Centennial-scale Holocene climate variations amplified by Antarctic Ice Sheet discharge

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Introduction

Climate reconstructions indicate that climate models systematically underestimate Holocene climate variability on centennial to multi-millennial timescales[1]. Based on reconstructed Antarctic Ice Sheet (AIS) discharge variability and a hierarchy of ice sheet and climate models we show that the AIS was much more dynamic during the Holocene than previously assumed[2]. Induced by small subsurface temperature fluctuations, dynamic AIS discharge variations induce regional and far-field climate variability. Coupled ice-sheet-ocean dynamics effectively concentrate spectral power in relatively low, multi-centennial frequencies.

Ice-berg-rafted debris:
Reconstructions of AIS discharge based on ice-berg-rafted debris (IBRD) from the Scotia Sea, reveal that the AIS has experienced much greater variability during the Holocene than previously considered, particularly at multi-centennial timescales (Figs 1 and 2).

Ice sheet modeling:
This is corroborated by high-resolution ice-sheet modeling (PISM)[3]. The sensitivity of the AIS to subsurface ocean temperature changes, an important uncertainty in ice-sheet modeling, is constrained by reconstructions of the deglacial history of the AIS[3]. Using this sensitivity, small Holocene subsurface ocean temperature changes in concert with strong internal icesheet feed backs result in substantial (1σ=48mSv) discharge variations (Fig 1) at multi-centennial timescales (Fig 2).

Transient climate simulations:
To investigate the impact of such AIS discharge variations on the climate, we performed transient simulations with the UVIC EMIC covering the Holocene (Fig 1), and equilibrium simula-tions with CESM1.2 at 1°-resolution.
The AIS discharge varitions induce changes in Antarctic Bottom Water formation (AABW) and accompanying changes in Southern Ocean surface and sub-surface temperatures (Fig 1), sea ice cover and in the strength of the AMOC.

Multi-centennial variability:
Looking at the frequency spectra, we find that the AIS is rather insensitive to sub-centennial subsurface temperature changes, and similarly, AABW formation is only affected by AIS discharge variations on centennial to multi-centennial timescales. Ice sheet and ocean dynamics thus both appear effective at concentrating spectral power in relatively low frequencies, for which previous model-data comparisons have suggested climate models lack climate variability.

Atmospheric teleconnections:
To assess the impact of AIS discharge variations on far-field areas we turn to high resolution CESM equilibrium simulations.
The CESM results for the Southern Ocean are comparable to UVic. For instance SST anomalies of -0.24K and -0.34K, respectively.
Apart from a Southern Ocean cooling in response to AIS discharge variations, we also find minor cooling over the SH mid-latitudes and the low latitude regions (Fig 3).
In line with previous simulations, we find that SH cooling impacts the meridional temperature gradient, position and strength of the large-scale meridional atmospheric circulation cells and low latitude precipitation (Fig 4). However, because of the relatively small forcing and comparably large internal variability, the changes are minor and one should be carefull when interpreting the results. In the annual mean, zonal winds increase in the SH and decrease just north of the equator. However, the changes are charaterized by a strong seasonal aspect. Similarly, the Southern Ocean and low-latitude precipitation changes are not year round. Furthermore, the simulated low-latitude precipitation changes are small (max 10%) and it is thus questionable if proxy-based precipitation reconstructions would be able to resolve such multi-centennial variations.

