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Authors:
Roger C. Creel
Roger.creel@whoi.edu
Department of Physical Oceanography, Woods Hole Oceanographic Institution, Falmouth MA, USA

Robert E. Kopp
Department of Earth and Planetary Sciences and Rutgers Climate and Energy Institute, Rutgers University, New Jersey, USA.

Andrea Dutton
Department of Geoscience, University of Wisconsin–Madison, Madison, WI, USA.

Maureen Raymo
Lamont-Doherty Earth Observatory and Department of Earth and Environmental Sciences, Columbia University, New York, USA.

Catherine Britt
Department of Earth, Geographic, and Climate Sciences, University of Massachusetts Amherst, Amherst, MA, USA

Rob DeConto
Department of Earth, Geographic, and Climate Sciences, University of Massachusetts Amherst, Amherst, MA, USA

North American ice sheet persistence during past warm periods should inform future projections

Roger C. Creel[1], Robert E. Kopp[2], Andrea Dutton[3], Maureen Raymo[4], Catherine Britt[5], Rob DeConto[5]

(1) Department of Physical Oceanography, Woods Hole Oceanographic Institution, Woods Hole, MA, USA.
(2) Department of Earth and Planetary Sciences and Rutgers Climate and Energy Institute, Rutgers University, New Jersey, USA.
(3) Department of Geoscience, University of Wisconsin–Madison, Madison, WI, USA.
(4) Lamont-Doherty Earth Observatory and Department of Earth and Environmental Sciences, Columbia University, New York, USA.
(5) Department of Earth, Geographic, and Climate Sciences, University of Massachusetts Amherst, Amherst, MA, USA.

Abstract

How fast sea level rises in the next century will depend on how fast the Antarctic Ice Sheet responds to warming. Projections of future Antarctic Ice Sheet behavior are shaped by the assumption that peak sea level during past warm periods occurred after ice sheets had disappeared from North America. Here we present emerging evidence from paleoceanography and allied disciplines to argue that North American ice sheets endured well into some of the warmest interglacials of the last million years. We begin by reviewing the evidence for North American ice sheets persistence during past warm periods. We then show that overlooking this feature of past interglacials may lead projections of future ice sheet mass loss to systematically underestimate Antarctic Ice Sheet sensitivity to future warming. Finally, we propose that this paradigm shift opens avenues for future research that will increase confidence in the accuracy of climate and sea level projections.

Main

Sea level is rising along virtually all of the world's densely populated coastlines, driven by mass loss from ice sheets and glaciers, groundwater fluxes, and seawater thermal expansion in response to anthropogenically-driven global warming (Fox-Kemper et al. 2021). One of the largest and deepest unknowns in sea level projections is how fast the Antarctic Ice Sheet (AIS) may shed mass over the 21st century and beyond (Fox-Kemper et al. 2021). Much of the spread in AIS projections represents uncertainty about which processes may drive change, how fast those processes operate, and how to represent those processes in projections (Lempert et al. 2003, Kopp et al. 2017).

The need to address these uncertainties in future AIS projections has turned attention to past times when the AIS endured climates as warm as Earth's now is or may soon be. These intervals include the Last Interglacial (LIG, 130 - 115 ka), Marine Isotope Stage 11c (426 - 396 ka, hereafter MIS-11, Tzedakis et al. 2022), and the Pliocene (5.3 - 2.6 Ma), particularly the mid-Piacenzian Warm Period (MPWP, 3.3 - 3 million years ago, Ma, Dutton et al. 2015). Each interval provides a useful window into how the AIS behaves in an Earth system whose state differs somewhat from present or historical climates (Kageyama et al. 2018). During the LIG, when peak global mean sea level (GMSL) reached between 2 and >9 meters above present (Figure 1), atmospheric CO_2 concentrations remained near pre-industrial (~1850 CE) levels and global mean surface air temperature was comparable to the early 21st century (about 0.5-1.5°C above pre-Industrial levels, World Meteorological Organization, 2024; Goessling et al., 2025), while polar temperatures were at least several degrees Celsius warmer than pre-industrial levels (Rantanen et al., 2022). During MIS-11, when peak GMSL likely exceeded 6 meters and may have reached as high as 13 meters above present (Raymo and Mitrovica, 2011; Roberts et al., 2012; Chen et al., 2014), high latitude temperatures were slightly colder than the LIG (Tzedakis et al. 2022), however, the exceptional duration of this interglacial (>30,000 years) allowed polar ice sheet melt to occur over a much longer time interval. Finally, the MPWP, when sea levels may have reached 20 meters above present (Dumitru, Austermann, et al., 2019; Richards et al., 2023), represents the most recent time atmospheric CO_2 concentrations rivaled those of the early 21st century, with CO_2 levels reaching 394 (+34/-9) ppm during the KM5c interglacial (~3.205 Ma, de la Vega et al., 2020). Pliocene ice sheet configurations and sea levels are therefore considered the closest analogues for the multi- millennial-scale sea level rise that present warming may cause (Dutton et al., 2015).

