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Local insolation changes enhance Antarctic interglacials: Insights from an 800,000-year ice sheet simulation with transient climate forcing

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ABSTRACT

The Antarctic ice sheet – storing ∼27 million cubic kilometres of ice – has the potential to contribute greatly to future sea level rise; yet its past evolution and sensitivity to long-term climatic drivers remain poorly understood and constrained. In particular, a long-standing debate questions whether Antarctic climate and ice volume respond mostly to changes in global sea level and atmospheric greenhouse gas concentrations or to local insolation changes. So far, long-term Antarctic simulations have used proxy-based parameterizations of climatic drivers, presuming that external forcings are synchronous and spatially uniform. Here for the first time we use a transient, three-dimensional climate simulation over the last eight glacial cycles to drive an Antarctic ice sheet model. We show that the evolution of the Antarctic ice sheet was mostly driven by CO_2 and sea level forcing with a period of about 100,000 yr, synchronizing both hemispheres. However, on precessional time scales, local insolation forcing drives additional mass loss during periods of high sea level and CO_2, enhancing the Antarctic interglacial and putting northern and southern ice sheet variability temporarily out of phase. In our simulations, partial collapses of the West Antarctic ice sheet during warm interglacials are only simulated with unrealistically large Southern Ocean subsurface warming exceeding ∼4 °C. Overall, our results further elucidate the complex interplay of global and local forcings in driving Late Quaternary Antarctic ice sheet evolution, and the unique and overlooked role of precession therein.

1. Introduction

Understanding the sensitivity of the Antarctic ice sheet (AIS) – which stores enough water to raise global sea level by tens of meters – to climate change is critical; yet its past evolution and the drivers thereof remain poorly constrained. During the Late Quaternary (roughly the past one million years), global climate alternated between cold glacials and warm interglacials with a period of approximately 100,000 yr (100 ka) and corresponding global sea level changes of more than 120 m (Waelbroeck et al., 2002) (Fig. 1a). Most of these changes in sea level are thought to have originated from the Northern Hemisphere (NH) ice sheets. Still, the Antarctic contribution to glacial sea level drops is estimated to be more than 10 m, with the glacial Antarctic grounding line extending up to the continental shelf break (Bentley et al., 2014). During some previous interglacials the polar ice sheets were smaller than presently by 6–9 m sea level equivalent (SLE) ice volume (Dutton et al., 2015). A portion of these past sea level highstands has been attributed to Antarctic ice sheet variability (Dutton et al., 2015; Golledge et al., 2014; Mercer, 1981) – supported by geological evidence suggesting that the West Antarctic ice sheet (WAIS) collapsed (partially) multiple times during the Quaternary (McKay et al., 2012) – but the climatic drivers of this Antarctic ice loss have not yet been identified.

Glacial–interglacial climate variability ultimately derives from periodic changes in insolation caused by variations in the earth's orbit and tilt (Laskar et al., 2004; Milankovitch, 1941). Precession drives seasonal insolation changes with a period of ∼21 ka that are modulated by eccentricity, and anti-phased between the hemispheres (Fig. 1a). Annual mean insolation changes are mostly

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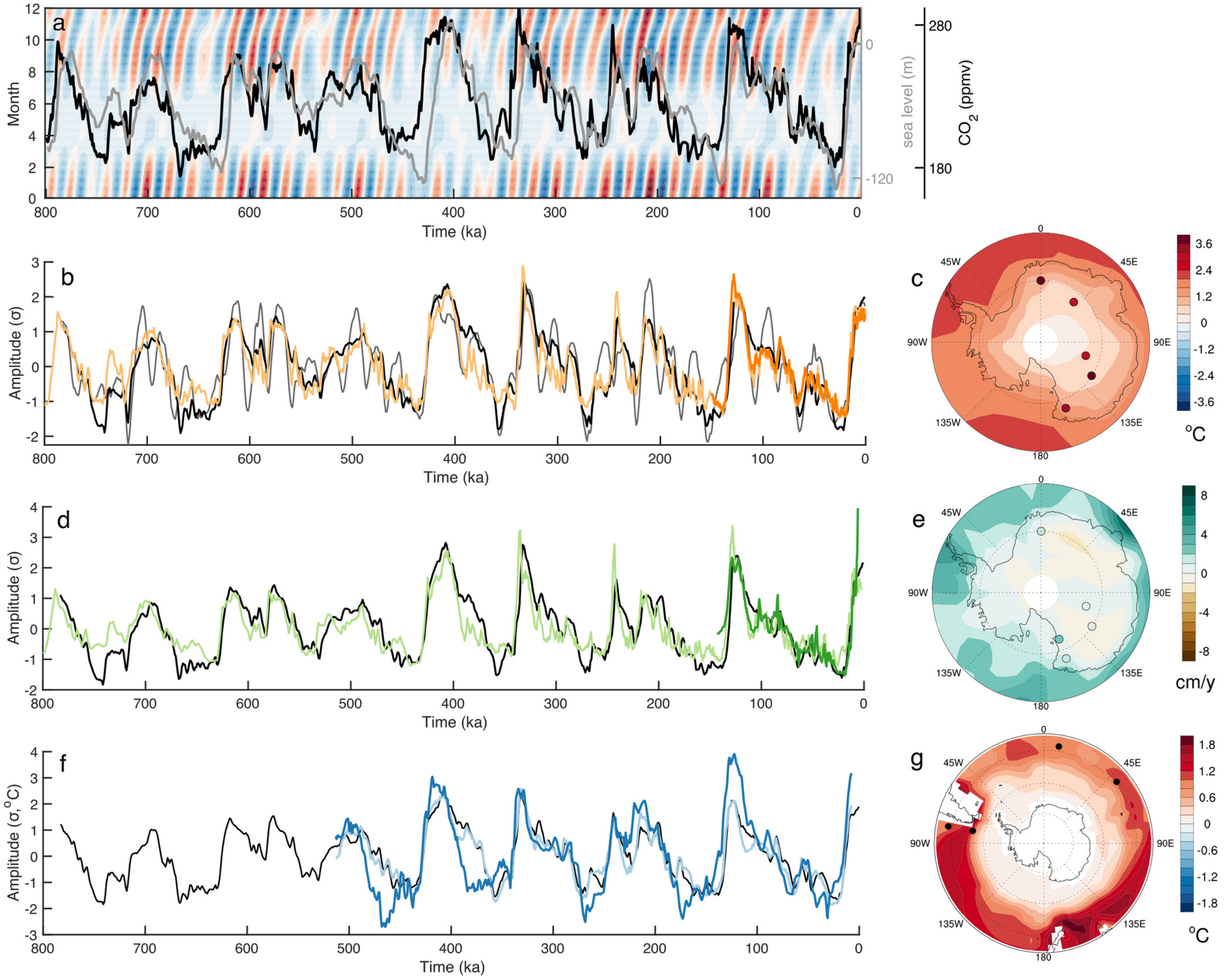