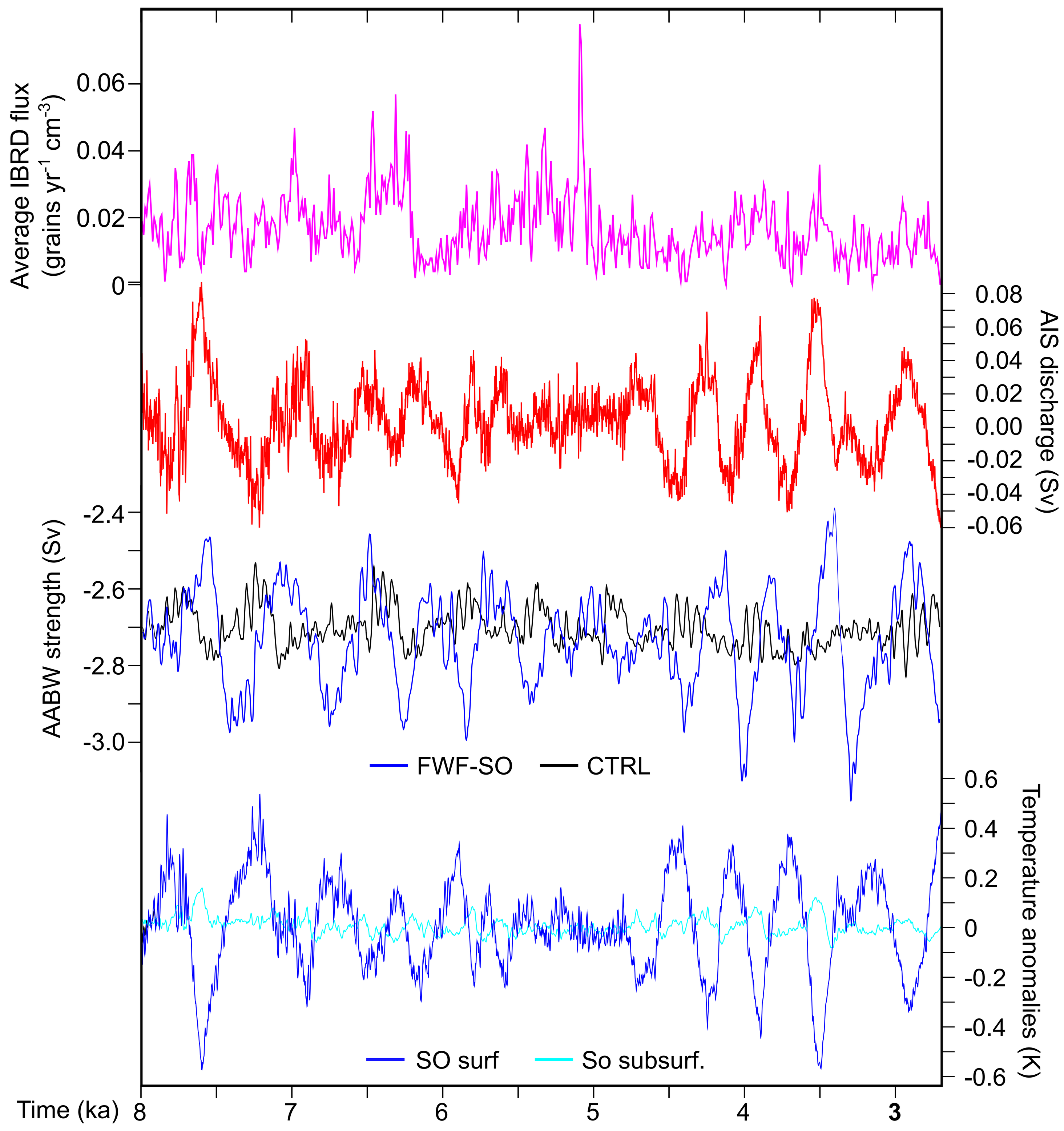

Figure 1:
Scotia Sea IBRD stack. PISM-based AIS discharge forcing. Simulated AABW export for the UVic transient 8-2.7ka experiment. Unforced in black and simulation including PISM-based AIS discharge forcing in blue. Southern Ocean temperature anomalies relative to long-term mean in forced experiment (surface in dark blue and subsurface in light blue). A 10-year running mean is applied to all data except for the IBRD stack, which has decadal means.

