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Modest global-scale cooling despite extensive early Pleistocene ice sheets

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ABSTRACT

Expanded continental ice sheets and lowered greenhouse gases were the major radiative perturbations at the Last Glacial Maximum (LGM), and while they had similar magnitudes when averaged over the globe, their spatial distributions were dramatically different. It is consequently unclear how much each contributed to cooling around the world, and the overall global mean cooling in turn. Part of the difficulty in separating their effects is that ice sheets and greenhouse gases closely covaried over the late Pleistocene. The situation may have been different during the early Pleistocene though. Then, the ice sheets seem to have, at least on occasion, reached extents comparable to the LGM, but CO_2 levels were relatively high, similar to those of late Pleistocene interglacials. A global compilation of 11 sea surface temperature records shows substantially less cooling in most regions during the Marine Isotope Stage 100 and 98 glacials at ~2.5 Ma than during the LGM, suggesting that the thermal reach of the ice sheets was relatively limited and perhaps consistent with a more important role for greenhouse gases in driving temperatures around much of the world.

1. Introduction

The Northern Hemisphere ice sheets were important agents of Pleistocene climate change through their orography, freshwater discharge and routing, control on sea level, and, perhaps most significantly, their albedo (Clark et al., 1999). But how large was the ice sheet albedo effect on temperature, both in magnitude and spatial extent? This question is relevant to unraveling the dynamics of glacial cycles as well as better constraining climate sensitivity from paleoclimate data because ice sheets and greenhouse gases were the two dominant radiative forcings at the Last Glacial Maximum (LGM).

Nonetheless, while ice sheet and greenhouse gas forcings were of similar magnitude on a global average basis, they had markedly different spatial distributions – the former was massive but restricted to high-latitude landmasses, while the latter was modest but globally near-uniform (Broccoli, 2000). Simple global energy balance models often consider different forcings to have similar efficacies, regardless of their type or spatial distribution, but this may not necessarily be the case since these factors can influence the local feedbacks that ultimately control the magnitude of the global climate response (Armour et al., 2013). For instance, Shindell (2014) found that global temperature has responded more sensitively to anthropogenic aerosols than greenhouse gases over recent decades due to the inhomogeneous distribution of aerosols. Climate sensitivity could also depend on background state, since feedback strength might vary nonlinearly with temperature. Several recent paleo studies have detected such a nonlinearity, suggesting that global temperature may have responded more weakly to radiative forcing during Pleistocene glacials than interglacials (Köhler et al., 2015; Friedrich et al., 2016; Snyder, 2016). It is therefore not clear how much ice sheets contributed to cooling of the glacial world.

I suggest that a few key glacials during the early Pleistocene, with apparently extensive ice sheets but relatively high CO_2, may provide a novel evaluation of this problem.

2. Background

2.1. Ice sheet-driven cooling in models

Climate models uniformly agree that maximum cooling from the ice sheets occurred over and downwind of them, but there is less consensus on how far this cooling reached around the world. For instance, a pioneering simulation by Manabe and Broccoli

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(1985) suggested that the reduction in shortwave absorption due to ice sheet albedo was almost entirely compensated locally by reduced longwave emission from the colder ice sheet surface. Other studies, however, have pointed to a variety of mechanisms that could link ice sheet-cooling in the high latitudes to the tropics or Southern Hemisphere, such as the shallow meridional overturning circulation in the North Pacific (Philander and Fedorov, 2003), stronger trade winds and tropical mixing/upwelling due to an enhanced pole-to-equator temperature gradient (Bush and Philander, 1998), southward displacement of the intertropical convergence zone (Chiang and Friedman, 2012), changes in the flux or temperature of northern-sourced deep waters exported to the Southern Hemisphere (Imbrie et al., 1992), and exposure of continental margins such as the Sunda Shelf with sea level fall (Bush and Fairbanks, 2003). Furthermore, whereas the radiative forcing from lowered greenhouse gases during the LGM is well-constrained (-2.8 ± 0.25 W/m^2; Köhler et al., 2010), the forcing from ice sheets and associated sea level lowering is less certain, with estimates ranging from -2.2 to -4.6 W/m^2 (Braconnot et al., 2012; Köhler et al., 2010; Schmittner et al., 2011). Consequently, models simulate a wide range in the fraction of LGM global cooling attributable to ice sheets, from 20 to 70%, with much of the remainder explained by greenhouse gases (Fig. 1). There may thus be something of a trade-off in the relative importance of these factors for explaining LGM cooling, with implications for climate sensitivity to greenhouse gas forcing.