While these past warm periods differ in terms of astronomical forcing, atmospheric CO_2 concentration, and other boundary conditions, they have been assumed to share one feature: the absence of North American ice sheets. The assumption appears largely justified during the Pliocene: while the Cordilleran Ice Sheet may have started to expand at ~3.1 Ma, Northern Hemisphere glaciation only intensified at ~2.7 Ma as ice on North America expanded to mid-latitudes (Balco and Rovey, 2011), and the Cordilleran Ice Sheet reached its largest Plio-Pleistocene extent (McClymont et al. 2023). However, mounting evidence suggests that North America's Laurentide and Cordilleran Ice Sheets persisted during the early stages of the Pleistocene's warmest interglacials. This persistence has implications not just for understanding Earth history but also for harnessing that history to help improve projections of 21st century sea level rise and ice sheet mass loss. In this Perspective, we summarize the current state of knowledge concerning North American ice sheet presence during past interglacials; discuss how this persistence could alter understanding of sea level, ice sheets, ocean circulation, and atmospheric dynamics during past warm periods; and outline the implications for future ice sheet and sea level projections.

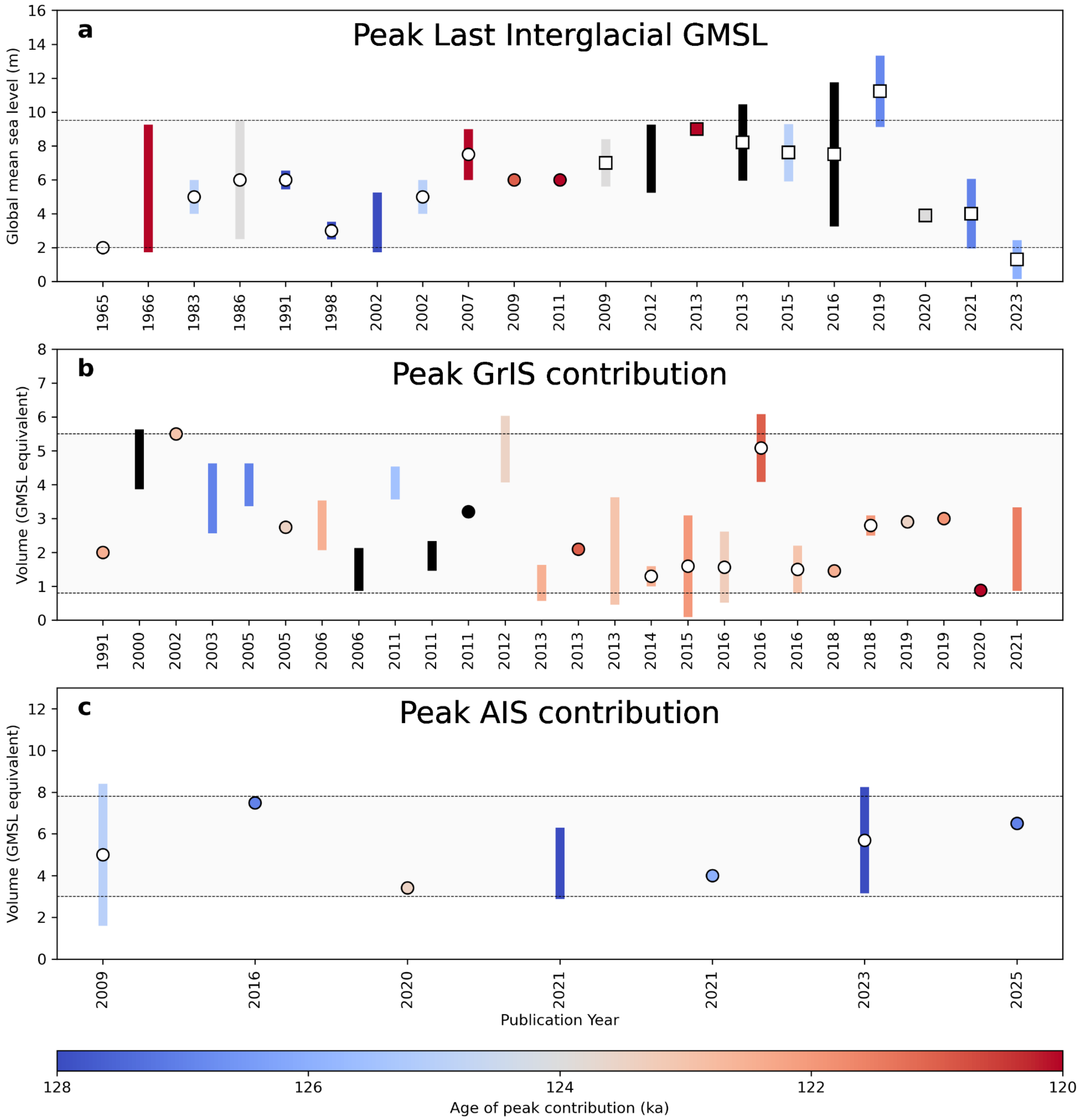

Figure 1. **Compilation of Last Interglacial (LIG) reconstructions of peak global mean sea level (GMSL) and Antarctic and Greenland Ice Sheet (AIS, GrIS) contributions.** Estimates of (a) peak LIG GMSL and GMSL contributions from the (b) GrIS and (c) AIS are plotted in order of publication year from left to right. Colorbar denotes timing of peak contribution in thousands of years (kyr) before 1950. Vertical bars denote ranges; circles indicate best estimates; squares in panel a mark estimates corrected for glacial isostatic adjustment. AIS estimates are limited to those directly modeled either by an ice sheet simulation or GIA model. Horizontal light gray bands delineate minimum envelopes of agreement among studies, i.e. bounds that encompass or intersect with all estimates given their uncertainties.

