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Low post-glacial rebound rates in the Weddell Sea due to Late Holocene ice-sheet readvance

Sarah L. Bradley [a,b,*], Richard C.A. Hindmarsh [a], Pippa L. Whitehouse [c], Michael J. Bentley [c], Matt A. King [d]

[a] British Antarctic Survey, Cambridge, UK
[b] Institute for Marine and Atmospheric research, Utrecht University, Utrecht, Netherlands
[c] Department of Geography, Durham University, Durham, UK
[d] Surveying and Spatial Sciences, School of Land and Food, University of Tasmania, Hobart, Australia

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ABSTRACT

Many ice-sheet reconstructions assume monotonic Holocene retreat for the West Antarctic Ice Sheet, but an increasing number of glaciological observations infer that some portions of the ice sheet may be readvancing, following retreat behind the present-day margin. A readvance in the Weddell Sea region can reconcile two outstanding problems: (i) the present-day widespread occurrence of seemingly stable ice streams grounded on beds that deepen inland; and (ii) the inability of models of glacial isostatic adjustment to match present-day uplift rates. By combining a suite of ice loading histories that include a readvance with a model of glacial isostatic adjustment we report substantial improvements to predictions of present-day uplift rates, including reconciling one problematic observation of land sinking. We suggest retreat behind present grounding lines occurred when the bed was lower, and isostatic recovery has since led to shallowing, ice sheet re-grounding and readvance. The paradoxical existence of grounding lines in apparently unstable configurations on reverse bed slopes may be resolved by invoking the process of unstable advance, in accordance with our load modelling.

1. Introduction

The Weddell Sea sector remains one of the most poorly studied regions of the Antarctic Ice Sheet (AIS), and there are still many gaps in our understanding of past and present grounding-line behaviour in this region. Ice sheet grounding lines located in regions where the bed deepens inland ("reverse bed slopes") are generally inherently unstable (Schoof, 2007). Such configurations are common along the Weddell Sea sector of the West Antarctic Ice Sheet (WAIS), leading to concerns that small perturbations may produce wide-spread ice sheet retreat and sea-level rise (Joughin and Alley, 2011). The potential rate of operation of this instability is exacerbated by the relatively low ice-thickness gradients upstream of the grounding line (Ross et al., 2012). It remains unclear how the ice sheet could have evolved into an apparently unstable state from a thicker and more extensive Last Glacial Maximum (LGM) configuration (Bentley et al., 2010). It may be that the grounding line is unstable but is only retreating slowly or, it may be that a combination of the buttressing effect of the Filchner-Ronne Ice Shelf (FRIS) (Gudmundsson, 2013) and local perturbations to sea surface height and bedrock elevation due to ice load changes (Gomez et al., 2013) act to stabilize the grounding line. Alternatively, the controls on grounding line motion may have evolved such that the grounding-line is unstable, but now advancing subsequent to post-LGM retreat.

Little is known of changes within the Weddell Sea area of WAIS over recent decades to millenia (Bentley et al., 2010; Le Brocq et al., 2011; Whitehouse et al., 2012a; Hillenbrand et al., 2013); some large scale ice sheet reconstructions assume deglaciation terminated between 4 and 2 kyr (before present, BP) (Peltier, 2004; Whitehouse et al., 2012a) while others assume monotonic thinning to 1 kyr BP (Ivins et al., 2013). A previous investigation (Bindschadler et al., 1990) found evidence for re-grounding of the ice sheet in the Siple Coast region within the past 1000 years. A more recent glaciological investigation (Siegert et al., 2013) used radar-echo sounding data to investigate the englacial layering and surface forms within the slow-flowing Bungenstock Ice Rise (BIR), which separates the fast-flowing Institude and Möller ice streams (IIS and MIS, respectively) within the Weddell Sea embayment (Fig. 1). That study found evidence for Late Holocene (at the ear-

* Corresponding author at: Institute for Marine and Atmospheric research, Utrecht University, Utrecht, Netherlands.
E-mail address: d80ngv@gmail.com (S.L. Bradley).