Fig. 1. Southern Hemisphere climate response to Late Quaternary forcing. **a**, Daily insolation anomalies at 65°S resulting from orbital forcing (shading; colours range from −65 to +65 Wm^{-2}) (Laskar et al., 2004), global sea level forcing (grey) (Spratt and Lisiecki, 2016), and CO_2 concentration (black) (Lüthi et al., 2008) over the last 800 ka. **b**, Normalised Principal Component (PC) 1 of modelled annual mean 2 m-air temperatures (black; explained variance (EV) 98.9%), normalised PC1 of modelled annual maximum 2 m-air temperatures (grey; EV 94.5%), normalised PC1 of reconstructed surface air temperatures at five ice core locations (dark orange; 94.0%) (EPICA Community Members, 2006; Jouzel et al., 2007; Kawamura et al., 2007; Parrenin et al., 2004; Stenni et al., 2011; Uemura et al., 2012) and normalised composite of Antarctic surface air temperature reconstructions (light orange) (Parrenin et al., 2013). **c**, EOF1 of modelled annual mean 2 m-air temperatures (shading) and reconstructed surface air temperatures at five ice core locations (dots) (EPICA Community Members, 2006; Jouzel et al., 2007; Kawamura et al., 2007; Parrenin et al., 2004; Stenni et al., 2011; Uemura et al., 2012). **d**, Normalised PC1 of modelled annual mean precipitation (black; EV 83.5%), normalised PC1 of reconstructed accumulation at five ice core locations (dark green; 81.2%) (Bazin et al., 2013; Steig et al., 2000; Vallelonga et al., 2013) and normalised composite of Antarctic accumulation reconstructions (light green) (Bazin et al., 2013; Steig et al., 2000; Vallelonga et al., 2013). **e**, EOF1 of modelled annual mean precipitation (shading) and reconstructed accumulation at five ice core locations (dots) (Bazin et al., 2013; Steig et al., 2000; Vallelonga et al., 2013). **f**, Normalised PC1 of modelled ocean temperatures at 400-m depth (black; 94.6%), composite of modelled SST anomalies (light blue) and composite of reconstructed SST anomalies (dark blue) at four locations (Cortese et al., 2007; Ho et al., 2012; Martínez-Garcia et al., 2009; Nürnberg and Groeneveld, 2006). **g**, EOF1 of modelled ocean temperatures at 400-m depth (shading) and locations of SST reconstructions in f (black dots). Normalised PC1s are in units of standard deviation σ. (For interpretation of the colours in the figure(s), the reader is referred to the web version of this article.)

driven by obliquity forcing at the 41-ka period. Teasing out the causes of AIS variability is complicated by the fact that other components of the earth system also respond to orbital forcing and become additional drivers of Antarctic ice volume changes. For instance, NH ice sheets are thought to be most directly sensitive to changes in NH summer insolation at the precessional period (21 ka) (Milankovitch, 1941), but feedbacks internal to the earth system amplify this insolation forcing and nonlinearly combine into a global climate and carbon cycle response with a period of ∼80–120 ka (Shackleton, 2000). The resulting glacial reduction of atmospheric greenhouse gas concentrations, in particular of CO_2 (Fig. 1a), is an important driver of glacial global cooling, and thus climate variability in Antarctica (Timmermann et al., 2014). At the same time, global sea level variations deriving from NH ice sheet changes also affect the AIS by forcing movement of the grounding line at the 100-ka period (Huybrechts, 2002; Schoof, 2007), while meltwater fluxes associated with northern ice sheet retreat lead to surface warming in the Southern Hemisphere (SH) (He et al., 2013). The relative role of these ice sheet drivers (local insolation changes; remote forcing through changes in global sea level, greenhouse gas concentrations, and NH ice sheets) in driving AIS variability warrants further elucidation and will be the focus of this paper.

Of particular interest here is the role that precession plays in Antarctic climate and ice sheet variability. Raymo et al. (2006) for