Institution: University of Aberdeen

Unit of Assessment: 7 (Earth Systems and Environmental Sciences)

Title of case study: Stability of ice sheets

1. Summary of the impact

This case study details the impact of current glaciological research at the University of Aberdeen on the Earth's polar ice sheets on practitioners and services in the non-academic science community, specifically the British Antarctic Survey (BAS) and European Space Agency (ESA). In addition, the research has informed public understanding of the stability of the polar ice caps under the influence of climate change. The beneficiaries of our research are professional scientists in Environmental and Earth Sciences working at BAS and ESA who have used our findings to constrain computer modelling of ice sheet dynamics and to calibrate and validate measurements of ice sheet mass change. We have been involved in major international collaborative field research on the Antarctic and Greenland Ice Sheets to better define the current basal and surface boundaries of the ice sheets and to improve the understanding of the sensitivity of the ice sheets' boundaries to climate change over a range of timescales.

2. Underpinning research

Glaciologists at the University of Aberdeen (UoA) have for over ten years undertaken field-based research on the Antarctic Ice Sheets (AIS) and the Greenland Ice Sheet (GrIS). Their published work has made an impact on the non-academic science community, in particular the British Antarctic Survey and the European Space Agency, by improving understanding of (i) the current surface and basal geometries and properties of the ice sheets, and (ii) the sensitivity of the surface and basal processes to climate change over a range of timescales. This work has informed, and continues to inform, the scientific basis for assessment of the threat posed by anthropogenic climate change on ice sheet mass balance and consequently on global sea level rise. Through press interest and public outreach their work has contributed to the improvement in public understanding of the issues and uncertainties associated with glacial polar science and the environmental impacts of climate change.

West Antarctic Ice Sheet

The West Antarctic Ice Sheet is bounded on three sides by ocean and is predominantly grounded below sea level. This geometry gives rise to complex and poorly understood physics that control the flow of ice from the interior to the oceans. To be reliable predictors of ice sheet stability, computer models require much better knowledge of the geometry and physical properties of the bed of glaciated catchments that drain to the ocean. To this end, **Bingham** (Lecturer 2009-2012; Senior Lecturer since 2013) undertook the first systematic over-snow radar and seismic surveys of the vast **Pine Island Glacier** (PIG), West Antarctica's most rapidly thinning region (1,2), with colleagues including post-doctoral researcher **Scott** (employed at Aberdeen 2004-2006). Bingham mapped new regions of basal topography and differentiated wet and dry basal sediments. He also analysed data from airborne radar surveys to infer past ice-flow dynamics. **Bingham** also undertook the first systematic geophysical data acquisition across Ferrigno Ice Stream, a key region of high surface velocity and ice mass discharge from the Bellingshausen Sea margin of West Antarctica. His field investigations and subsequent analyses revealed that a spatially distinct region of high glacier ice velocities is steered far into the interior of the ice sheet by the existence of a significant tectonic rift that underlies the ice (3). The work has brought into focus the importance of the long-term geological antecedent conditions in determining the sensitivity of contemporary ice sheets to marine forcings and provided an important contribution to Antarctic bed mapping in a previously unsurveyed area.

Greenland Ice Sheet

The European Space Agency's (ESA) CryoSat mission is the first satellite radar altimeter dedicated to measuring change in the Earth's land and marine ice masses. The mission aims to provide cm-scale accuracy in measurements of ice-sheet elevation change. An integral component of achieving this aim was a dedicated field measurement campaign to undertake validation experiments (CryoVex) to "ground truth" an airborne version of the satellite radar altimeter before the launch of the satellite itself. In 2004 and 2006 **Mair** (Lecturer 2002-2006, Senior Lecturer since 2006), post-doctoral researcher **Scott** and colleagues completed a range of geophysical field experiments along a transect of the GrIS. They quantified the amount of summer surface melt that subsequently refreezes in the snowpack, the impact of this on the derivation of ice sheet mass change from surface elevation change (4), and used this information to help develop improved methods for deriving ice sheet surface elevation measurements from radar measurements. They demonstrated that radar reflections from ice layers below the ice sheet surface can create a stronger signal than from the ice sheet surface (5); explained their cause, temporal and spatial variability; and highlighted potential for erroneous surface elevation change measurements by satellite radar altimeters where these phenomena are not accounted for (6).

