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Testing the sensitivity of the East Antarctic Ice Sheet to Southern Ocean dynamics: past changes and future implications

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ABSTRACT: The stability of Antarctic ice sheets and their potential contribution to sea level under projected future warming remains highly uncertain. The Last Interglacial (135 000–116 000 years ago) provides a potential analogue, with global temperatures 2 °C higher and rates of sea-level rise >5.6 m ka^{-1}, leading to sea levels 6.6–9.4 m higher than present. The source(s) of this sea-level rise remain fiercely debated. Here we report a series of independent model simulations exploring the effects of migrating Southern Hemisphere Westerlies (SHWs) on Southern Ocean circulation and Antarctic ice-sheet dynamics. We suggest that southerly shifts in winds may have significantly impacted the sub-polar gyres, inducing pervasive warming (0.2–0.8 °C in the upper 1200 m) adjacent to sectors of the East Antarctic Ice Sheet (EAIS), which due to their geometries and connectivity to the Southern Ocean are highly sensitive to ocean forcing. We conclude that the EAIS potentially made a substantial, hitherto unsuspected, contribution to interglacial sea levels, and given 21st-century projections in the Southern Annular Mode and associated SHW migration, we highlight how pervasive circum-Antarctic warming may threaten EAIS stability. Copyright © 2013 John Wiley & Sons, Ltd.

KEYWORDS: East Antarctic Ice Sheet; Last Interglacial; Southern Annular Mode; Southern Hemisphere Westerlies; Southern Ocean.

Introduction

Geological (Naish *et al.*, 2009; Raymo and Mitrovica, 2012) and model-based (Pollard and DeConto, 2009) reconstructions suggest that sectors of the Antarctic ice sheets may have collapsed or lost substantial mass during previous interglacials. To date, however, their relative stability under these different climate boundary conditions remains unclear, contributing to the high degree of uncertainty in future sea-level projections (Joughin and Alley, 2011). The Last Interglacial (LIG; 135 000–116 000 years ago or henceforth 135–116 ka) is a key period in this regard: warmer than present day (a so-called 'super-interglacial') (Turney and Jones, 2010) and associated with an early global rate of sea level rise exceeding 5.6 m ka^{-1}, culminating in global sea levels 6.6–9.4 m above present (Kopp *et al.*, 2009; Dutton and Lambeck, 2012) (Fig. 1). However, to date, continent-wide ice-sheet model simulations of the LIG (Pollard and DeConto, 2009; Fyke *et al.*, 2011) imply a far more limited Antarctic contribution to eustatic sea levels at the LIG than suggested by geological and biological evidence (Grobe and Mackensen, 1992; Carter *et al.*, 2002; Kopp *et al.*, 2009; Barnes and Hillenbrand, 2010; Dutton and Lambeck, 2012), despite the fact that large sectors of the West and East Antarctic ice sheets (WAIS and EAIS, respectively) are marine-based and potentially vulnerable to collapse (Mercer, 1978; Joughin and Alley, 2011).

Quantified LIG temperature reconstructions suggest ocean temperatures in the mid to high latitudes of the southern hemisphere were between 0.7 and 1.9 °C higher than present (Duplessy *et al.*, 2007; Rohling *et al.*, 2008; Turney and Jones, 2010; McKay *et al.*, 2011). In contrast, ice-sheet model simulations have been used to suggest that ocean temperatures would need to 'warm by roughly 5 °C' above pre-industrial levels to induce significant ice-shelf basal melt and destabilize the WAIS, before having any effect on the EAIS (Pollard and DeConto, 2009). However, a growing body of evidence suggests a significant oceanic role in marine-based ice-sheet evolution (Shepherd *et al.*, 2004; Pritchard *et al.*, 2009; Golledge *et al.*, 2012; Pritchard *et al.*, 2012), implying the inferred high threshold response may reflect model uncertainty, specifically in relation to spatial resolution, ice-flow characteristics, Southern Ocean temperature forcing and ice shelf sensitivity to basal melting (Holland *et al.*, 2008; Pollard and DeConto, 2009; Fyke *et al.*, 2011). Regardless, even factoring in a collapse of the WAIS, the LIG eustatic sea-level rise (SLR) budget remains unresolved (Kopp *et al.*, 2009; Dutton and Lambeck, 2012; Stone *et al.*, 2013). Recent assessments of potential contributions – including ocean thermal expansion (McKay *et al.*, 2011) and wasting of the Greenland and West Antarctic ice sheets (Overpeck *et al.*, 2006; Bamber *et al.*, 2009; Stone *et al.*, 2013) – leave some 0.8–3.5 m of SLR unaccounted for during the LIG.

