Institution: University of Edinburgh

Unit of Assessment: 7

Title of case study:
Informing climate change policy and planning through improved estimates of sea-level rise from global ice-sheet and glacier melt.

Period when the underpinning research was undertaken:
1 August 2013 – 31 December 2020

Details of staff conducting the underpinning research from the submitting unit:

Name(s):	Role(s) (e.g. job title):	Period(s) employed by submitting HEI:
Robert Bingham	Professor of Glaciology and Geophysics	2013 – present
Thomas Cowton	PDRA in Ice-Ocean Interactions	2015 - 2016
Damon Davies	PhD Student	2013 – 2018
Luca Foresta	PhD Student	2013 – 2017
Daniel Goldberg	Reader in Glaciology	2013 – present
Noel Gourmelen	Reader in Remote Sensing of the Cryosphere	2013 – present
Sian Henley	Lecturer in Marine Science	2008 – present
Peter Nienow	Professor of Glaciology	2004 – present
Donald Slater	PhD Student	2013 – 2017
Kate Snow	PDRA in Ice-Ocean Interactions	2016 – 2018

Period when the claimed impact occurred:
1 August 2013 – 31 December 2020

Is this case study continued from a case study submitted in 2014? Y/N
N

1. Summary of the impact (indicative maximum 100 words)

University of Edinburgh (UoE) data and modelling of ice-sheet and glacier melting from the world's polar and high-mountain regions have fundamentally reduced uncertainties in estimates of future global sea-level rise, informing decisions by international policymakers. UoE researchers have improved the spatial and temporal resolution for satellite monitoring of changing ice sheets and glaciers through developing algorithms underpinning EUR300,000,000 worth of satellite mission development by the European Space Agency. They have also acquired field geophysical data and made theoretical developments in ice-sheet numerical modelling that have informed the Intergovernmental Panel on Climate Change (IPCC) reports, which underpin scientific advice to international and national government policies on climate change mitigation and adaptation.

2. Underpinning research (indicative maximum 500 words)

The team of ice-sheet and glacier scientists at the University of Edinburgh have acquired important new satellite and field data and developed novel numerical modelling techniques to monitor change around the world's ice-covered regions. These include the ice-covered continents of Antarctica (57 times the area of the UK) and Greenland (9 times the area of the UK), and major ice-covered mountain belts such as the Himalayas and Andes.

Satellite observations gathered over glaciers worldwide have been critical to substantially

improving estimates of the rates of ice loss and to quantifying their contribution to sea-level rise. The vast majority of ice loss is concentrated around the margins of Antarctica and Greenland, and high-mountain regions such as the Himalayas, Iceland and South America. Gathering observations that are global and of sufficient spatial and temporal resolution is key to generating robust assessments of glaciers' health. To this end, UoE researchers have developed new methodologies to process radar altimetry data from the CryoSat satellite, exploiting the full signal waveform to generate swath of elevation as opposed to a single elevation measurement as was previously extracted **[3.1, 3.2, 3.3]**. These have led to an order of magnitude increase in the resolution at which ice loss can be routinely and globally mapped from space. This methodology has been applied to reassess climate impact on ice volumes and sea-level rise contribution, showing that Greenland today is losing ice seven times faster than two decades ago, and pinpointing where the ocean is eroding ice under rapidly melting Antarctic ice shelves. Data products from this have been made available publicly to the community, and support a candidate satellite mission concept for the European Commission Copernicus satellite programme Sentinel **[5.1, 5.2]**.

Field data acquired from the deep interior of Antarctica have been critical to constraining British Antarctic Survey models of future ice retreat from Antarctica and its consequent contributions to global sea-level rise. Numerical models that are used to predict future ice retreat and contributions to rising sea levels require knowledge of the geometry and physical properties of the beds of glaciated catchments that drain to the ocean. To this end, over the November 2013 – February 2014 austral field season, UoE researchers acquired and analysed ice-penetrating radar datasets over Pine Island Glacier (PIG), West Antarctica's most rapidly thinning region, as part of NERC's iSTAR (Ice Sheet Stability Research) Programme. Maps of the ice bed and properties produced over the subsequent years **[3.4]** have fundamentally informed numerical modelling of PIG's future **[5.3]**.

