SCAR Fellowship Report

Tidal processes in ice-sheet grounding zones

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Introduction

The grounding zone, where grounded ice meets the floating ice shelf, is strongly affected by tidal processes and is one of the most sensitive parts of the ice-sheet system. Mass balance estimates are typically produced as the difference between snow accumulation on grounded ice and ice flux across the grounding line, and therefore depend on having an accurate knowledge of grounding line geometry and velocity. The use of satellite and in-situ measurements of tidal processes on an ice stream and ice shelf enables inference of bed characteristics, ice thickness in the grounding zone, subglacial hydrology and ice rheology.

This has been done frequently in the past using linear elastic beam models or derivations thereof. Typically the flexural profiles produced by these models are compared to satellite and tiltmeter measurements of glacier profiles at different points in the tidal cycle which can often produce a very good fit. However, the goodness of fit in these cases does not necessarily mean that the elastic beam approximation is an appropriate tool for all investigations of flexure and related processes. Since approximations of this kind are made so frequently in a variety of applications it is crucial to evaluate how suitable they are in each case and highlight where they might not be valid.

Project Objectives

The aim of the visit was to work closely with the group at Gateway Antarctica to develop a model of ice shelf flexure in order to identify what insights in ice rheology can or cannot be gained by making measurements of this phenomenon. The use of a full-Stokes viscoelastic finite element model which has not been done before in this context enabled us to investigate processes that would not be captured by models with simpler physics.

During the course of the 15/16 field season an exciting dataset was collected on the Southern McMurdo ice shelf consisting of GPS, tiltmeter, firn density, and radar measurements, all co-located with satellite interferograms. Radargrams across the grounding zone showed strong evidence for large basal crevasses. This observation, in conjunction with estimates of the surface density profile of the ice shelf, motivated us to investigate a situation where typical assumptions made in the elastic beam models break down and consequently where the beam model itself would be the wrong tool to use.

Fellowship outcomes

The commercial full-Stokes finite element software MSC Marc has been used extensively in the past to investigate ice-shelf tidal processes. We setup the model in 2D (x,z) using ice thickness and basal crevasse locations obtained from a 4km radargram line through the grounding zone (a portion of the model domain is shown in Fig. 1). A nonlinear Maxwell rheological model was used for ice, such that deformation consists of an instantaneous elastic response and a delayed viscous response, rather than assuming linear elasticity as is often done. Both viscosity and ice stiffness (or Young's modulus, E) varied with depth by implementing temperature-viscosity and density-stiffness relationships. The finite element mesh consisted of ~50,000 quadratic triangular elements, refined in the grounding zone leading to a resolution of up to 4m.

