle, UK

The Larsen C ice shelf (LCIS), situated on the Antarctic Peninsula, is the fourth largest ice shelf in Antarctica. After the collapse of the Larsen B ice shelf in 2002, the future stability of the LCIS and the consequences of its thinning, or collapse, has been called into question. Satellite observations show that the LCIS has been thinning over the past two decades and in July 2017 it calved one of the largest icebergs ever recorded. This reduction in ice shelf thickness and extent can lead to a reduction in buttressing at the grounding line and an acceleration of the grounded ice that flows into the shelf. Here, the LCIS and its tributaries are studied with a numerical ice flow model, Úa, which uses finite element methods to solve the shallow shelf approximation (SSA) to the full Stokes equations. Diagnostic model runs are used to assess the instantaneous response of the system to a series of perturbations to the thickness of the shelf. Observed LCIS thinning rates are used to evaluate contemporary changes in the region whilst further experiments are carried out with prescribed shelf thickness changes to assess the sensitivity of the response to different levels of thinning.

A simplified approach for estimating iceberg freshwater flux into glacial fjords

AN Moyer[1], DA Sutherland[2], PW Nienow[1], and AJ Sole[3]

[1]University of Edinburgh, School of Geosciences, Edinburgh, UK
[2]University of Oregon, Department of Earth Sciences, Eugene, OR, USA
[3]University of Sheffield, Department of Geography, Sheffield, UK

Iceberg discharge has been estimated to account for up to 50% of the freshwater flux delivered to the fjords surrounding the Greenland Ice Sheet. The amount, timing and location of meltwater produced via submarine melting of icebergs can have a large impact on the local fjord water circulation and heat budget. In particular, both the energy lost to melting and the input of cold freshwater from iceberg melt alters the amount of heat reaching tidewater glacier termini and thus their potential submarine melting, which has implications for glacial calving, retreat and acceleration. Here, we use remotely sensed data to examine the size and distribution of icebergs in Sermilik Fjord, southeast Greenland, during the 2017 melt season. Icebergs are identified and delineated using both spectral and spatial properties, and submerged volumes are estimated using an assumed relationship with iceberg surface area. Using previously observed iceberg velocities and changes in volume with distance down-fjord, we estimate freshwater flux into the fjord, accounting for changes in iceberg volume through time (i.e., a non-steady state scenario). This method provides a simplified approach for estimating both spatial and temporal variations in iceberg freshwater flux entering glacial fjords.

Subglacial Lakes in Ellsworth-Whitmore Block, West Antarctica

Felipe Napoleoni[1], Michael Bentley[1], Steward Jamieson[1], Neil Ross[2], Andrew Smith[3]

[1]Durham University
[2]Newcastle University
[3]British Antarctic Survey

Recent studies in Antarctica, have revealed more than 400 lakes partially interconnected in a hydrological system beneath Antarctic Ice Sheet (Wright and Siegert, 2012). This hydrological system affects the transient acceleration of ice streams and ice sheet behaviour (Fricker et al., 2007), which is a key process influencing sea-level change (Stearns et al., 2008). West Antarctic Ice/sheet (WAIS) has enough ice to contribute up to 3.3 m to sea level rise (Bamber et al., 2009), and thus it is fundamental to understand the dynamic of the ice-sheet (Bentley, 2010; Ross et al., 2014). Here we present the Radio Echo sounding data analysis of potential subglacial lakes in Ellsworth-Whitmore (EWM) Block.

Developing Python software tools for quantifying elevation changes in the Arctic

Steven Palmer[1], James Sanders[1],

[1]Geography, College of Life & Environmental Sciences, University of Exeter, UK,

The Arctic is one of the most rapidly warming regions on Earth, and increasing temperatures are leading to significant changes in both glaciated and ice-free terrain. This project aims to develop python software tools to detect and quantify elevation changes across the Arctic, using the NGA-NSF ArcticDEM dataset. It is intended that these tools will comprise of (i) automated data download for a user-defined area of interest, (ii) change detection performed on the time series of available DEMs, and (iii) quantification of change in these sub-areas. Areas of detected change will be filtered for noise and bias corrected, then subset for further quantification of change. Results will be presented in easily-digestible output images alongside key statistics, such as the histogram of elevation changes over the target area. While the code is being developed for the Batagaika thermokarst feature in Siberia, the code should be easily adaptable for use in research projects across the Arctic.

Estimation of Englacial Seismic Properties using Full Waveform Inversion: Scope and Sensitivity

Emma Pearce[1], Adam Booth[1], Graham Stuart[1], Ian Jones[2],

[1] School of Earth and Environment, University of Leeds, Leeds, LS2 9JT, United Kingdom.
[2]ION Geophysical, 31 Windsor St, Chertsey, KY16 8AT, United Kingdom.