This raises an important question: might circulation changes in the Southern Ocean have induced accelerated mass loss from other sectors of Antarctica – specifically marine-based sectors of the EAIS – contributing to global sea level at the LIG? Here we explore the sensitivity of Southern Ocean circulation – and by association the EAIS – to the location and intensity of the Southern Hemisphere Westerlies (SHWs) during the transition from Stage 6 into Stage 5e. With

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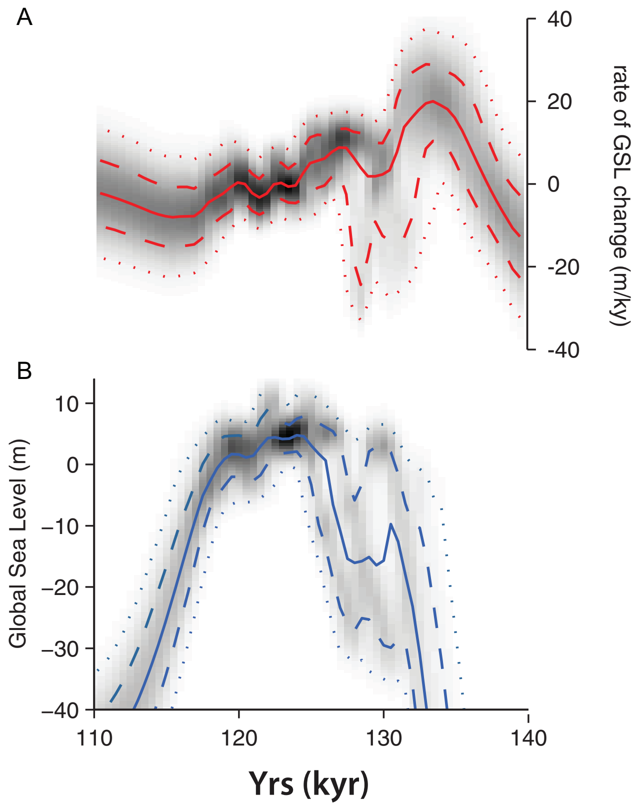

Figure 1. Probability density plots of global sea level: (A) 1000-year average rate of global sea level rise (m ka^{-1}); (B) 1000-year average global sea level (GSL). Dashed lines mark the 16th and 84th percentiles; dotted lines mark the 2.5th and 97.5th percentiles. Adapted from Kopp *et al.* (2009). This figure is available in colour online at wileyonlinelibrary.com.

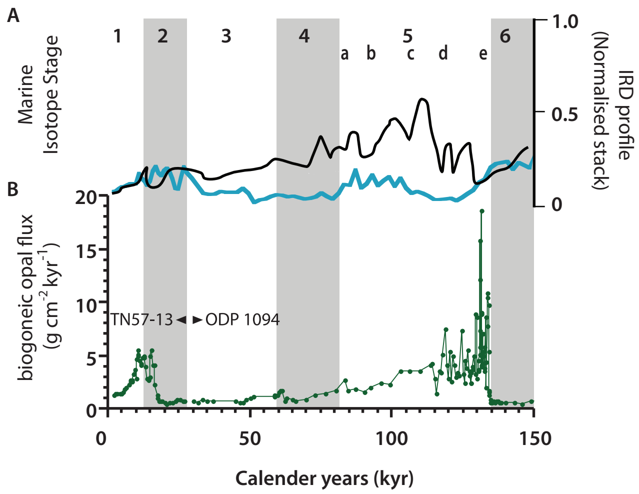

Figure 2. Proxy records of: (A) normalized stacked ice-rafted debris (IRD) profiles from the Weddell Sea (black line), and the Campbell Plateau (blue line). These composite records are based on datasets that were normalized to between zero and 1 (*x*-axis) by division of the maximum IRD concentration (Carter *et al.*, 2002). (B) Biogenic particle flux, reconstructed by ^{230}Th normalization for biogenic opal flux, a proxy for Southern Ocean upwelling triggered by SHW southward migration (Jaccard *et al.*, 2013), plotted against Marine Isotope Stages (MIS) over the past 150 ka. This figure is available in colour online at wileyonlinelibrary.com.

contemporary atmospheric circulation changes apparently inducing ocean warming along some sectors of Antarctica (Shepherd *et al.*, 2004; Miles *et al.*, 2013), and CMIP5 multi-model analysis with poleward trending winds revealing marked effects on the sub-polar gyres (Wang, 2013), we undertook a series of model experiments in which the SHWs – the principal driver of Southern Ocean circulation (Boning *et al.*, 2008; Toggweiler and Russell, 2008; Sijp and England, 2009; D'Orgeville *et al.*, 2010) – shifted poleward during the LIG, probably brought about by a decreased latitudinal temperature gradient at this time (Gille, 2002; Anderson *et al.*, 2009; Turney and Jones, 2010; Thompson *et al.*, 2011).

Methods

We used the University of Victoria Earth System Climate Model (UVic ESCM (Weaver *et al.*, 2001), and based the southward migration of the SHWs on reconstructions of Southern Ocean circulation changes, as recorded by biogenic opal flux (a proxy of wind-induced upwelling; Anderson *et al.*, 2009; Jaccard *et al.*, 2013), and latitudinal shifts in Southern Ocean fronts (Howard and Prell, 1992) at the onset of the LIG, centred on 135 ka (Fig. 2). To explore the sensitivity of Southern Ocean circulation to the location and intensity of the SHW's during the transition from Stage 6 into Stage 5e, we investigated a maximum seasonal poleward migration of 9°S relative to preindustrial. While this shift is at the upper end of estimated past variations in the SHW jet location (Jaccard *et al.*, 2013), even more modest shifts have been demonstrated as having significant implications for Southern Ocean circulation, and importantly on sub-polar gyre trends (Oke and England, 2004; Wang, 2013).