Evidence for North American ice sheets persisting during past interglacials

Reconstructing North American ice sheet growth and decay prior to the last glacial cycle is challenging because the ice sheet's footprint at Last Glacial Maximum (~26 ka) erased nearly all older terrestrial sedimentary deposits. Nevertheless, indirect evidence has accumulated—much of it from marine sediments—that constrains the ice sheet's Plio-Pleistocene evolution.

LAST INTERGLACIAL

The strongest evidence for the presence of North American Ice Sheets during the early Last Interglacial (LIG) comes from marine sedimentary archives. North Atlantic sediments hold a red layer estimated to occur within a few thousand years of 125 ka according to age models of several deep sea cores (Nicholl et al., 2012; Zhou et al., 2021), or at 126.5 ± 1 ka using a speleothem U-Th based chronology (Tzedakis et al., 2018). This layer resembles a red layer of ~8.2 ka age deposited when a proglacial lake flooded under then burst through a remnant Laurentide ice dam to enter the Labrador Sea (Kerwin, 1996; Jennings et al., 2015; Brouard et al., 2021, Figure 2a). The Laurentide held enough water at ~8.2 ka to raise global mean sea level (GMSL) 3 - 5+ meters (Ullman et al. 2016, Matero et al. 2020) and was likely of similar size as late as ~126 ka. Laurentide persistence in the LIG is further supported by lead isotope measurements in Labrador Sea sedimentary records which indicate that the LIS lost considerable mass around ~126.5 ka (Molinek et al. 2024) and suggest glacial erosion of the Canadian craton had ended by 122 ka (Parker et al., 2022), by which point the LIS had almost certainly disappeared (Miller et al., 2022).

