Antarctic Ice Sheet-Ocean Interactions Amplify Multi-Centennial Climate Variability

P Bakker[a,*], N R Golledge[b,c], P U Clark[a], A Schmittner[a], M E Weber[d]

a) Oregon State University, USA b) Victoria University of Wellington, New Zealand c) GNS Science, New Zealand
d) University of Cologne, Germany. *Now at MARUM, Bremen, Germany. Contact: pbakker@marum.de

Introduction

The **Antarctic Ice Sheet** (AIS) is generally assumed static over the course of the Holocene and of little impact on the global climate. Here we suggest that variability in AIS discharge, driven by subsurface ocean temperature changes and internal ice-sheet dynamics, is important for **Holocene multi-centennial global climate variability.** AIS-ocean interactions can both amplify ocean temperature variability and skew the power spectrum towards multi-centennial climate variability.

High-resolution **ice-berg rafted debris** (IBRD) records of the Antarctic coast confirms the existence of Holocene multi-centennial AIS discharge variability.

Missing AIS-ocean interactions can explain part of the **missing Holocene** multi-centennial climate **variability** in **GCMs**[1]. Moreover, if indeed the AIS played a more active role during the Holocene, this opens up new possibilities to study AIS-ocean interactions and constrain future climate change projections.

Methodology

AIS simulations: The high-resolution Parallel Ice Sheet Model (PISM[2]) was used to simulate the AIS evolution since the Last Glacial Maximum and found to be in line with proxy-based evidence[3]. The simulation was forced by oxygen-isotope-based surface mass balance changes and by mid-depth (400-700m) Southern Ocean (SO) temperature variations simulated with a global climate model (Fig 1A) The ocean forcing dominates the ice sheet response[3].

The simulated AIS discharge variations during the period of interest (8-2.7ky BP; Figs 1B-C) are small compared to deglacial changes, but, as we will show, not insignificant with a magnitude of ~48 mSv on multi-decadal to multimulti-centennial timescales.

Global climate simulations: The impact of multi-centennial AIS discharge variability on Holocene climate is investigated with the UVic[4] global coupled climate model of intermediate complexity (EMIC). In the UVic simulations all forcings and boundary conditions are kept at pre-industrial levels except a PISM-based AIS discharge forcing. AIS discharge is equally distributed over the ocean south of 60°S (FWF).

In two sensitivity experiments we found that the details of the spatial distribution or the neglect of ice-melt heat fluxes do not significantly impact the results (not shown).

IBRD records: Two IBRD records from the Scotia Sea (MD07-3133 and MD07-3134) are in the main pathway of AIS icebergs circumnavigating the continent, so-called 'iceberg-alley', and provide a spatially integrated signal of AIS variability. A Holocene high resolution stack (following[5]) reveals multi-centennial variability (Fig 1D and 3).

Periods of strong and weak AABW: Changes in Antarctic Bottom Water Formation (AABW) are simulated by UVic. Periods of strong and weak AABW are defined as all times that AABW was outside the 1σ band (red lines Fig 1E). Here we focus on periods of weak AABW, thus with AABW <2.6Sv. Note that all data presented here has been smoothed with a 10-year running mean.

Results

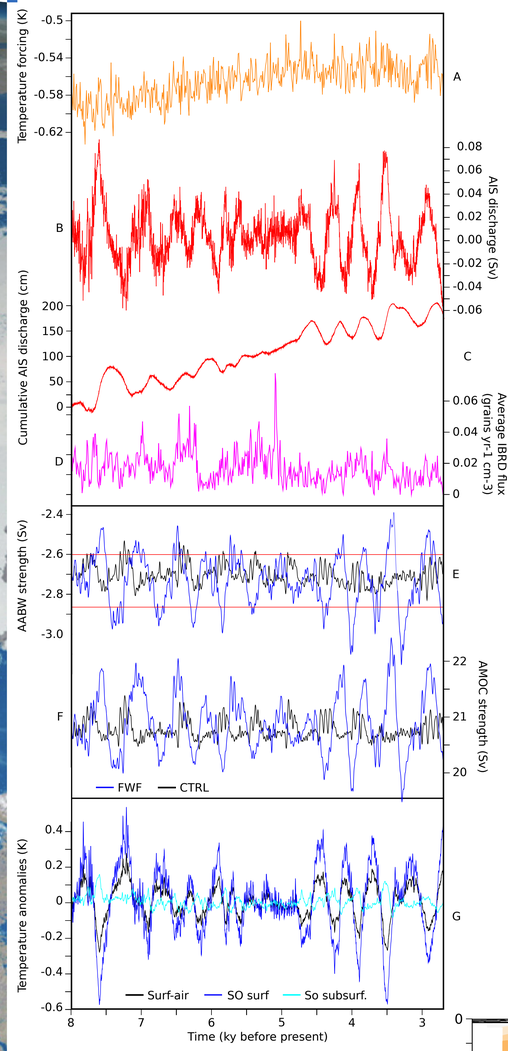

Fig 1: A) LOVECLIM-based subsurface (400-700m) Southern Ocean (<50°S) temperature forcing of AIS simulation, B) Cumulative AIS meltwater forcing from PISM simulation (cm), C) AIS meltwater forcing from PISM simulation (Sv), D) IBRD stack from the Scotia Sea, E) AABW strength (Sv; given as minimum overturning streamfunction in the Southern Ocean), F) AMOC strength (Sv; given as maximum overturning streamfunction in Atlantic <500m), and G) temperature anomalies (K) in FWF for global surface air, Southern Ocean surface and Southern Ocean subsurface (400-700m).