The UVic ESCM is well suited to address questions related to ocean circulation on long time scales; it consists of an ocean general circulation model (Modular Ocean Model, version 2) (Pacanowski, 1995) coupled to a vertically integrated two-dimensional energy–moisture balance model of the atmosphere, a dynamic–thermodynamic sea-ice model a land surface scheme, a dynamic global vegetation model (Meissner *et al.*, 2003) and a sediment model (Archer, 1996). The model, as described by Weaver *et al.* (2001), has a resolution of 3.6° in longitude and 1.8° in latitude and conserves energy, water and carbon to machine precision without the use of flux adjustments. The UVic ESCM also includes a fully coupled carbon cycle taking into account the terrestrial carbon fluxes and reservoirs (Meissner *et al.*, 2003; Matthews *et al.*, 2005) as well as the inorganic (Ewen *et al.*, 2004) and organic (Schmittner *et al.*, 2008) carbon cycle in the ocean. It is driven by seasonal variations in solar insolation at the top of the atmosphere and seasonally varying wind stress and wind fields (Kalnay *et al.*, 1996), and a newer version includes a fully coupled ice sheet (Fyke *et al.*, 2011).

LIG simulations were integrated to equilibrium for over 8000 years under boundary conditions corresponding to 135 ka BP (orbital parameters corresponding to 135 ka BP (Berger, 1978); atmospheric CO_2 of 204.5 p.p.m.; and elevated topography corresponding to Last Glacial Maximum (LGM) conditions (Peltier, 1994)). Simulations were then forced with a combination of changes in the position of the SHWs, the strength of the SHWs and transient changes in orbital parameters as indicated in Table 1. Atmospheric CO_2 concentrations were calculated prognostically in the transient simulations. Figure 4 shows an example time series of ocean temperature anomalies averaged over 68–72°S, 140–180°E and 0–1200 m depth. Shown are the differences in temperature between each sensitivity simulation and the equilibrium simulation. Significant and sustained levels of warming can be seen in all simulations with shifted westerlies regardless of the other boundary conditions, but are sensitive to the changes in wind intensity (Table 1).

Results from the UVic ESCM simulations were assessed against a series of high-resolution (5 km grid square) ice-sheet

Table 1. List of model experiments integrated with the UVic ESCM.

Name	Orb. para.	Location of SHWs	Strength of SHWs
Equilibrium simulation			
135_c	135 ka	PD	–
Sensitivity experiments			
135	135 ka	South	1
135_orb	Transient	South	1
135_orb_strong	Transient	South	1.5
135_strong	135 ka	South	1.5
135_orb_only	Transient	PD	1

Orb. para., orbital parameters; SHWs, Southern Hemisphere Westerlies. The location of SHWs is either PD (present-day) or south (shifted 9° southward). The strength of the westerlies has been multiplied by either 1 (no change) or 1.5 (50% increase in strength).

model experiments that investigate the dynamic response of a glacial maximum configuration Antarctic ice sheet to ocean forcing (Golledge *et al*., 2012). We use the Parallel Ice Sheet Model (PISM), a high-resolution (5-km resolved) three-dimensional, thermomechanical, continental ice-sheet model constrained by geological data that define lateral and vertical extents of the expanded Antarctic ice sheets around the time of the LGM. PISM combines the shallow-ice and shallow-shelf approximation equations across the entire domain, and thus is able to capture the dynamic behaviour within grounded ice of Antarctic ice sheets, and is able to simulate the drawdown of interior ice by ice streams at relatively high resolution. We employ boundary distributions from modified BEDMAP topography (Le Brocq *et al*., 2010), temperature and precipitation fields from gridded datasets (Comiso, 2000; van de Berg *et al*., 2006) and a spatially varying geothermal heat flux interpolation (Shapiro, 2004). Our ice-sheet model simulations are based on ocean-perturbation experiments in which the oceanic heat flux and sea level are isochronously increased by 30–100% of glacial to interglacial transition values, and by 25 m and 50 m, with respect to LGM values (Fig. 5) (Golledge *et al*., 2012).

Our model computes ice thickness and temperature changes, isostatic depression of topography, migration of grounding lines and the growth of ice shelves. Interaction between modelled ice shelves and their surrounding ocean is accounted for using a mass balance determination based on heat flux across the ice–water boundary. Our perturbation experiments use isochronous changes to oceanic heat flux and sea-level values and run for 3000 years. The response of the ice sheet is considered in terms of changes in velocity and ice thickness which together yield mass flux. In all experiments, the ice-sheet response is transitory, marked by more rapid response early in the perturbation that slows as the model run proceeds. Although the rates and magnitudes of change vary depending on the imposed forcing, the pattern remains consistent (Fig. 5).