Higher LIG insolation forcing relative to the Holocene has been cited as the reason the LIS disappeared prior to the LIG (e.g. Quiquet and Roche, 2024). However, the presence of the LIS can depress regional temperatures by increasing albedo and altering atmospheric circulation patterns (Mitchell et al., 1988, Ullman et al., 2014, Gregoire et al. 2018). An early LIG Laurentide could have cooled the Northern Hemisphere. This hypothesis is supported by coupled ice sheet-climate simulations (Hirose et al. 2025); sea surface temperature proxies recording lower-than-present sea surface temperatures from 128 - 126.5 ka in the Norwegian sea (Ezat et al. 2024); a cold freshwater pulse entering the North Atlantic at ~126 ka (Irvali et al., 2012) accompanied by iceberg rafted debris (Irvali et al., 2016); and North Atlantic SST temperature proxies lagging behind ice volume proxies in early MIS-5e (Cline et al., 1984). We note, however, that the GrIS may have also contributed to cooling and freshening in the North Atlantic during the early LIG. Furthermore, morainal evidence suggests that the LIS at penultimate glacial maximum (MIS-6) was larger than at Last Glacial Maximum in eastern but not western North America (Stanford et al., 2016, 2021; Ehlers et al., 2011), which supports the survival into the LIG of a large MIS-6 LIS ice mass centered on eastern North America.

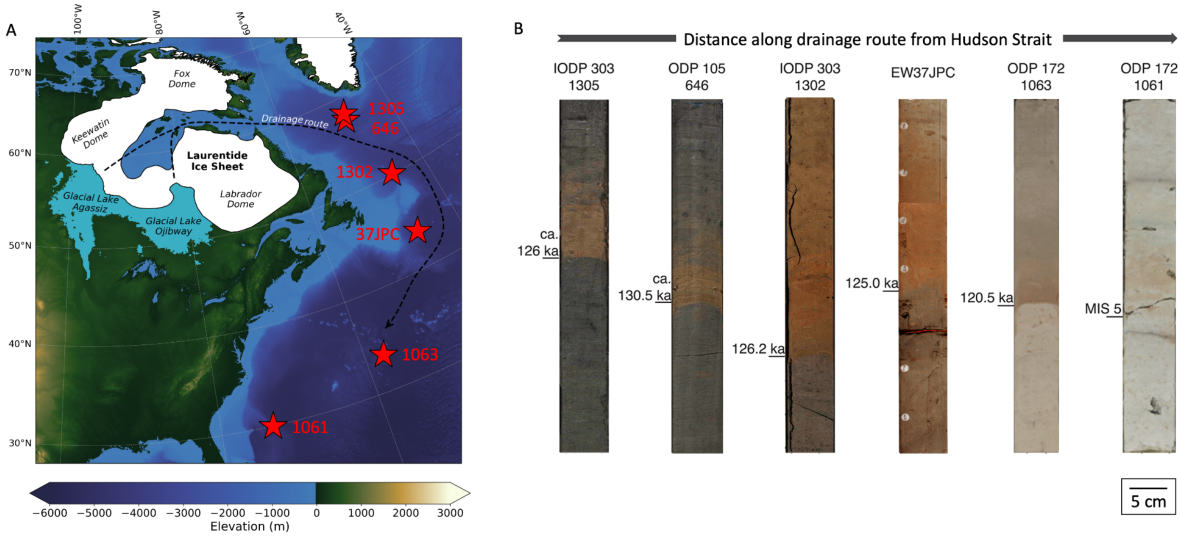

Figure 2. Marine sedimentary evidence for Laurentide Ice Sheet persistence into the Last Interglacial (LIG). (A) Location of sediment cores with a red layer thought to be produced by a Last Interglacial Laurentide Outburst (LILO) flood event. White and blue areas denote Laurentide Ice Sheet (Dalton et al., 2023) and glacial lake Agassiz-Ojibway (Clarke et al. 2004) at ~8.5 ka, a Holocene period analogous to ~126 ka. Red stars denote sediment cores. (B) Sediment cores with LIG red layer, modified from Zhou and Mcmanus (2022). Cores include International Ocean Discovery Program (IODP) Expedition 303 Sites U1305-C4H2 and U1302-C2H6; Ocean Drilling Program (ODP) Leg 105 Site 646-B2H5; Lamont-Doherty Earth Observatory EW9303-37JPC; and ODP Leg 172 Sites 1063-B4H5 and 1061-D4H7. Ages of red layer interpolated from original sources following Zhou and Mcmanus (2022). MIS: marine isotope stage.