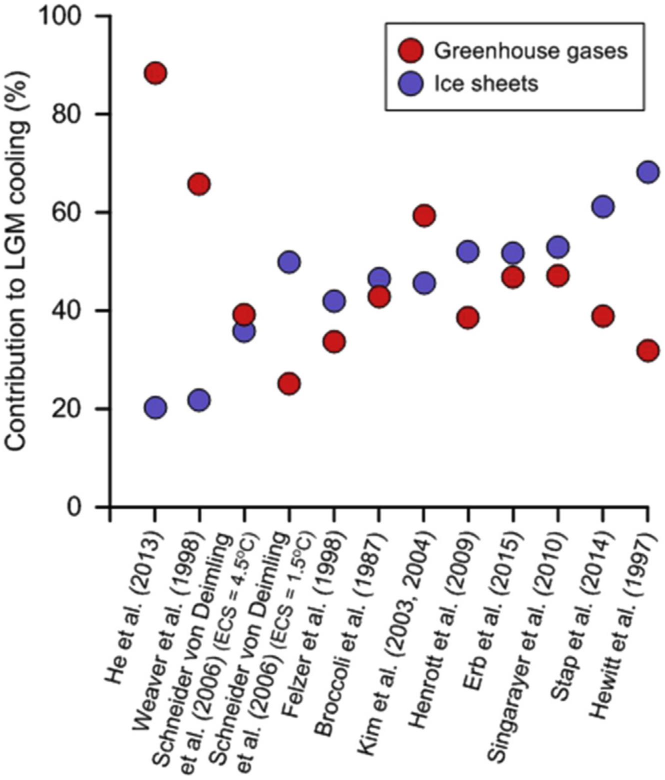

Fig. 1. The fraction of global surface air temperature cooling at the Last Glacial Maximum attributable to expanded ice sheets (blue) and lowered greenhouse gases (red) in published model simulations that isolate the effect of each forcing. There is considerable spread among the models, and a general trade-off between the amount of cooling due to ice sheets versus greenhouse gases. Two end members of Schneider von Deimling et al.'s (2006) simulations are shown, with equilibrium climate sensitivities (ECS) of 4.5 °C and 1.5 °C. (Broccoli and Manabe, 1987; Erb et al., 2015; Felzer et al., 1998; He et al., 2013; Henrot et al., 2009; Hewitt and Mitchell, 1997; Kim et al., 2003; Kim, 2004; Singarayer and Valdes, 2010; Stap et al., 2014; Weaver et al., 1998). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.2. *Ice sheet-driven cooling in proxies*

These contrasting views on the thermal reach of the ice sheets are also implicit in interpretations of the paleorecord. For instance, sea surface temperature (SST) records from tropical warm pools are often considered a prime target for constraining climate sensitivity (Hargreaves et al., 2012; Lea, 2004) and inferring paleo-CO_2 trends (de Garidel-Thoron et al., 2005), since greenhouse gas forcing may dominate in these regions far removed from the ice sheets (Broccoli, 2000). On the other hand, a classical Milankovitch view might instead suggest that ice sheet albedo was the primary mechanism that translated Northern Hemisphere summer insolation forcing into global-scale ice-age cooling (Broecker and Denton, 1989; Paillard, 2015). Indeed, a recent analysis of Plio-Pleistocene CO_2 and SST records found that climate sensitivity to greenhouse gas forcing was twice as large during the late Pleistocene as the Pliocene/early Pleistocene, but that this two-fold difference could be explained by the strengthened albedo feedback from expanded late Pleistocene ice sheets (Martinez-Boti et al., 2015). Hansen et al. (2008) likewise concluded that “It is no wonder that late Cenozoic climate fluctuated so greatly. When substantial ice is present on the planet … climate is sensitive, and largely climate swings occur in response to small orbital forcings.” One simplifying assumption of past studies such as these, however, is that ice sheet albedo forcing is linearly related to global ice volume as inferred from sea level records. More complex modeling instead suggests a nonlinear radiative forcing-sea level relationship due to the latitudinal dependency of ice sheet area, which translates into a nonlinear climate sensitivity (Köhler et al., 2015).

Several arguments have been advanced to suggest a spatially restricted influence of the ice sheets on temperature, though each has caveats. Warming over the last deglaciation plateaued by the onset of the Holocene around most of the world (Shakun et al., 2012), even though nearly one-third of the LGM ice volume was still to melt — however, the Scandinavian Ice Sheet was gone (Cuzzone et al., 2016) and the Laurentide Ice Sheet (LIS) was largely confined to northern Canada (Dyke, 2004), perhaps too small to have a substantial radius of influence. Likewise, global SSTs tended to fall before sea level during glacial inceptions of the late Pleistocene (Shakun et al., 2015) — though modest increases in ice volume could have been expressed as extensive snow and ice cover that produced much of the LGM albedo forcing early in each glacial cycle (Köhler et al., 2015). Additionally, mountain glacier (Broecker and Denton, 1989) and proxy temperature records (Shakun et al., 2012) suggest comparable magnitudes of cooling in both hemispheres during the LGM, seemingly at odds with the greater cooling expected from ice sheets in the Northern Hemisphere — but this hemispheric symmetry could be consistent with efficient transmission of ice sheet-driven cooling across the equator by the ocean and atmosphere. Lastly, statistical attempts to separate the contributions of various forcings to temperature records from the tropics (Lea, 2004) and Southern Hemisphere (Lorius et al., 1990) spanning the past few glacial cycles typically suggest a sizeable role for greenhouse gases — but their covariation with other late Pleistocene forcings, including ice sheets, renders the solutions rather ambiguous. A time interval with LGM-like ice sheet extent but Holocene-like CO_2 levels would help to better tease apart their respective influences.

2.3. *Constraints on early Pleistocene ice sheet extent*

Although marine $\delta^{18}O$ implies that global ice volume was largest during the late Pleistocene (Fig. 2e), a few rare terrestrial deposits show that at least parts of the Northern Hemisphere ice sheets obtained their greatest extent earlier in the Pleistocene. This