Results and discussion

The impacts of a southerly shift in the SHWs on the Southern Ocean during the LIG can be assessed from Fig. 3. Figure 3B and C show the circulation in our two key simulations (shown here as a vertically integrated stream function; a measure of volume transport in Sv), induced by the shift in SHWs during the LIG. Our control simulation (equilibrated to 135 ka without migration or intensification of the SHWs) shows the circulation of the three deep-reaching cyclonic gyres that

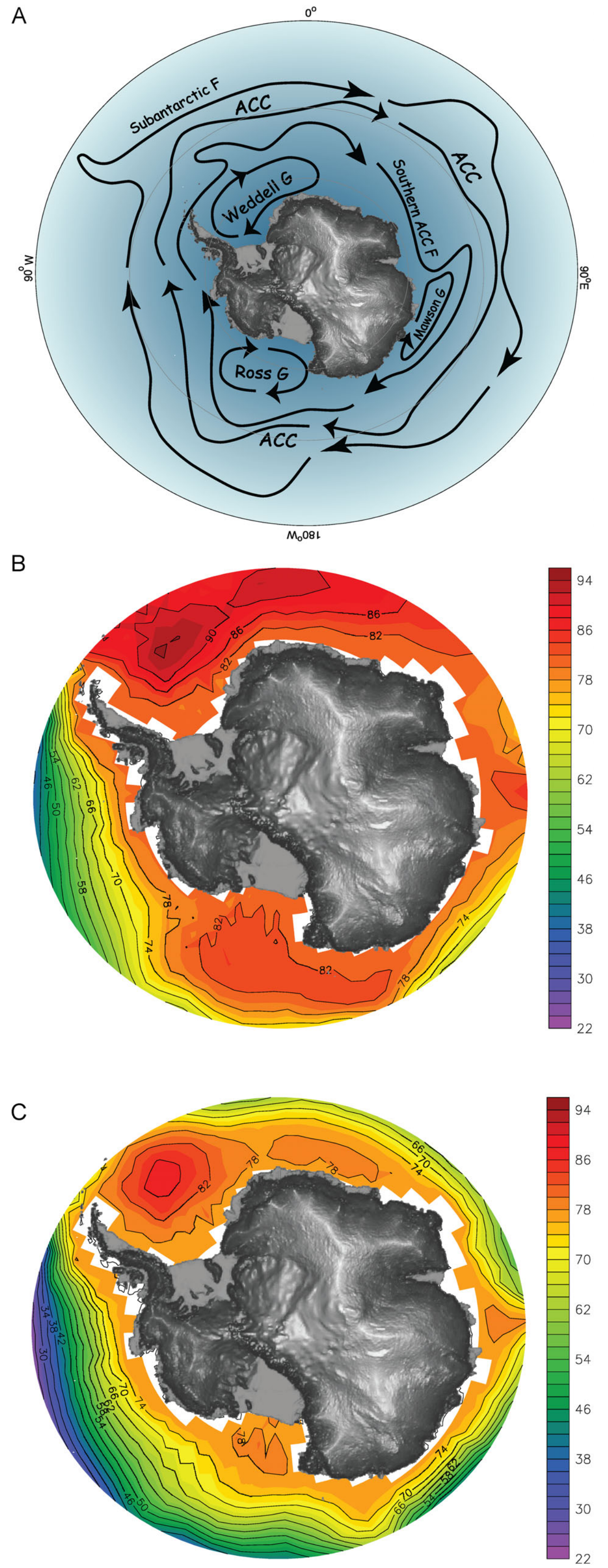

Figure 3. (A) The Southern Ocean surface flow features, showing the broad-scale flow of the Antarctic Circumpolar Current (ACC), south of the sub-Antarctic front, and the Ross, Weddell and Mawson sub-polar gyres. The Antarctic ice sheet is represented by the RADARSAT-1 synthetic aperture radar mosaic of the ice-sheet surface from the Antarctic Mapping Mission (AMM-1), © CSA 2001. (B) Vertically integrated streamfunction in Sv ($10^6\,m^3\,s^{-1}$) for the control simulation under 135 ka BP boundary conditions. (C) Vertically integrated streamfunction in Sv ($10^6\,m^3\,s^{-1}$) with SHW forcing shifted 9°S. This figure is available in colour online at wileyonlinelibrary.com.

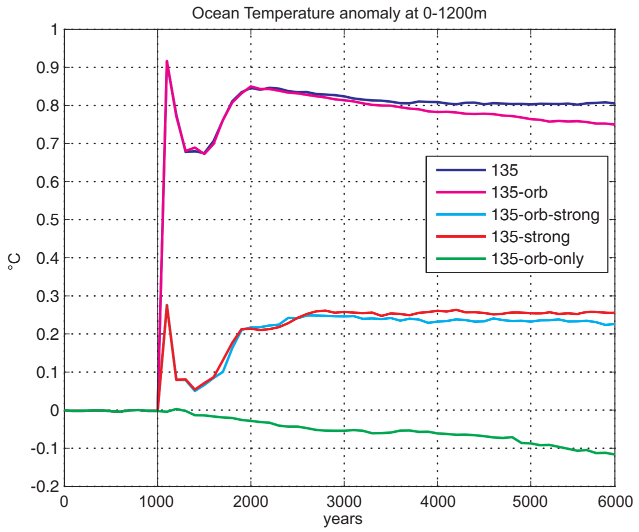

Figure 4. Example time series of temperature anomalies averaged over 68–72˚S, 140–180˚E and 0–1200 m depth from the UVic ESCM simulation over 6000 years. Shown are the differences in temperature between each sensitivity simulation and the equilibrium control simulation (Table 1). The vertical black line indicates the start of the transient simulations. This figure is available in colour online at wileyonlinelibrary.com.