Numerical modelling strategies developed by UoE scientists have informed us about the impact of oceans on the flow and retreat of ice around West Antarctica and Greenland, and have additionally demonstrated the important role that climate variability plays in the ice-ocean system **[3.3, 3.5, 3.6]**. These findings **[3.5]** have been cited by the recent IPCC Special Report on the Ocean and Cryosphere in a Changing Climate and the numerical tools developed for the studies have proven key components of wider community efforts to project West Antarctica's future **[3.6; 5.3].**

3. References to the research (indicative maximum of 6 references)

[3.1] Foresta, L., **Gourmelen, N.**, Pálsson, F., **Nienow, P.**, Björnsson, H. & Shepherd, A. (2016) Surface elevation change and mass balance of Icelandic ice caps derived from swath-mode CryoSat-2 altimetry. ***Geophysical Research Letters***, *43*, 12,138-12,145. doi:10.1002/2016GL071485. [30 citations].

[3.2] Gourmelen, N., Escorihuela, M., Shepherd, A., **Foresta, L.**, Muir, A., Garcia-Mondejar, A., Roca, M., Baker, S. and Drinkwater, M.R. (2018) CryoSat-2 swath interferometric altimetry for mapping ice elevation and elevation change. ***Advances in Space Research***, *62*, 1226-1242. doi:10.1016/j.asr.2017.11.014. [20 citations].

[3.3] Gourmelen, N., Goldberg, D.N., Snow, K., Henley, S.F., Bingham, R.G., Kimura, S., Hogg, A.E., Shepherd, A., Mouginot, J., Lenaerts, J.T.M., Ligtenberg, S.R.M. and van de Berg, W.J. (2017) Channelized melting drives thinning under a rapidly melting Antarctic ice shelf. ***Geophysical Research Letters***, *44*, 9796-9804. doi:10.1002/2017GL074929. [27 citations].

[3.4] Bingham, R.G., Vaughan, D.G., King, E.C., **Davies, D.**, Cornford, S.L., Smith, A.M., Arthern, R.J., Brisbourne, A.M., De Rydt, J., Graham, A.G.C., Spagnolo, M., Marsh, O.J. & Shean, D.M. (2017) Diverse landscapes beneath Pine Island Glacier influence ice flow. ***Nature Communications***, *8*, article 1618. doi:10.1038/s41467-017-01597-y. [31 citations].

[3.5] Slater, D.A., **Nienow, P.W., Cowton, T.R., Goldberg, D.N.** and Sole, A.J. (2015) Effect of near-terminus subglacial hydrology on tidewater glacier submarine melt rates. ***Geophysical Research Letters***, *42*, 2861–2868. doi:10.1002/2014GL062494 [65 citations].

[3.6] Snow, K., Goldberg, D.N., Holland, P.R., Jordan, J.R., Arthern, R.J., & Jenkins, A. (2017) The response of ice sheets to climate variability. ***Geophysical Research Letters***, *44*, 11,878– 11,885. doi:10.1002/2017GL075745. [9 citations].

In Section 5, source **5.1**, research that has been cited by the 2019 Intergovernmental Panel on Climate Change *Special Report on the Ocean and Cryosphere in a Changing Climate* is also detailed.

The underpinning research listed was published in highly ranked academic journals (Scopus citations as of December 2020 shown above), and supported by peer-reviewed grants. Examples include:

Bingham, R.G. (2013-2016). iSTAR-C: Dynamical control on the response of Pine Island Glacier. [NE/J005665]. *NERC*. GBP50,001.

PI, Nienow, P. (2013-2016) Investigating controls on flow variability in Greenland's tidewater glaciers: the impact of runoff on fjord circulation and termini melt rates. [NE/K015249]. *NERC*. GBP272,410.

PI, Goldberg, D. (2014-2018) Is ice loss from West Antarctica driven by ocean forcing or ice and ocean feedbacks? [NE/M003590]. *NERC*. GBP236,092.

PI, Gourmelen, N. (2015-2020). Mountain Glacier Change from CryoSat. [4000114224/15/I-SBo]. *ESA*. EUR482,792.

PI, Gourmelen, N. (2016-2019). Cryo Top Evolution. [4000116874/16/I-NB]. *ESA*. EUR500,000.

4. Details of the impact (indicative maximum 750 words)

Changes taking place in the Arctic, Antarctic and other glaciated regions are drivers for disruptive global changes, especially sea-level rise, with major ramifications for people living both in polar regions and worldwide. Research conducted by the group has provided key input to climate change decision-making by international policymakers, in particular through key contributions on sea-level rise to the reports of the Intergovernmental Panel on Climate Change (IPCC). These reports are the formal scientific input to the decision-making processes of international climate change negotiations and agreements. We evidence our research cited in the 2019 IPCC *Special Report on the Ocean and Cryosphere in a Changing Climate* in **[5.1]** while our data and modelling contributions to the IPCC Sixth Assessment (due 2021) are evidenced below in this section ("Informing policy…")

Improving technology to provide accurate assessment of climate change impacts on ice sheets and glaciers and their contribution to sea-level change