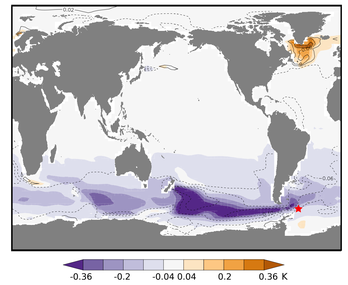

Fig 2: SST (K; shading) and SSS anomalies (contours) for periods of weak AABW formation. Red star indicates the sites of the Scotia Sea IBRD records.

Multi-decadal Holocene subsurface Southern Ocean temperature variations (Fig 1A) induce multi-centennial changes in AIS discharge (Fig 1B-C). Those result in large changes in SO buoyancy, that in turn impact vertical heat exchange and AABW formation (Fig 1E). Maximum AIS-AABW correlation of -0.53 at lag of 70 years. Multi-centennial AABW fluc-tuations are 2.7 times larger in FWF compared to CTRL.

The regional surface expression for periods of weak AABW are maximum SSS and SST anomalies of ~0.1 and ~0.4K respectively (Fig 2). The global surface response is ~0.2K (Fig 1G).

The subsurface temperature response is opposite to the surface (Fig 1G and 3). Although small, these ~0.15K AIS discharge forced subsurface temperature variations are ~4 times larger than subsurface temperature forcing applied to the PISM ice sheet model (Fig 1A), thus providing potential for a strong positive feedback.

AABW fluctuations also negatively impact the AMOC (Fig 1F) and triple multi-centennial AMOC variability compared to the CTRL simulation. AMOC variability also introduces North Atlantic SST variations of up to 0.4K (Fig 2).

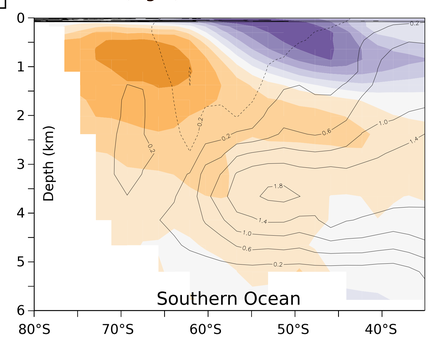

Fig 3: Southern Ocean temperature anomalies (K; shading) and meridional streamfunction anomalies (Sv; contours) for periods of weak AABW formation.

Discussion & Conclusions

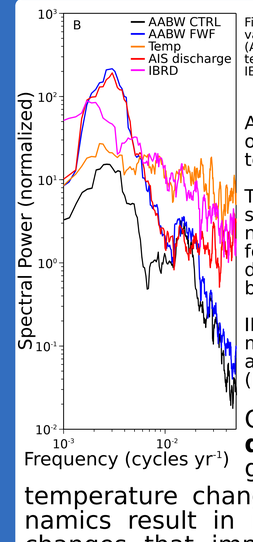

Fig 3: Normalized frequency spectrum of Holocene AABW variability in unforced (AABW CTRL) and forced simulations (AABW FWF), LOVECLIM-based subsurface Southern Ocean temperature forcing (Temp), AIS discharge and reconstructed IBRD stack.

AIS discharge increases AABW variability on multi-centennial time-scales compared to the CTRL simulation (Fig 3).

The AIS is very sensitive to >100yr subsurface temperature variations, but not to higher frequencies. In turn, AABW formation is strongly affected by AIS discharge on multi-centennial time-scales, but not so for periodicities <50 year.

IBRD records confirm the existence of multi-centennial AIS discharge variability, albeit with a flatter frequency distribution (Figs 1D and 3).

Our results suggests a **more dynamic Holocene AIS** than generally assumed. Subsurface temperature changes and internal ice-sheet dynamics result in multi-centennial AIS discharge changes that impact the SO and, via oceanic teleconnections, global climate variability.

The coupled **ice-ocean system** effectively concentrates **spectral power** in **multi-centennial frequencies**, those that are underestimated in GCMs[1]. Scotia Sea IBRD records confirm existence of multi-centennial AIS discharge variations.

GCM simulations should be done to confirm the EMIC's response to AIS discharge variations, and a **two-way ice-ocean coupling** is needed to assess the impact of the **positive AIS discharge - subsurface ocean temperature feedback**.

Potentially AIS's sensitivity can be constrained by combining model results with Holocene sea-level, discharge and temperature reconstructions. Incorporating ice-climate interactions in GCMs is important to understand past, attribute present and project future climate change.

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References:
1) Laepple, T., and P. Huybers (2014), Ocean surface temperature variability: Large modeldata differences at decadal and longer periods, PNAS, 111 (47), 16682–16687.
2) Beuler, E., and J. Brown (2009), Shallow shelf approximation as a sliding law in a thermomechanically coupled ice sheet model, Geophys. Res. , 114, F03008.
3) Golledge et al. (2014), Antarctic contribution to meltwater pulse 1A from reduced Southern Ocean overturning, Nat. Comm., 5, 5107.
4) Weaver et al. (2001), The UVic Earth System Climate Model: Model description, climatology, and applications to past, present and future climates, Atmos. Ocean, 39 (4), 361–428.
5) Weber et al. (2014), Millennial-scale variability in Antarctic ice-sheet discharge during the last deglaciation, Nature, 510 (7503), 134–138.