extend from the Antarctic Circumpolar Current (ACC) to the Antarctic continental margin (Fig. 3B). The better known of these are the Weddell and Ross gyres, which occupy the ridge-bounded Weddell and Ross Seas, respectively (Carter *et al.*, 2009; Fig 3A). These, together with the third Antarctic–Australian Gyre located to the south of the Kergulen Plateau (Mawson, 1940; Bindoff *et al.*, 2000; McCartney and Donohue, 2007) – here referred to as the Mawson Gyre in recognition of the discovery of this oceanographic feature during the Australasian Antarctic Expedition 1911–1914 (Mawson, 1940) – transport heat and salt from the ACC to the Antarctic continental margin (Carter *et al.*, 2009). Crucially, recent research suggests these gyres are strongly connected (McCartney and Donohue, 2007). Our model predictions support this connectivity (equilibrated to 135 ka, after migration and intensification of the SHWs), demonstrating that a southerly migration of the SHWs, and the associated change in wind stress over the Southern Ocean, has a significant impact on the strength and locations of these gyre systems as well as on circum-Antarctic circulation, with an accompanying marked southward shift of the ACC. The modelled circulation changes decrease the strength and extent of these deep gyres, effectively confining them, and impacting the ACC or the Antarctic Slope Current (Fig. 3C).

Analysis of the Southern Ocean temperature anomalies triggered by these circulation changes suggests this mechanism can result in long-term regional warming at the western margins of the Weddell Sea, Prydz Bay and Ross Sea (Fig. 6). This warming is related to a decreased transport of cold water out of the respective basins due to the geographical confinement of the gyres. While the magnitude of the warming down to a depth of 500 m varies between the sites, it ranges from 0.2 ˚C in the Weddell Sea to 0.6 ˚C in Prydz Bay and 0.9 ˚C in the Ross Sea (Fig. 6). The warming is shown to be robust, being present in all our simulations involving a southward shift of the SHWs, although the magnitude is attenuated if the SHWs are also increased in intensity (Fig. 4). Importantly, the simulated warming is pervasive, remaining stable for several millennia throughout the depth profile (Fig. 4). It is also noted that the magnitude of warming is on the order of that recorded in the ACC over recent decades (Boning *et al.*, 2008), and locally in the Amundsen Sea, associated with rapid ice-sheet drawdown triggered by marine ice-sheet instability (Shepherd *et al.*, 2004; Joughin and Alley, 2011).

Although our simulations using the UVic ESCM show warming at several localities in the Southern Ocean – including the Antarctic Peninsula – it is the marked pervasive warming in the Ross and Weddell seas and Prydz Bay that have significant implications for WAIS and, importantly, EAIS stability (Fig. 6). Through comparison of the resultant warming predicted by the UVic ESCM, and the outputs from the PISM ice-sheet model (Golledge *et al.*, 2012), we can see that the foci of the ocean warming are adjacent to the sectors of the ice sheet that are predicted to respond most rapidly to ocean forcing. These sites correspond with sectors of the EAIS that are drained by fast-flowing outlet glaciers – conduits that originate in the interior of the ice sheet (Golledge *et al.*, 2012). Previous experiments suggest that these major arteries of the ice