Geophysical techniques, including field deployments of seismic methods, are the only practical means of extrapolating *in situ* ice properties from control points, and are therefore widely applied to quantify the mechanical and thermal structure of glaciers. Seismic velocities and amplitude losses are used to determine, for example, the density, crystal fabric and temperature of ice masses (e.g., Smith et al., 2002; Peters et al., 2012). A velocity distribution is often obtained from inverting the observed travel-time of a refracted seismic wave, and can be used to establish the density variation of firn profiles (Kulessa et al., 2016) via empirical velocity-density conversions (Kohnen 1974). However, the recent innovation of computational Full Waveform Inversion (FWI) techniques (Virieux and Operto, 2009) aims to constrain subsurface seismic properties by replicating the entire recorded wavefield, thus circumventing the limitations of travel-time inversion and/or empirical density conversions. However, the use of FWI algorithms in glaciology is currently limited despite their potential advantages.
In principle, FWI can be performed to recover any subsurface seismic property, depending on the complexity of the seismic modelling algorithm applied (Warner et al. 2013). Seismic quantities including velocity, absorption and density (relating, e.g., to ice fabrics, fracture networks and compaction regimes) can therefore be estimated. In this paper, we consider the sensitivity of FWI methods to the variability of firn compaction gradients, and compare their performance to conventional travel-time tomography methods. Varying firn densities from different glaciological settings (including Antarctica, Greenland, and Norway) have been simulated to assess the sensitivity of an FWI approach. We apply FWI-compliant considerations to the interpretation of seismic refraction data from Norway's Hardangerjøkulen ice cap, acquired in Spring 2018, comparing responses from sites with differing firn thickness and accumulation history. Preliminary observations suggest that FWI-compliant data acquisition is possible within the glaciological setting, therefore an FWI-based interpretation is worth pursuing.

References:
Kohnen, H., 1974; *Journal of Glaciology*, *13*(67), pp.144-147.
Kulessa B et al., 2016; European Geosciences Union, Vienna, Austria.
Peters et al., 2012; Journal of Geophysical Research, 117, F02008.
Smith et al., 2002; Journal of Geophysical Research, 107, B8.
Virieux, J. et al., 2009; Geophysics, 74(6), pp.WCC1-WCC26.
Warner et al., 2013; *Geophysics*, *78*(2), R59-R80.

New Bathymetry for the Southeastern Filchner-Ronne IceShelf: Implications for Modern Oceanographic Processes and Glacial History

S. H. R. Rosier[1,2], C. Hofstede[3], A. M. Brisbourne[2], T. Hattermann[4,3], K. W. Nicholls[2], P. E. D. Davies[2], P. G. D. Anker[2], C.-D. Hillenbrand[2], A. M. Smith[2], H. F. J. Corr[2]

[1] Department of Geography and Environmental Sciences, Northumbria University, Newcastle-upon-Tyne, UK
[2] British Antarctic Survey, Cambridge, UK
[3] Alfred Wegener Institute, Bremerhaven, Germany
[4] Akvaplan-niva AS, Tromsø, Norway

The Filchner-Ronne Ice Shelf, the ocean cavity beneath it, and the Weddell Sea that bounds it, form an important part of the global climate system by modulating ice discharge from the Antarctic Ice Sheet and producing cold dense water masses that feed the global thermohaline circulation. A prerequisite for modelling the ice sheet and oceanographic processes within the cavity is an accurate knowledge of the sub-ice sheet bedrock elevation, but beneath the ice shelf where airborne radar cannot penetrate, bathymetric data are sparse. Here, we present new seismic point measurements of cavity geometry from a particularly poorly sampled region south of Berkner Island that connects the Filchner and Ronne ice shelves. An updated bathymetric grid formed by combining the new data with existing data sets reveals several new features. In particular, a sill running between Berkner Island and the mainland could alter ocean circulation within the cavity and change our understanding of paleo-ice stream flow in the region. Also revealed are deep troughs near the grounding lines of Foundation and Support Force ice streams, which provide access for seawater with melting potential. Running an ocean tidal model with the new bathymetry reveals large differences in tidal current velocities, both within the new gridded region and further afield, potentially affecting sub-ice shelf melt rates.