3. References to the research

1. Smith, AM., Bentley, CR., **Bingham, RG**. & Jordan, TA. (2012). *'Rapid subglacial erosion beneath Pine Island Glacier, West Antarctica'*. Geophysical Research Letters, vol 39, pp. L12501. *One of several papers reporting key geophysical products from surveying of Pine Island Glacier that are being used in BAS ice-sheet modeling of the glacier's future.*

2. Fretwell, P.T. and 55 authors inc. **R.G. Bingham** (2012) *Bedmap2: improved ice bed, surface and thickness datasets for Antarctica.* The Cryosphere Discussions, 6, 4305-3361. *This paper reports on the construction of the Scientific Committee for Antarctic Research (SCAR) product BEDMAP2, with several Aberdeen-acquired-and-analysed surveys forming key inputs to the final product.*

3. **Bingham, R.G**., Ferraccioli, F., King, E.C., Larter, R.D., Pritchard, H.D., Smith, A.M. & Vaughan, D.G. (2012). *'Inland thinning of West Antarctic Ice Sheet steered along subglacial rifts'.* Nature, 487, 468-471*. Providing a new subglacial topographic dataset in a previously unexplored area that has formed a direct input to BEDMAP2, this paper also formed the basis for raised public understanding of Antarctic ice loss through associated press reporting in 2012* (Funded by NERC-Antarctic Funding Initiative Collaborative Gearing Scheme Grant Ice flow into Eltaning Bay, Bellingshausen Sea, West Antarctica)

4. Parry, V., Nienow, P., **Mair, D., Scott, J**., Hubbard, B., Steffen, K. and Wingham, D. 2007. *"Investigations of meltwater refreezing and density variations in the snowpack and firn within the percolation zone of the Greenland Ice Sheet".* Annals of Glaciology, 46, 61-68.

5. Scott, J.B.T., Nienow, P.W., **Mair, D.W.F.,** Parry, V., Morris, E.M., and Wingham, D.J. 2006. *"The importance of seasonal and annual layers in controlling backscatter to radar altimeters across the percolation zone of an ice sheet",* Geophysical Research Letters, **33**, L24502, doi: 10.1029/2006GL027974. (NERC-Consortium Grant "Validation and Provision of CryoSat Measurements of Fluctuations in the Earth's Land and Marine Ice Fluxes")

6. Scott, J.B.T., **Mair**, **D.W.F.,** Nienow, P.W., Parry V.L. and Morris. E.M. 2006. *"High frequency ground based radar measurements in the percolation zone of the Greenland Ice Sheet".* Remote Sensing of Environment. **104**, 361-373 (NERC-Consortium Grant "Validation and Provision of CryoSat Measurements of Fluctuations in the Earth's Land and Marine Ice Fluxes").

4. Details of the impact

Our cryospheric research offers benefits to the non-academic scientific community and to the public, through improved understanding of the stability of polar ice sheets and via our contributions

to public debates and understanding of sea level change and climate change.

Non-academic scientific beneficiaries

Over the last decade, the findings of our research have been disseminated to the scientific community via several pathways, and have had direct impact on the work of non-academic scientific institutions. The scientific output from Antarctica (Bingham) is being used by the **British Antarctic Survey** to reduce the uncertainty surrounding ice sheet boundary conditions and processes, and to improve constraints on future model-based predictions of ice sheet response to climate change. The scientific output from the Greenland Ice Sheet (Mair) is currently still being used by the **European Space Agency** Cryosat programme to calibrate and validate satellite radar based ice sheet measurements models. Additionally, Mair had central input to the design of ESA's CryoVex field experiments. As a result, over the REF-reporting period Bingham has been invited, on the basis of his geophysical findings, to contribute to glaciology/Antarctic tectonics workshops at NASA (Washington D.C., February 2009) and the Polar Research Institute of China (Beijing, October 2010), and Mair was invited to participate in the ESA/NASA workshop on satellite ice sheet altimetry in Reykjavik in June 2009.

British Antarctic Survey (BAS)

Our acquisition, processing, analysis and provision to BAS of key ice-penetrating geophysical datasets across some of West Antarctica's most remote regions has contributed to greatly-reduced uncertainties in BAS's programme of numerically modelling the ice-sheet's future. BAS ice-sheet modelling activities over the last six years have been dedicated to providing greatly improved predictions of the ice-sheet's fate and contribution to global sea-level rise over the next 200 years, to be included in the Intergovernmental Panel on Climate Change's 5th Assessment Report (IPCC AR5, due 2014). A key deficiency of earlier generations of models was the dearth of key model-input data such as basic subglacial topography in some of West Antarctica's most rapidly diminishing regions. Since 2006, our multiple-month field campaigns across these areas have provided the key input datasets most required by BAS modellers to meet the IPCC AR5 goal. The radar and seismic data that we have collected have also been integral to the construction and 2013 release of the Scientific Committee for Antarctic Research (SCAR) product "BEDMAP2", a new digital map of subglacial topography that is central to a range of core activities conducted at BAS, including "whole ice-sheet" modelling, geological reconstructions and ice-core palaeoclimatic interpretations. The Science leader of the IceSheets programme at BAS confirmed: *"[…] the datasets you collected have assisted in filling a crucial data gap […] and supported our ice sheet modelling activities[…] which in turn were prepared to support the upcoming assessment of the IPCC*" (1].