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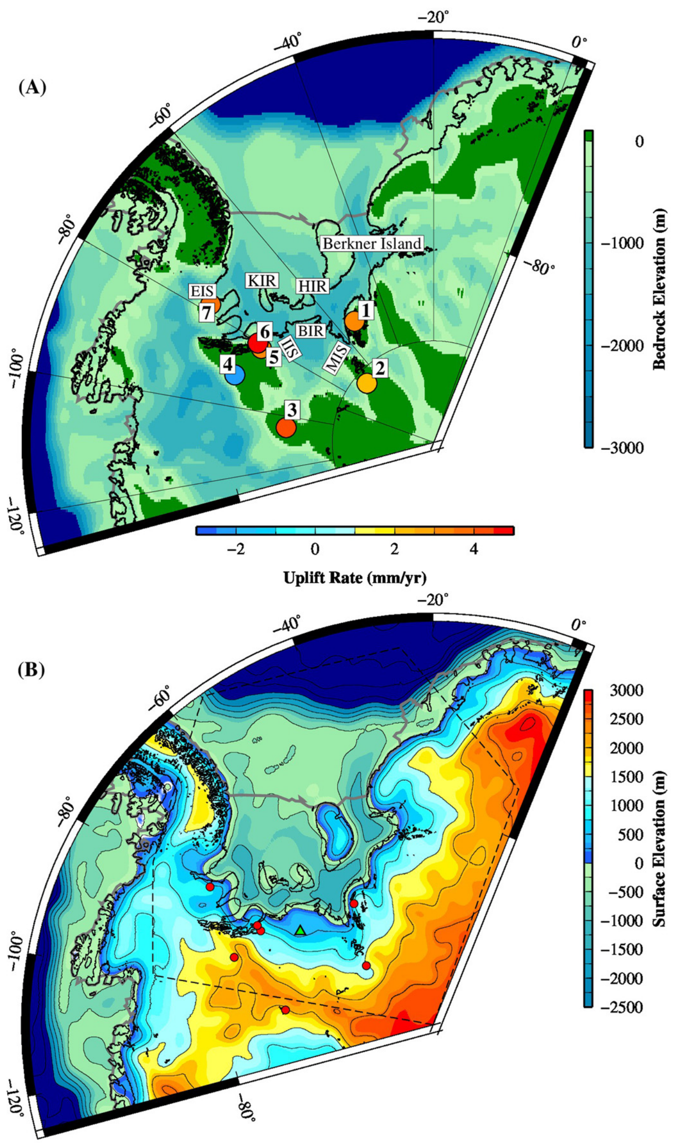

Fig. 1. Bedrock and ice sheet configuration of the Weddell Sea region. (A) Location map showing the seven GPS sites and their elastic-corrected present-day uplift rates, overlain on a map of the present-day bedrock topography (Fretwell et al., 2013) (see Table S1 for more site details). The black contour marks the present-day grounding line (see Bedmap2, Fretwell et al., 2013) and the solid gray line marks the present-day calving front. Labelled are the Bungenstock (BIR), Korff (KIR), and Henry (HIR) Ice Rises and the Institute (IIS), Möller (MIS) and Evans (EIS) Ice streams, with GPS site 7 located on the Fowler Peninsula. Areas of the bed above sea level are denoted by dark green shading; the Ellsworth Mountains lie approximately due north of GPS sites 5 and 6. (B) Present-day surface elevation of grounded ice, calculated by combining the present day ice thickness taken from the W12 ice model (Whitehouse et al., 2012a) with the present-day bedrock topography shown in (A). The grounding line position is only coarsely resolved in this model; this is sufficient for the purposes of GIA modelling. Bathymetry is shown in ice shelf regions and the open ocean. Red circles indicate GPS sites; the green triangle represents the location of the Robin Subglacial Basin. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

liest 4 kyr BP) flow reorganization across the BIR and proposed two hypotheses to explain this change (see Fig. 5 and Table 1 in Siegert et al., 2013); (i) ice-stream flow was reorganized without significant ice volume change or movement of the grounding line position or (ii) the grounding line retreated inland of the present-day position, with readvance of the ice sheet to its present-day configuration driven by bedrock uplift and subsequent ice sheet re-grounding.