Impact of tundra snow layer thickness on modelled radar backscatter

Nick Rutter[1], Mel Sandells[2], Chris Derksen[3], Josh King[3], Peter Toose[3], Leanne Wake[1], Tom Watts[1], Richard Essery[5], Phil Marsh[6], Alex Roy[7]

[1]Northumbria University
[2]CORES Science and Engineering
[3]Environment and Climate Change Canada
[4]University of Alaska Fairbanks
[5]Edinburgh University
[6]Wilfrid Laurier University
[7]Université de Sherbrooke

Microwave radar backscatter within an Arctic tundra snowpack is strongly influenced by spatial variability of the thickness of internal layering; often comprising two dominant snow layers (basal depth hoar overlain by wind slab). Determining the relative proportions of depth hoar and wind slab from a snowpack of a known depth may help our future capacity to invert forward models of electromagnetic backscatter to improve simulations of snow water equivalent.

Extensive measurements of snow microstructure were made within Trail Valley Creek, NWT, Canada in April 2013 and March 2018 at 54 pit and 9 trench locations (trench extents ranged between 5m to 50m). Ground microstructure measurements included traditional stratigraphy, near infrared stratigraphy, Specific Surface Area (SSA), and density. Trench measurements of stratigraphy showed the mean proportion of depth hoar was just under 30% of total snow depth and the mean proportion of wind slab was consistently greater than 50%, which showed an increasing trend with increasing total snow depth. Measurements of density and SSA in each major snowpack layer were distinctly clustered allowing application of median values as important parameters in the snow microwave radiative transfer (SMRT) model to estimate radar backscatter.

SMRT was used to quantify how spatial variability in the measured microstructural parameters of a synthetic snowpack affect one-dimensional retrievals of snow water equivalent (SWE). A three layer snowpack retrieval experiment over snow depths typical of Arctic tundra demonstrated that a SSA ~10% smaller than the median of the depth hoar layer, the most important layer for scattering, was required to retrieve SWE within a ±30 mm SWE error budget. The impact of SSA variability in wind slab was smaller and negligible for fresh snow.

Drumlin and MSGL formation underneath the Rutford Ice Stream, West Antarctica

Rebecca Schlegel[1], Andy M. Smith[2], Tavi Murray[1], Edward C. King[2], Alex M. Brisbourne[2], Roger A. Clark[3], Adam D. Booth[3]

[1]University of Wales Swansea, Singleton Park, Swansea SA28PP, UK
[2]British Antarctic Survey, Natural Environment Research Council, Madingley Road, Cambridge CB3OET, UK
[3]University of Leeds, Woodhouse Lane, Leeds LS2 9JT, UK

The Rutford Ice Stream is a fast flowing ice stream in West Antarctica draining into the Ronne Ice Shelf. It has been subject of ongoing research over the past three decades, which has acquired significant radar, seismic, passive seismic and GPS datasets. 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, while changes (erosion and deposition) at the bed have been observed over time. During field season 2017/18 we acquired new radar grids using the British Antarctic Survey's Deep Look Radio Echo Sounder (DELORES) with a centre frequency ~3.5 MHz. In total 2,265 km of radar data were collected covering three grids with between line spacing of 20 m and an inline spacing ~1.5 m. The first grid targeted the upstream end of an MSGL, the second, an area where the flow mechanism changes from sediment deformation to basal sliding, and the third, an area where erosion has previously been observed. This high density grid spacing is suitable for the application of both 3D migration and synthetic aperture radar (SAR) processing. We aim to: (i) image the landforms beneath Rutford Ice Stream in high resolution; (ii) understand erosion and sediment transport to be able to explain drumlins and MSGL formation, and (iii) compare the two different processing techniques. We present preliminary results from our field campaign: the processing and interpretation of the data are ongoing.

The pre-glacial geomorphology of Antarctica and its relevance to the Antarctic Ice Sheet

David Sugden[1] and Stewart Jamieson[2]

[1] Institute of Geography, School of GeoSciences, University of Edinburgh, Edinburgh, EH8 9XP
[2] Department of Geography, Durham University, South Road, Durham, DH1 3LE