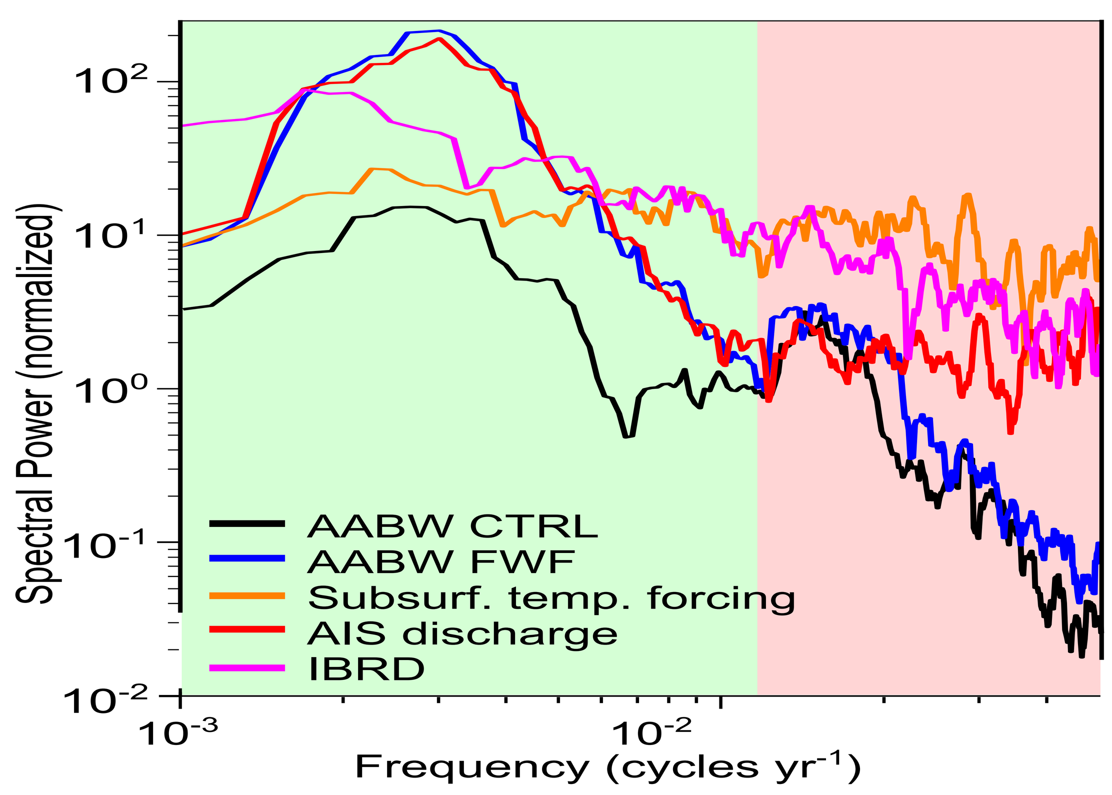

Figure 2:
Frequency spectra for simulated AABW export changes in CTRL, simulation including AIS melt (AABW FWF), LOVECLIM-based subsurface Southern Ocean temperature changes used as forcing of the UVic model ('Subsurface temperature forcing') and the AIS discharge and reconstructed IBRD stack from the Scotia Sea. Data are normalized to a mean of 0 and standard deviation of 1 to allow direct comparison of the shape of the spectra. Shading indicates the range of periodicities over which AIS discharge does (green) and does not (red) affect AABW.