Persistence of substantial LIS ice until at least ~126.5 ka aligns with indications that the peak contribution of the Greenland Ice Sheet (GrIS) occurred late in the LIG during the Northern Hemisphere summer insolation maximum (Fig. 1b, Yau et al. 2016, Bradley et al. 2018). While peak LIG GMSL estimates remain spread between 2 and >9 meters (Fig. 1a), GrIS contributions have in the last decade largely centered on a peak contribution of 1-3 meters occurring after 124 ka (Fig. 1b), though contributions as high as 5 meters are possible (Yau et al., 2016). This convergence in timing has occurred in part thanks to the expanding catalogue of GrIS ice cores, which reveal where the LIG ice sheet was and was not (Voosen, 2020).

By contrast, the AIS likely reached its LIG minimum prior to 126 ka (Figure 1c, DeConto and Pollard, 2016; Golledge et al., 2021, Barnett et al., 2023). The AIS maximum contribution remains uncertain, between 3 and 8 meters (Fig 1c). A larger contribution aligns with evidence that the West Antarctic ice sheet (WAIS) may have collapsed completely (Lau et al. 2023), accompanied by a contribution from East Antarctica (Iizuki et al. 2023). If complete WAIS collapse occurred, the ice sheet likely regrew quickly, as the WAIS contribution after 126 ka requires preservation of the Weddell Sea's Ronne Ice Shelf (Golledge et al. 2021, Wolff et al., 2025).

Taken together, the above ice histories imply that Laurentide persistence may have coincided with maximum Antarctic melt— an implication supported by glacial isostatic adjustment modeling showing that WAIS collapse and LIS persistence produces a relative sea level oscillation whose amplitude and spatial geometry resemble field observations (Creel and Austermann, 2024). The individual ice sheet histories also suggest that at no point during the LIG did Earth's remaining three ice sheets reach a simultaneous minimum, likely due to the anti-phased summer solar insolation intensity experienced at each pole.

MIS-11 INTERGLACIAL

Until recently, discussion of MIS-11 interglacial ice volumes did not consider North American ice sheets. Assessments of MIS-11 sea level, for instance, place peak GMSL in the later part of the interglacial at 6 - 13 meters above present, and partition contributions between Greenland and Antarctica under the assumption that the LIS and Eurasian Ice Sheets had terminated earlier in the interglacial (Raymo and Mitrovica, 2012; Roberts et al., 2012, Chen et al. 2014). Underpinning this inference is the argument that GMSL stability from 410 to 401 ka—as identified from the oxygen isotope stack (e.g. Lisiecki and Raymo, 2005)—implies an absence of interglacial ice volume changes. This argument enabled Raymo and Mitrovica (2012) to correct sea level indicators from Bermuda and the Bahamas for the ongoing effects of glacial isostatic adjustment (GIA) from the preceding glacial termination (Termination V) under the assumption that these sites, situated on the Laurentide's peripheral bulge, would have subsided continuously throughout the interglacial.

The assumption that constant GMSL implies no interglacial volume changes is undercut by the general pattern of interhemispheric ice volume asynchrony during Plio-Pleistocene interglacials (Raymo et al., 2006; Rohling et al., 2019; Barnett et al., 2023; Creel et al., 2024; de Boer et al., 2017). It is instead likely that constant GMSL masked asynchronous minimum ice volumes from each major ice sheet and that these asynchronous changes largely balanced each other out. Interglacial collapse asymmetry and delayed disappearance was tested by Chen et al. (2014) for the MIS-11 Greenland and Antarctic ice sheets, but not for the Laurentide due to lack of published evidence. However, recent lead isotope analysis of Labrador Sea sediments suggests that Laurentide deglaciation may have continued past ~410 ka and that MIS-11 GMSL may have risen slowly in part because of the delayed disintegration of the LIS (Parker et al. 2023). Updating the timing of MIS-11 Laurentide disappearance would likely lead to revisions in existing peak GMSL estimates that account for GIA (e.g. Raymo and Mitrovica. 2012; Chen et al., 2014).