The EU *Copernicus* Earth Observation programme was established to fulfil the growing need amongst European policymakers to access accurate and timely information services to better manage the environment, understand and mitigate the effects of climate change and ensure civil security. The new cryospheric processing techniques developed at Edinburgh since 2013 **[3.1, 3.2, 3.3]** have been crucial to developing a new European Space Agency (ESA) EUR300,000,000 satellite mission concept for polar ice and snow topography monitoring within the *Copernicus* programme. The head of Research and Development at ESA's Climate Department highlights: "*This objective is possible thanks to the techniques that you have robustly demonstrated and applied during the last 7 years. The project is now entering into its second implementation phase. I am pleased to recognise the direct benefit of your involvement with industry via the two industrial consortiums led by Airbus Defense and Space and by OHB Sweden (with a budget of EUR300,000,000). Doing so, you are ensuring implementation of the latest techniques and that the consortium translate user requirements in to sensor and spacecraft design specifications. In this way, your research will lead to the broadest possible scientific legacy."* **[5.2]**.

The team's new algorithms have also supported the continuing development and applications of the EUR170,000,000 ESA Cryosat satellite mission which monitors ice sheets and sea-ice volume. The CryoSat Mission Manager for ESA states that the team's algorithms have resulted in "an *increase the quantity of observation [of ice change] by two orders of magnitude … which has led to more accurate volume estimates and applications beyond the sole Greenland and Antarctic Ice Sheets that CryoSat was designed to monitor, e.g. over the ice fields of Patagonia". The new work has also been used to argue for continuing funding [EUR10,000,000 per annum] of the mission operational exploitation* **[5.3]**. Additionally in 2019, and on the research by the Edinburgh team, ESA launched the EUR400,000 CryoTEMPO programme to provide "*easy to use and hassle free"* products on ice-sheet and glacier changes observed by satellites for non-specialist users **[5.3]**.

The team's activities in satellite remote sensing also led, in 2019, to the formation of a startup company *Earthwave*, which now employs seven staff and has GBP347,000 annual turnover from clients in the UK and Europe **[5.5]**.

Informing policy through more accurate estimates of the Antarctic contribution to sea-level rise.

Much UK national policy on mitigating sea-level rise is informed by the IPCC; in turn, the IPCC is informed by major national programmes such as the GBP2,4000,000 British Antarctic Survey (BAS) numerical-modelling programme that is dedicated towards providing greatly improved predictions of the Antarctic Ice Sheet's fate and its contribution to global sea-level rise over the next 200 years. Over the reporting period the BAS programme has been underpinned by geophysical measurements of the shape and condition of Antarctica's ice-sheet bed acquired and processed into subglacial topographic maps by the UoE-led team **[3.4]**, and numerical-modelling equations and strategies that were developed at Edinburgh **[3.6]** which have contributed to greatly-reduced uncertainties in BAS' programme for numerically modelling the ice-sheet's future. To quote BAS' Director of Science *'Our British Antarctic Survey … contributions to IPCC have been underpinned by modelling strategies and equations formulated by Dan and his team at Edinburgh since late 2013'* and *'Datasets Rob and his team produced… have been crucial in providing underpinning numerical modelling of West Antarctica's future which has been undertaken to support the upcoming sea-level rise assessments for the IPCC 6th assessment reports, used as the primary evidence bases for global policymakers in planning sea-level defences'* **[5.4]**. For example, 18 of the group's research papers since 2013 were cited in the 2019 IPCC Special Report *Ocean and Cryosphere in a Changing Climate* **[5.1]** in which the Amundsen Sea Sector of West Antarctica and Greenland (a focus of our data gathering and modelling efforts) were highlighted in the Summary for Policymakers as key sources of future sea-level rise.

Sources to corroborate the impact (indicative maximum of 10 references)

[5.1] List of research papers since 2013 from staff conducting the underpinning research at Edinburgh cited in the 2019 IPCC *Special Report on the Ocean and Cryosphere in a Changing Climate*. Chapter 2: https://www.ipcc.ch/site/assets/uploads/sites/3/2019/11/06_SROCC_Ch02_FINAL.pdf and Chapter 3: https://www.ipcc.ch/site/assets/uploads/sites/3/2019/11/07_SROCC_Ch03_FINAL.pdf
[5.2] Head of Science Section, *European Space Agency,* (testimonial letter, 03/12/2020)
[5.3] CryoSat Mission Manager, *European Space Agency*, (testimonial letter 17/11/2020)
[5.4] Director of Science, *British Antarctic Survey*, (testimonial letter 26/02/2020)
[5.5] CEO and co-founder, *Earthwave,* (testimonial letter 09/12/2020).