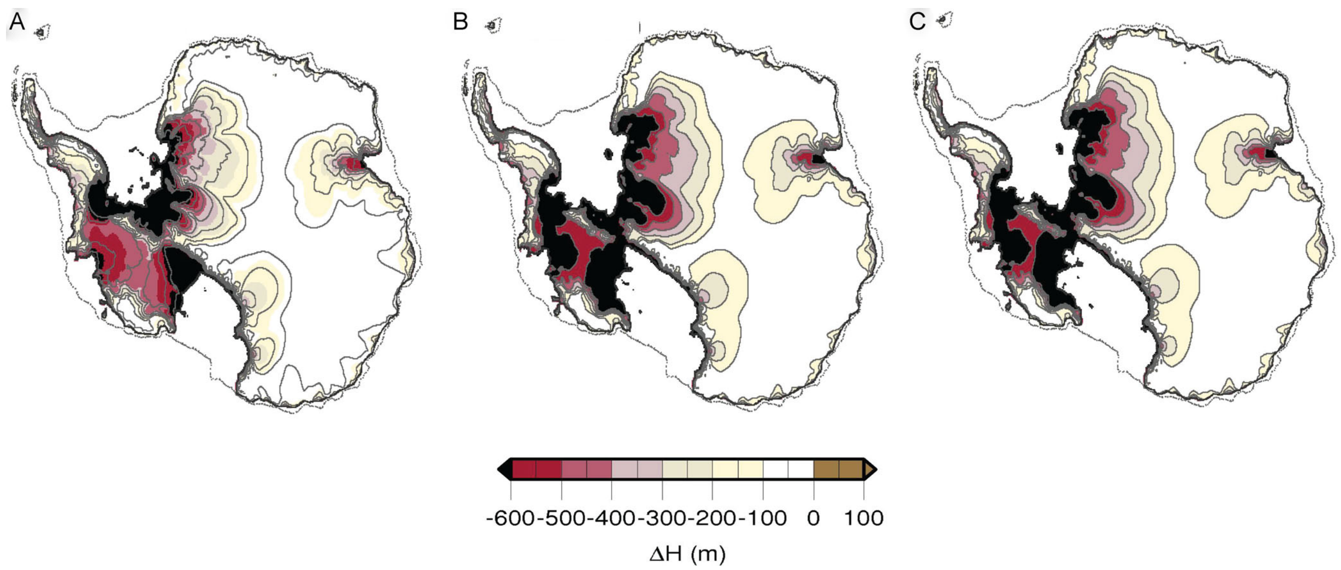

Figure 5. Ice-sheet thickness change (m) predicted from ensemble ice-sheet modelling experiments using PISM. (A) Surface thinning at 1000 model years after isochronous imposition of a 25-m rise in sea level and a glacial to interglacial increase in oceanic heat flux increases; (B) as A, but after 3000 model years; (C) as B but with a 50-m increase in sea level. This figure is available in colour online at wileyonlinelibrary.com.

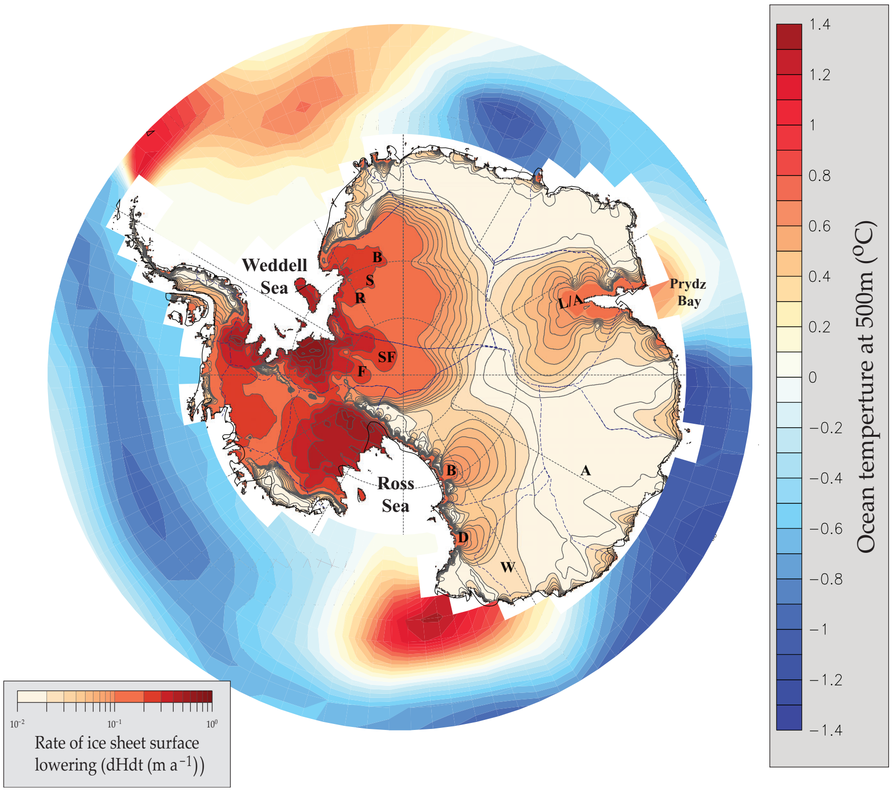

Figure 6. Southern Ocean temperature anomalies (°C) at 500 m depth under 135 ka BP boundary conditions (shifted SHWs minus control simulation), together with the pattern of ice-sheet thinning from an independent glacial–interglacial ocean-forcing model experiment (see also Fig. 4). EAIS drainage basins are marked F, Foundation; SF, Support Force; R, Recovery; S, Slessor; B, Bailey basins; L/A, Lambert/Amery Basin; B, Byrd; D, David; W, Wilkes; Aurora. This figure is available in colour online at wileyonlinelibrary.com.

sheet are highly sensitive to changes in ocean temperature and sea level at the periphery of the continent, and are able to induce drawdown from the EAIS, transmitting changes felt in the Weddell Sea, the Ross Sea and Prydz Bay rapidly to the interior of the ice sheet.

We propose that the sensitivity of these sectors of the ice sheet relates to two major factors: firstly the coincidence of EAIS basins with concave ice-sheet surface profiles; secondly, the basins' connectivity to the ocean. The basins' bed topography and ice-sheet geometry control the mass flux from the ice sheet; those which have a weak or sliding bed have a faster flow regime, resulting in a concave surface profile (Cuffey and Paterson, 2010). In contrast, basins where ice is flowing slowly with little or no basal sliding exhibit a parabolic, or convex, surface profile and much lower ice fluxes. Our results imply that basins with concave surface profiles are particularly susceptible to ocean forcing, bringing about greater rates of surface lowering than in other areas (Figs 5 and 6). These conditions exist – and importantly may well persist over the Plio-Pleistocene glacial/interglacial cycles due to hysteresis within large ice sheets (Cook et al. 2013; Schoof, 2007) – in several key locations of the EAIS, namely the five major EAIS drainage basins of the eastern Weddell Sea (the Foundation, Support Force, Recovery, Slessor and Bailey basins), the Lambert/Amery Basin, and the Byrd and David catchments of the western Ross Sea (Fig. 6).