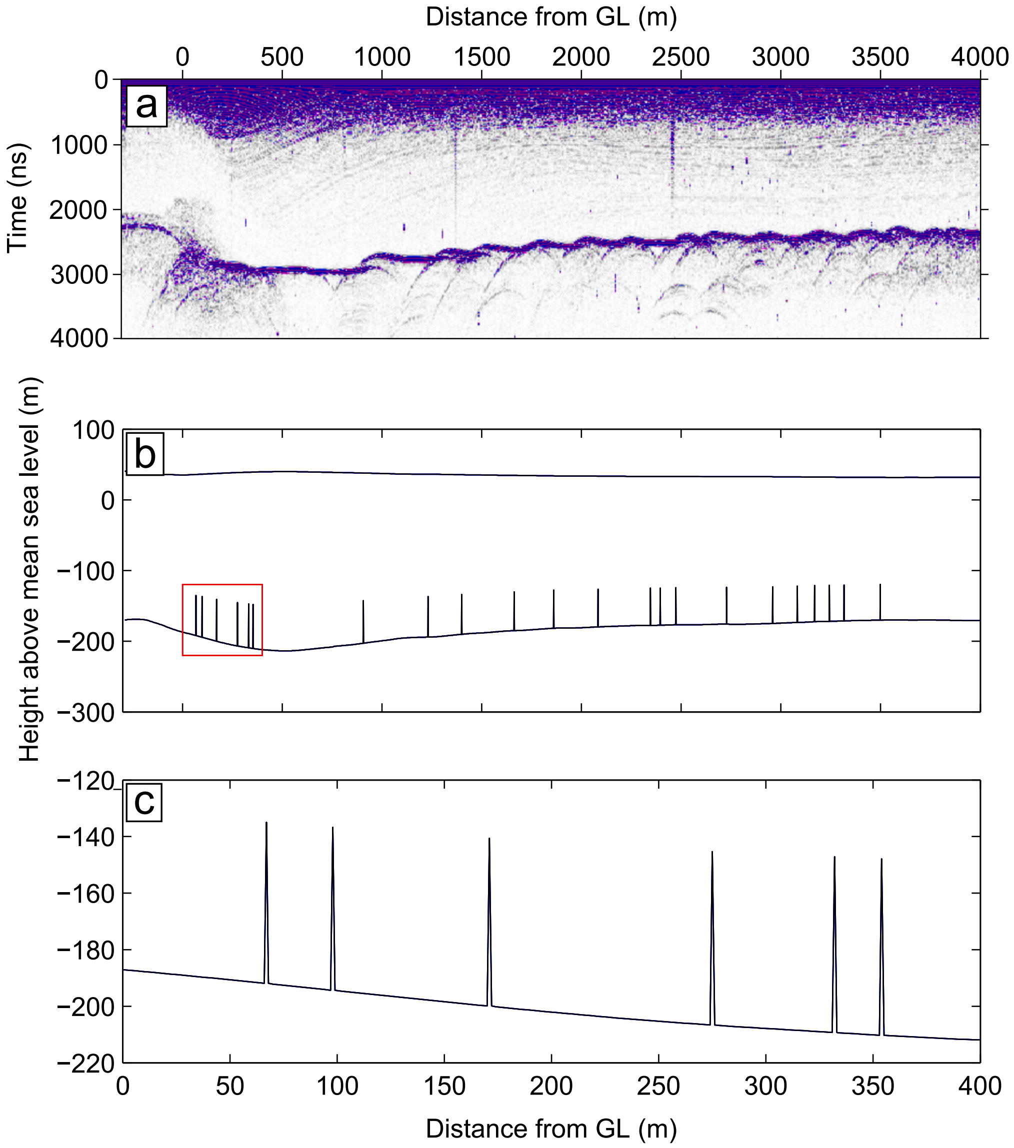

Figure 1. Grounding zone of White Island, showing (a) the original radargram and (b) a portion of the model domain showing ice surface and bed, including basal crevasses. The full domain extends beyond the region shown here.

The model setup described above represents a number of significant advances over the typical elastic beam approach that have typically been used to investigate flexural processes. In spite of their many simplifying assumptions, elastic beam models are very successful at reproducing ice shelf flexure curves with only a few tuneable parameters. Using the full-Stokes model in conjunction with the extensive dataset collected by in-situ and remote sensing techniques allowed us to test these assumptions in a way that has not been possible before.

We began by tackling the problem as has been done in the past, by plugging ice thickness into the model and adjusting the ice stiffness until we matched the flexural profile as measured by differential interferograms. This was done first for a model geometry that included the basal crevasses observed in the radargram and then for a geometry without crevasses. The resulting best fits of these flexural profiles are compared to the profile measured by satellite differential interferometry in Fig. 2. With a crevassed geometry the model suggests a stiffness of 5.2GPa whereas if crevasses are not included we instead find a stiffness of 3.2GPa is needed. This clearly demonstrates that if the flexural profile is being used to try and estimate ice stiffness then prior knowledge of basal crevassing is needed.