The nature of the bed of the Antarctic Ice Sheet, important in influencing glacier flow, depends on modifications made by glaciers to a pre-glacial topography. Thus knowledge of the subglacial landscape of Antarctica is relevant to the understanding of the Antarctic Ice Sheet. We believe that geomorphology has much to contribute, but that the lack of coherent hypotheses about the nature and origins of the pre-glacial landscape is holding back understanding. This paper approaches the problem by using southern hemisphere land masses in Africa and Madagascar as analogues of the pre-glacial landscape of Antarctica. We find that the Antarctic landscape evolved in a similar way to passive margin evolution in southern Africa. Rifting associated with the breakup of Gondwana abruptly changed river base levels and caused rapid erosion on the flanks of rifts mostly within tens of millions of years. Typically, patterns of erosion and deposition introduce isostatic responses that enhance the uplift of rift-margin escarpments. Rift-margin plains, often coastal or adjacent to large rivers and backed by escarpments are typical, while large low-gradient continental river basins characterise the interior. Younger rift margins such as that bounding the Ross Sea display continuous mountain escarpments while older rift margins are more broken up. In East Antarctica ice has removed the pre-existing regolith from lowlands, especially in zones of ice convergence, and excavated deep troughs below sea level along the courses of major trunk rivers; the latter are a focus of possible ice-sheet instability. The micro-continents of West Antarctica are similar in size to Madagascar and apparently share a similar topography with coastal plains, backing escarpments and interior uplands.

Assessing the impact of ice algae on Greenland Ice Sheet melting

Andrew Tedstone[1], Joseph Cook[2], Christopher Williamson[1], Jenine McCutcheon[3], Xavier Fettweis[4], Mark Flanner[5], Jonathan Bamber[1] and Martyn Tranter[1]

[1] School of Geographical Sciences, University of Bristol, UK
[2] Department of Geography, University of Sheffield, UK
[3] School of Earth and Environment, University of Leeds, UK
[4] Department of Geography, University of Liege, Belgium
[5] Climate and Space Sciences and Engineering, University of Michigan, USA

Areas of dark ice have appeared along the margins of the Greenland Ice Sheet during most melt seasons since at least 2000. Dark ice exhibits very low albedo and, as albedo is a major control upon the surface energy balance and hence melt rates, it is essential to understand the evolution of dark ice under projected climate change. However, regional climate models have not simulated the albedo of dark ice because the processes responsible for dark ice have not been identified.

Recent field evidence indicates that the darkening along the western margins of the GrIS is driven strongly by the growth of pigmented ice algae. Here, we use observations made along the south-west margin of the GrIS over two melt seasons together with regional climate modelling to assess the impact that ice algae has upon GrIS melting.

We demonstrate that the growth of ice algae and their impact upon ice albedo can be physically parameterised in a regional climate model. We model the quantity of ice algae present on the surface as a function of meteorological conditions. We explore the importance of inorganic particulate material in providing spatial constraints upon algal growth. We then compute the surface albedo, including the impact of surface impurities, by solving the two-stream Snow, Ice and Aerosol Radiative (SNICAR) 2-stream model coupled to the regional climate model MAR. This approach enables us the explore the sensitivity of GrIS melting and runoff to ice algae both in the past and by the end of the 21st century.

Mass balance of Arctic ice caps from CryoSat-2 swath altimetry

Paul Tepes[1], Noel Gourmelen[1], Flora Weissgerber[1], Pete Nienow[1], Michel Tsamados[4], María José Escorihuela[2], Jan Wuite[3], Thomas Nagler[3], Luca Foresta[1], David Brockley[4], Steven Baker[4], Mònica Roca[2], Andrew Shepherd[5] and Stephen Plummer[6]

[1]University of Edinburgh, UK; [2]isardSAT, Spain; [3]ENVEO, Austria; [4]University College London, UK; [5]Centre for Polar Observation and Modelling, University of Leeds, UK; [6]ECSAT Harwell Centre, UK

Arctic glaciers and ice caps (GIC) accounted for ~35% of global sea-level rise since the early 2010s. Their ice mass is expected to decline over the course of the 21st century as a result of enhanced greenhouse gas concentrations, net radiation imbalance and polar amplification. Estimating GIC mass budgets for the entire Arctic region is challenging because satellite ground track spacing and footprints of modern altimetry sensors are coarse compared with the small size of GICs, their steep slopes and complex topography. Here, we use high-definition swath processing of CryoSat-2 radar altimetry data to quantify ice losses from GICs between 2010 and 2017 at pan-arctic scale. Two-fold rates of loss from marine-terminating outlet glaciers compared with land-terminating margins in the Barents/Kara archipelagos suggest that profuse warm Atlantic water incursions have a major impact on the loss of Arctic land ice outside of Greenland. Our results draw attention to the importance of quantifying ocean warming in the Arctic to improve regional climate projections and to reduce uncertainty in the parametrisation of future-generation climate models.