The Foundation, Support Force, Recovery, Slessor and Bailey basins drain extensive areas of the EAIS in the eastern Weddell Sea, and are in direct contact with the ocean through marine outlets that drain into the Filchner Ice Shelf in the glacially over-deepened Thiel/Crary Trough in the eastern Weddell Sea. Each of these basins and their associated ice streams exhibit concave profiles, evident from visual inspection of the RADARSAT-1 synthetic aperture radar mosaic of the Antarctic ice-sheet surface (Fig. 7), where concave profiles are evident in each of the sectors described. Geophysical surveys suggest that the Slessor Glacier is underlain by thick marine sediments which encourage basal sliding (Rippin *et al.*, 2006), supporting our interpretation of the dynamic nature of these low-profile basins draining into the eastern Weddell Sea. Similarly, the extensive Lambert/Amery Basin is connected to the open ocean through the Amery Ice Shelf into Prydz Bay and, as with the EAIS outlets in the eastern Weddell Sea, the basin has a concave profile which continues deep into the interior of the ice sheet (Fig. 7). Finally, the most extensive warming we observe is in the Ross Sea region, extending along the western edge of the embayment, and continues to areas at the grounding line of the East Antarctic Ice Sheet in George V Land. Our ice-sheet modelling experiments suggest that the David and Byrd catchments have the potential to draw down significant volumes of ice from the EAIS interior into the Ross Sea. Importantly, flux changes in the David Basin cause drawdown within the extensive Wilkes subglacial basin (Fig. 6). In common with the other basins described above, the David and Byrd catchments currently exhibit concave profiles, suggesting weakness at their bed and potential for high mass flux.

Importantly, multi-proxy geological and biological evidence support this, suggesting that marked warming in the high-latitude Southern Ocean at the transition into the LIG (Carter *et al.*, 2002) was associated with destabilization of the Antarctic ice sheets (Grobe and Mackensen, 1992; Kopp *et al.*, 2009; Barnes and Hillenbrand, 2010; Dutton and Lambeck, 2012) (Figs 1 and 2). Of particular note is the associated early rise in global sea level and rate centred on 132–131 ka (Fig. 1) with relatively high ice-rafted debris reported from ocean cores proximal to the Antarctic continent (compared with low values recorded in distal locations), all at a time of high biogenic flux in the Southern Ocean (Fig. 2). These observations are consistent with SHW forcing of ocean temperatures and melt-out of debris around the Antarctic.

Given the characteristics of the EAIS basins and their proximity to areas where ocean warming can occur, we

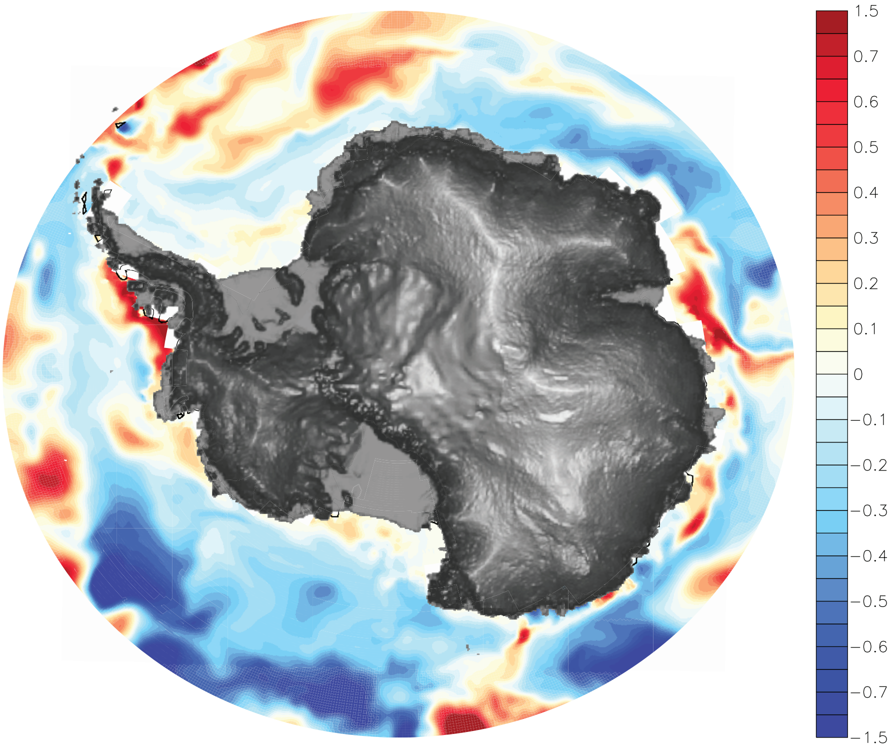

Figure 7. Ocean temperature anomalies (°C) at 500 m depth in response to projected 21st century SHWs as simulated by the UVic ESCM at 0.2×0.4 degree resolution model (SHWs shifted south by 3.5°S, with a 15% increase in wind strength between 30 and 70°S). The Antarctic ice sheet is represented by the RADARSAT-1 synthetic aperture radar mosaic of the ice-sheet surface from the Antarctic Mapping Mission (AMM-1) © CSA 2001. This figure is available in colour online at wileyonlinelibrary.com.