European Space Agency

Our early involvement with the ESA CryoSat Calibration and Validation experiments from 2004 to 2006 has contributed to the eventual success of CryoSat2 in mapping the elevation of the GrIS with unprecedented accuracy in April 2012. Our ground radar measurements were made at the same frequencies and wavelengths as the airborne radar equivalent of the CryoSat radar altimeter (ASIRAS) which flew across our transects directly over metallic corner reflectors which we erected and measured with differential GPS to determine precise elevations. From 2007 until the launch of CryoSat 2 in November 2010, ESA radar processing teams used our understanding of the temporal and spatial variations in the relative strength of natural surface and near-surface radar reflectors to help devise the most appropriate surface retracking algorithms and compared airborne and ground measurements of artificial corner reflector elevations to help determine absolute elevation accuracies. ESA also continue to use our accumulation and density measurements made across Greenland in 2004 and 2006 to characterise temporal and spatial covariance of annual

accumulation across the ice sheet and to constrain near surface densification models that are used to convert the ongoing CryoSat2 mission's elevation and volume change measurements to mass change outputs. The head of the Campaign Section at the ESA has clarified: "*the main goal of the CryoSat mission […] is to provide cm-scale accurate measurements of ice sheet elevation changes to determine the changes in the land and marine ice masses. Achieving this challenging goal requires the collection of independent measurements on the ground […]. For this the European Space Agency relies strongly on co-operation with scientists such as Dr. Mair*". ESA confirm the importance of the research findings in contributing to their work: "*valuable information on surface melt and refreezing of the snowpack during the summer season […] was and continues to be extremely useful both to better understand the nature of the CryoSat radar echos from the ice sheet, as well as transform ice sheet surface elevation measurements into ice sheet mass change*" (2).

Public Understanding of Science

Our research has also achieved significant wider societal impact. We have used radio, television, the internet and printed media to raise awareness of our work and explain the importance of polar science to different segments of the public. For example, **Bingham's** recent research on the influence of subglacial rifting on the diminishing West Antarctic Ice Sheet was reported in >200 international media outlets, including the BBC Website (3], BBC World and BBC Scotland Radio, Scientific American (4), Time Magazine and NERC Planet Earth Online. An explanatory video of the work was placed on YouTube and received 75,000 views in 3 days (5). **Bingham** has also appeared on Sky News (2009) and the BBC Website (2008) reporting on his research in West Antarctica (6). **Mair** has taken part in radio (BBC Scotland), TV (BBC, ABC) and newspaper interviews (Sunday Telegraph) both in the field and from the UK about his glacial research and its wider significance. In September 2012 **Bingham** and **Mair** organised, chaired and were panel members of a British Science Festival event, watched by an audience of over one hundred, presenting and debating the future of our polar regions.

5. Sources to corroborate the impact

1. Sources within the Science Leader Ice Sheets Programme, British Antarctic Survey will corroborate the contribution of the research to the wider British Antarctic Survey ice sheets programme, especially in providing data sets.

2. The Head of the Campaign Section, Directorate of Earth Observation Programmes, European Space Agency can corroborate the contribution of the research to the wider ESA CryoSat programme.

3. BBC News July 2012: http://www.bbc.co.uk/news/science-environment-18959399. *This source reports on the findings from research towards a public audience*

4. Scientific American 23 July 2012: http://www.scientificamerican.com/article.cfm?id=scientists-uncover-grand-canyon-in-antarctica. *This source, in a US publication, demonstrates the reach of interest in the research findings*

5. YouTube July 2012: http://www.youtube.com/watch?v=VZd47gfsfuA. *This source is a re-formatting, in a form accessible to the public, of the findings from research on the Antarctic Ice Sheet. It received 75,000 views in the first 3 days after it became available, coinciding also with the publication by UK and US media outlets.*

6. BBC News 24 February 2008: http://news.bbc.co.uk/1/hi/sci/tech/7261171.stm. *This source is an early report on public media of the results of research, concentrating specifically of the work of University of Aberdeen scientists.*