Sub-canopy longwave radiation and its impact on snow cover in boreal forests simulated by a global climate model

Markus Todt[1], Nick Rutter[1], Christopher G. Fletcher[2], Leanne M. Wake[1], Michael M. Loranty[3]

[1] Department of Geography, Northumbria University, Newcastle upon Tyne, UK
[2] Department of Geography and Environmental Management, University of Waterloo, Waterloo, Ontario, Canada
[3] Department of Geography, Colgate University, Hamilton, NY, USA

Boreal forests cover about a fifth of annual maximum snow cover extent over the Northern Hemisphere. Enhancement of longwave radiation beneath coniferous forests has been found to impact the surface energy balance and rates of snowmelt. Although modelling skill for snowmelt has been shown to be lower for forests than for open areas, model intercomparisons and evaluations of model parameterizations have not yet focussed on longwave enhancement.
This study uses forest stand-scale forcing for the simulation of sub-canopy longwave radiation by Community Land Model version 4.5 (CLM4.5), a component of Community Earth System Model (CESM) that was part of CMIP5, and measurements of sub-canopy longwave radiation from these forest stands for evaluation. CLM4.5 is found to overestimate the diurnal range of sub-canopy longwave radiation and simulation errors increase with decreasing cloudiness and increasing vegetation density.
The systematic dependence of simulation errors on meteorological conditions is used to estimate correction factors scaling sub-canopy longwave radiation in global simulations. Compared to control simulations, this modification results in differences in both snow cover and snowmelt found consistently throughout the snow season and across boreal forests. Snow temperatures are impacted continuously during snow season resulting in a change in snow-off dates.

Decadal Scale Ice Velocity Change at Land-Terminating Margins of the Greenland Ice Sheet

Joshua Williams[1], Dr. Noel Gourmelen[1], Hamish Morton[1], Prof. Pete Nienow[1]

[1]School of Geosciences, University of Edinburgh

Over the past two decades, the Greenland Ice Sheet has experienced significant mass loss, of which ~60% can be attributed to enhanced surface melt as a result of increasing Arctic air temperatures. The dynamic response of the Greenland Ice Sheet is impacted by feedbacks between surface meltwater delivery to the bed and ice flow. It was initially thought that an increased input of surface meltwater to the sub-glacial environment would act to increase basal water pressure, reduce basal drag and so enhance ice motion. However, recent studies over a land-terminating sector of the western Greenland ice sheet argue that enhanced surface melt will cause an expansion of a channelised sub-glacial drainage system, causing a reduction in glacier velocity as a result of a regional decrease in sub-glacial water pressure. Considerable uncertainties remain regarding processes linking hydrology and dynamics of the Greenland Ice Sheet, notably the impact of enhanced surface melt further inland and further north, where melt seasons are shorter.
Here, we present preliminary results following the derivation of surface velocity fields through repeat-image feature tracking, utilising the entire Landsat archive, for land-terminating margins across the Greenland Ice Sheet. From this data, inferences can be made into whether the negative feedback between surface meltwater production and ice velocity observed in the West Greenland sector around Leverett Glacier is observed across other sectors of the ice sheet, and what controls variability in the observed response.

Topographic controls on ice flow at the bottleneck between East and West Antarctica

Kate Winter[1,2], Neil Ross[2], Fausto Ferraccioli[3], Tom Jordan[3], Hugh Corr[3], René Forsberg[4], Kenichi Matsuoka[5], Arne Olesen[4], Tania Casal[6]

[1]Department of Geography and Environmental Sciences, Faculty of Engineering and Environment, Northumbria University, Newcastle upon Tyne, UK
[2]School of Geography, Politics and Sociology, Newcastle University, Newcastle upon Tyne, UK
[3]British Antarctic Survey, Cambridge, UK
[4]Geodynamics, National Space Institute, Technical University of Denmark, Lyngby, Denmark
[5]Norwegian Polar Institute, Tromsø, Norway
[6]European Space Agency/ESTEC, Noordwijk, Netherlands

Hypothesised drawdown of the East Antarctic Ice Sheet through the “bottleneck” zone between East and West Antarctica would have significant impacts for a large proportion of the Antarctic Ice Sheet. Earth observation satellite orbits and a sparseness of radio echo sounding data have restricted investigations of basal boundary controls on ice flow in this region until now. New airborne radio echo sounding surveys from the PolarGAP survey reveal complex topography of high relief beneath the southernmost Weddell/Ross ice divide, with three subglacial troughs connecting interior Antarctica to the Foundation and Patuxent Ice Streams and Siple Coast ice streams. These troughs route enhanced ice flow through the interior of Antarctica but limit potential drawdown of the East Antarctic Ice Sheet through the bottleneck zone. In a thinning or retreating scenario, these topographically controlled corridors of enhanced flow could however drive ice divide migration and increase mass discharge from interior West Antarctica to the Southern Ocean.