propose that regional ocean warming, in response to SHW migration, could have triggered significant ice-sheet draw-down, thereby making a substantial and hitherto unpredicted contribution to global sea level during the LIG. Assuming significant loss of ice from those portions of the EAIS below sea level, our PISM ice-sheet model output suggests a total potential contribution of 3–5 m to global SLR. This estimate precludes precipitation changes that would add mass to some sectors of the EAIS, although ice-sheet modelling predicts that this would further increase the rates of ice mass flux within the basins susceptible to down-draw, thereby offsetting any gain in mass balance, as suggested by future model projections (Winkelmann *et al.*, 2012). The above is a first-order estimate, given that it does not allow for possible incomplete retreat due to either ice-dynamic constraints, changes in ice-sheet profile outside these basins, or isostatic response to unloading, but it represents a volume that reconciles the current disparity between empirical and modelled LIG sea-level estimates (Kopp *et al.*, 2009).

Future Implications

Our interpretation of EAIS sensitivity to ocean forcing is of particular relevance to future sea-level projections, given that the core of the SHW is projected to continue to migrate polewards and strengthen under anthropogenic forcing, associated with an increasingly positive Southern Annular Mode state (Rind, 1998; Marshall, 2003; Oke and England, 2004; Thompson *et al.*, 2011). To test the implications of the above findings, we analysed the UVic ESCM forced with anthropogenically induced SHW anomalies projected for the late 21st century (a 3.5° southward shift with a 25% increase in wind strength) at $0.2 \times 0.4°$ resolution (Spence *et al.*, 2009), a scenario considered likely under the combined effects of ozone hole depletion and increasing greenhouse gas levels (Yin, 2005; Thompson *et al.*, 2011; Lee and Feldstein, 2013). The advantage of this model, over that used for the long-term pervasive change during the LIG, is that it allows us to simulate mesoscale features of the ocean response to forcing on centennial timescales (Wang, 2013). Within our model runs, we observe warming of ~0.4 °C within the uppermost 500 m of the Amundsen Sea (Fig. 7). These results are consistent with present-day observations (warming of ~0.5 °C) (Shepherd *et al.*, 2004), suggesting warming of this magnitude is not dependent on an extreme shift of 9° in the SHW and is likely to continue over the next hundred years, with migrating SHWs, increasing transitory upwelling of Circumpolar Deep Water onto the Antarctic continental shelf (Shepherd *et al.*, 2004; Boning *et al.*, 2008). Crucially, this simulation also reveals localized warming of between 0.1 and 0.4 °C in the Ross and Weddell seas and Prydz Bay, implying even relatively small shifts in SHWs may have far-reaching consequences for SLR in key locations. These estimates are of the same order of magnitude as those predicted by other recent 21st-century model simulations of the Weddell Sea using the Bremerhaven Regional Ice-Ocean Simulations (BRIOS) model with the atmospheric output of the HadCM3 climate model (Hellmer *et al.*, 2012). Worryingly, recent analyses of glaciological observational data from the Pacific region of the EAIS suggest this mechanism may already be operating (Miles *et al.*, 2013).

Conclusions

In summary, we propose that the EAIS may provide an important missing component of LIG SLR, reconciling empirical geological (Kopp *et al.*, 2009; Dutton and Lambeck, 2012) and model-based estimates. Specifically, we suggest that local ocean warming off the Weddell and Ross seas and in Prydz Bay, associated with a poleward shift in SHWs, led to accelerated mass loss from specific sectors of the EAIS, resulting in a 3–5 m contribution to SLR at the LIG. Ice-sheet modelling experiments suggest that sectors of the EAIS which exhibit concave profiles (characteristic of weaker bed conditions) are more susceptible to higher potential mass flux rates, making them highly sensitive to ocean forcing. These areas of sensitivity are not necessarily the deepest basins of the EAIS, which have been previously proposed as being vulnerable to ocean-driven instabilities (Fox, 2010). Instead, our findings imply that on millennial timescales, SHW migration can induce weakening of the three major sub-polar gyres while on decadal to centennial timescales, it can enhance CDW upwelling onto the Antarctic continental shelf, potentially triggering accelerated mass loss from these intrinsically weaker regions of the EAIS. Given projected poleward westerly airflow migration associated with a positive SAM (Thompson *et al.*, 2011) and the recent recognition that subglacial melt is already having a significant impact along some margins of the EAIS (Miles *et al.*, 2013), our findings have important implications for future ice-sheet dynamics and sea-level change. As such, detailed monitoring of Southern Ocean circulation and temperatures must be seen as a priority for future research.

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Abbreviations. ACC, Antarctic Circumpolar Current; EIAS, East Antarctic Ice Sheet; LGM, Last Glacial Maximum; LIG, Last Interglacial; PISM, Parallel Ice Sheet Model; SLR, sea-level rise; SHWs, Southern Hemisphere Westerlies; UVic ESCM, University of Victoria Earth System Climate Model; WAIS, West Antarctic Ice Sheet.

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