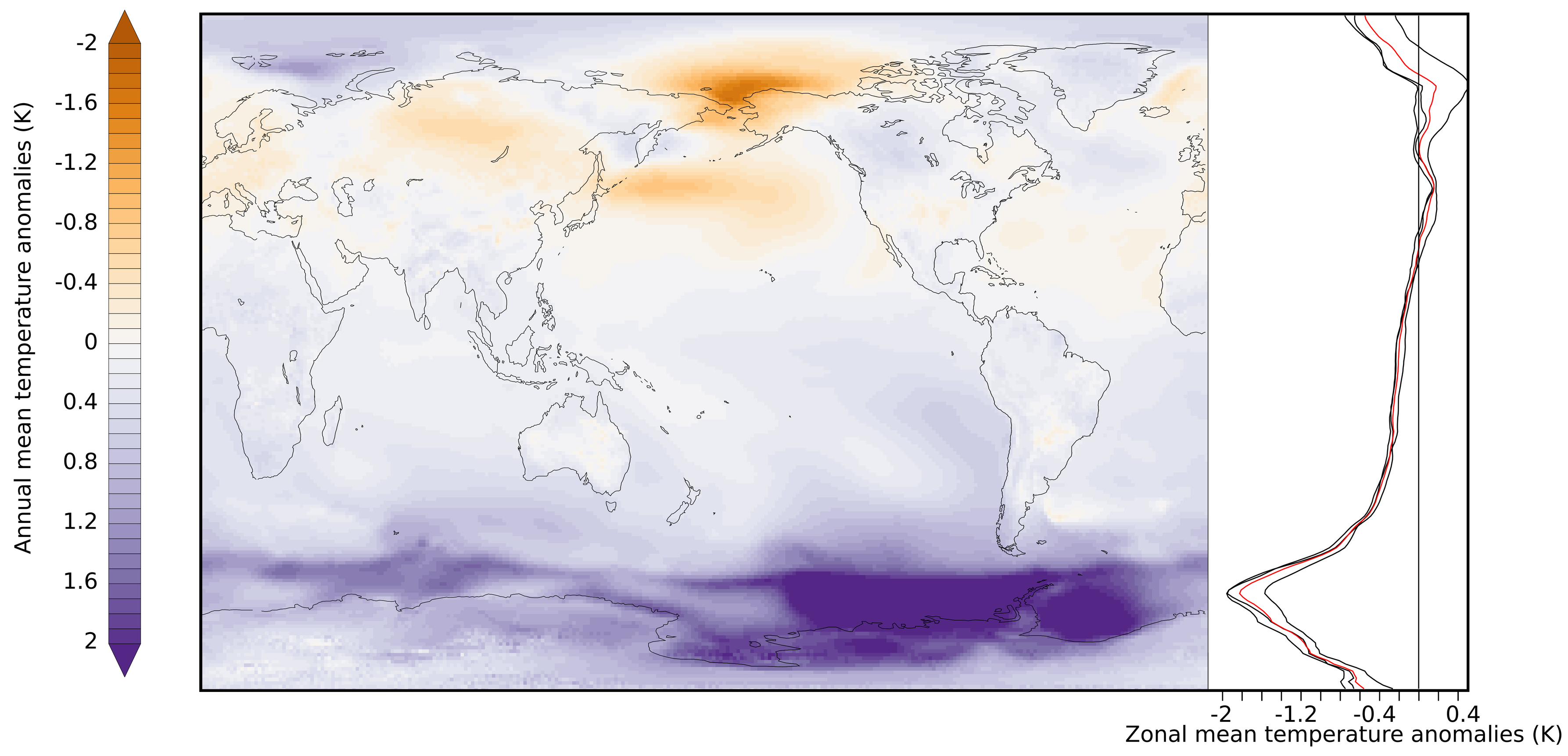

Figure 3:
CESM-based annual mean atmospheric temperature anomalies. Simulation is forced by a constant 48mSv AIS discharge forcing for 200yrs. Results are shown for the last 20yrs. Three-member mini ensemble was performed with slightly different initial conditions. Map and red line in right-hand panel show ensemble mean.