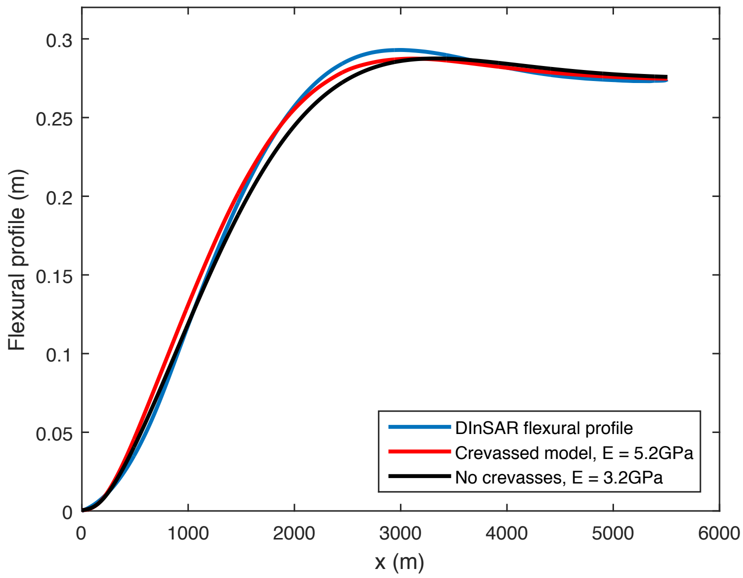

Figure 2. DInSAR flexure profile (blue curve) compared with best fits for the crevassed and control geometries (red and black lines, respectively). Both modelled curves are outputs from the full-Stokes viscoelastic model.

In order to investigate the strengths and weaknesses of the beam model in more detail we fitted a simple beam model to flexure profiles with only two parameters: ice stiffness and grounding line position. By performing a nonlinear regression of the beam equation on the profiles produced by various forms of our model we could compare how a beam model would interpret these data to the known model parameters that were used to generate them. Results of this analysis clearly show that the apparent ice stiffness needed to match observations changes dramatically depending on the inclusion of factors such as basal crevasses, and yet in all tests the elastic beam model provided a similarly good fit with the satellite derived flexural profile. Conversely, estimates of the grounding line position were reasonably accurate, although this may be fortuitous as a consequence of the steep local topography in the study area.

No previous model has included all of the processes investigated here and yet the misfit between these previous models and observations is always small unless ice thickness is poorly known. It might be expected that factors such as extensive crevassing might be expected to change the shape of a flexure profile to such an extent that a linear elastic beam model could no longer provide a good fit and yet our results show that this is not the case and misfit remained small in all the cases that we tested. The goodness of fit obtained by elastic beam theory does not imply that the rheological assumption on which it is based is correct. Deriving values for the Young's modulus in this manner and comparing with laboratory derived values, as has been done in numerous previous studies, does not provide satisfactory insight into ice rheology. These results imply that extreme caution should be used when fitting models to flexure profiles to estimate either Young's modulus or ice thickness since many other factors could be at play.

Education and Outreach

My visit to Gateway Antarctica was advertised on the department social media pages and during my stay in New Zealand I gave a talk at the University of Canterbury. I eagerly participated in weekly science discussions that included both Masters and PhD students working at the department which I found to be both useful and motivating, as a result I have started similar meetings in my own department.

Future Plans

A key aim of the SCAR fellowship was to initiate an enduring collaboration with the host research group at Gateway Antarctica. Their research interests closely align with my own and their modelling and remote sensing work around the Ross Ice Shelf compliments the work here at BAS on the Filchner-Ronne Ice Shelf. During my time in New Zealand we explored the possibility of modelling ice shelf fracture using the same finite element software that my work there was based on. This and other potential research ideas will hopefully lead to future collaboration between our two institutes.

Personal Impact

I greatly benefited from my experience working without the supervision and guidance that I was used to during my PhD, helping me to gain confidence in my ability to do independent research. My trip also highlighted the importance and benefits of exterior collaborations and as a result I am keen to find other research groups with whom I can work on new ideas.

Financial statement

All funds granted for this fellowship (USD $10000) were used for travel to work at Gateway Antarctica in Canterbury, NZ, accommodation, transportation and living expenses during the 3 month visit.

Publications/Presentations

Rosier, S. H. R., Marsh, O. J., Rack, W. Gudmundsson, G. H., Wild, C. T. and Ryan, M. *On the interpretation of ice shelf flexure measurements*. In review, Journal of Glaciology.

Rosier, S. H. R. Tidal controls on ice shelf flow. Antarctic research group seminar, 12th May 2016 Department of Geography, University of Canterbury.

Acknowledgements

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