Importantly, the two hypotheses potentially produce distinctly different patterns of present-day Glacial Isostatic Adjustment (GIA) (Ivins et al., 2000) – the ongoing solid Earth response to changes in ice–ocean surface loading – and consequently have different implications for present-day ice sheet stability. Additionally, the studies of Bindschadler et al. (1990) and Siegert et al. (2013) imply that the assumption of a simple monotonic Late Holocene deglaciation history of the WAIS needs to be re-evaluated.

Several GIA models for Antarctica have been developed (Whitehouse et al., 2012b; Gomez et al., 2013; Ivins et al., 2013; Argus et al., 2014) with the objective of simultaneously constraining the spatial and temporal history of the AIS and the rheological properties of the solid Earth. There are many differences in the inferred maximum size and deglaciation histories of the ice sheet (Peltier, 2004; Whitehouse et al., 2012a; Gomez et al., 2013; Ivins et al., 2013), with still very little known about the late Holocene history in the Weddell Sea – a period that will strongly influence the present-day GIA signal. This uncertainty is primarily due to the paucity of observations that can constrain the ice-loading history (Whitehouse et al., 2012a; Hillenbrand et al., 2013).

Here we investigate whether the post-LGM shallowing of the grounding line and a consequent GIA-induced readvance can explain the glaciological data (Siegert et al., 2013) and the absence of rapid retreat (Joughin and Bamber, 2005; Lambrecht et al., 2007) within this region. We develop a suite of revised Late Holocene deglaciation patterns to explore the two hypothesis proposed by Siegert et al. (2013). These revised ice-loading histories simulate thinning and re-thickening without grounding line migration, or an ice margin that undergoes an extended retreat behind the present-day grounding line, a stillstand and subsequent readvance to the present-day extent. By combining each of these simulations with a GIA model, predictions of the present-day uplift rates can be compared with those measured by Global Positioning System (GPS) at sites around the southern edge of the FRIS to assess the plausibility of the various ice-loading simulations.

2. Method

2.1. Glacial isostatic adjustment model

The GIA model used in this study to generate predictions of solid Earth deformation and present-day uplift rates adopts a spectral technique (Mitrovica et al., 1994) which has been extended to take into account perturbations in Earth's rotation (Mitrovica et al., 2001). The three model components (Earth model, sea level solver and ice model) are outlined in greater detail below.

The Earth model considers a compressible, spherically symmetric, self-gravitating Maxwell viscoelastic body, where the depth-dependence of the elastic parameters and density is taken from PREM (Dziewonski and Anderson, 1981) at a resolution of 10 km in the crust and 25 km in the mantle. The viscosity structure is parameterized into three main layers: a high viscosity (10^{43} Pa s) upper layer to approximate an elastic lithosphere, an upper mantle region extending from beneath the lithosphere to the 660 km discontinuity and a lower mantle region extending from there to the core–mantle boundary. The thickness of the lithosphere and the viscosity of the upper and lower mantle are user-defined parameters. It has been suggested that there is considerable lateral variability beneath the Antarctic continent (Morelli and Danesi, 2004; Chaput et al., 2014), from the relatively thin lithosphere and low viscosity mantle believed appropriate for the West Antarctic rift system to the thicker lithosphere and higher viscosity mantle of the craton below East Antarctica. Consequently, there have been considerable differences in the Earth model used in previous Antarctic GIA modelling studies (Peltier, 2004; Whitehouse et al., 2012b; Ivins et al., 2013). For the main basis of the study, the