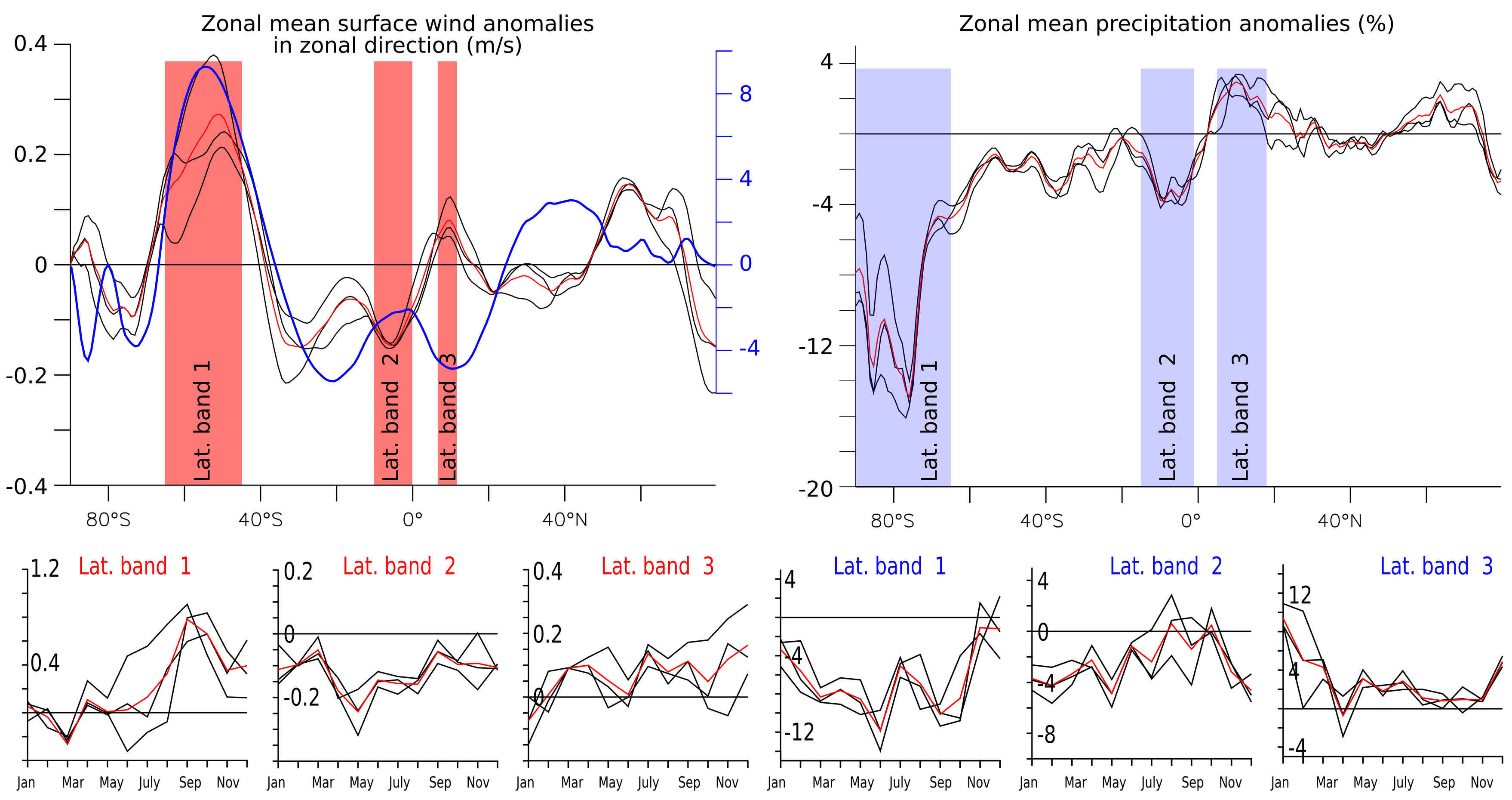

Figure 4:
Anomalies of zonal winds (left) and precipitation (right) simulated by CESM forced by 48mSv AIS discharge. Top panels give annual and zonal mean values as a function of latitude. The absolute zonal wind values are given for reference (blue in top left-hand panel). Bottom panels give seasonality for specific latitude bands. Individual ensemble members in black and ensemble mean in red. Precipitation anomalies are given as percentage change relative to the control simulation.

Conclusions

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 frequency spectrum towards more multi-centennial climate variability.
High-resolution ice-berg-rafted debris records from the Southern Ocean confirm the existence of Holocene multi-centennial AIS discharge variability.
Newly performed high-resolution climate model experiments corroborate the impact on mid-to-high latitude SH temperatures. Moreover, they show that through atmospheric teleconnections, AIS discharge induces shifts in low latitude precipitation. However, the changes are small and seasonal, potentially making it difficult to detect them in proxy-based Holocene climate reconstructions.

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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.
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3) Golledge et al. (2014), Antarctic contribution to meltwater pulse 1A from reduced Southern Ocean overturning, Nat. Comm., 5, 5107.