Such a revision would not immediately affect future projections. Ice sheet models used to project 21st century cryospheric evolution do not currently use MIS-11 ice volumes as a paleo-target, likely because of the dearth of ice volume constraints. In the past decade, however, subglacial sediment constraints on MIS-11 Greenland climate and ice extent from cosmogenic (Schaefer et al., 2016; Christ et al., 2023) and palynological (Willerslev et al. 2007) sources have accumulated, and modeling efforts are increasingly employing these bounds to quantify Greenland ice volume (Robinson et al., 2017, Crow et al. 2024). It is therefore likely that projections will, in future, add MIS-11 to the catalogue of paleoclimate calibration targets. When they do, it will be important to account for the possibility of North American ice sheet persistence into MIS-11.

EARLIER PLEISTOCENE INTERGLACIALS

Prior to MIS-11, direct proxy evidence for or against North American ice sheet persistence during interglacials exists but is piecemeal. For instance, glacio-volcanic deposits from British Columbia indicate that a continent-scale Cordilleran Ice Sheet existed during the middle of the MIS 15 interglacial (598 ± 7.5 ka, Wilson and Russell, 2018; Wilson et al. 2019). Modeling has confirmed the possibility of early-mid Pleistocene Cordilleran Ice Sheet persistence into interglacials. For example, coupled climate-ice sheet experiments suggest that a Cordilleran Ice Sheet with volume up to ~8 meters GMSL equivalent (Niu et al., 2021) persisted into MIS-13 (~530 to ~480 kyr BP, Railsback et al. 2015), but that no ice remained on eastern North America.

Nevertheless, as with the later Pleistocene, indirect evidence is also accumulating that more early-mid Pleistocene interglacial ice existed on North America than once thought. Integrated cosmogenic nuclide concentrations in Labrador Sea sediments are consistent with a substantial LIS covering Canada for all but 10-20 kyr of the last million years (Leblanc et al. 2023). This result is supported by terrestrial cosmogenic exposure records from sites near the centers of LIS loading (Corbett et al., 2016), and from indications that the LIS rapidly regained mass after the LIG ended (Andrews et al., 2024). Both findings suggest that complete LIS deglaciation was rare—a conclusion bolstered by the scarcity of periods with no Laurentide-sourced iceberg rafted debris in North Atlantic sediment cores (Mcmanus et al., 1999, Barker et al. 2022).

Should modeling efforts that project 21st century ice sheet change wish to use these earlier Pleistocene interglacials as calibration targets, more direct constraints on North American ice sheet size will be needed. A relatively untapped area of these constraints are the pockets of buried glacial ice that pepper Canada. Though the hottest periods of the mid-Holocene may have degraded Pleistocene permafrost deposits in the western Arctic (Burn, 1997), mean annual air temperatures in eastern Canada remained near freezing throughout the Holocene (Gajewski, 2015), which could have preserved relict Pleistocene ice masses, particularly those that are insulated beneath younger peat. These cryospheric time capsules could have survived across multiple glacial cycles even when buried beneath kilometers of Laurentide ice: mid-late Pleistocene erosion of upland landscapes in Arctic Canada may have been minimal because of cold-based glacial conditions (e.g. Briner et al., 2006). Cold temperatures and minimal erosion across the Pleistocene together raise the prospect that the buried ice found in Eastern Beringia (Froese et al., 2000) and the high Canadian Arctic (Coulombe et al., 2024) that dates to >700 ka is part of a larger trove of early-mid Pleistocene glacial ice and paleo-permafrost deposits (Reyes et al., 2010). These deposits would hold clues about North American ice sheet persistence during past warm periods and should be targeted for future work.

PLIOCENE

While North American glaciations intensified only after 2.7 Ma, evidence continues to emerge for episodes of significant Northern Hemisphere ice earlier in the Pliocene, including on North America. At ~4 Ma, iceberg rafted debris (IRD) records suggest that enough ice covered Greenland, Scandinavia, and Alaska to reach the coast (Schepper et al. 2014), while glacial tills from the Hudson Bay lowlands place initial Laurentide growth as early as 3.5 Ma (Gao et al. 2012). IRD pulses in the North Atlantic during Marine Isotope Stage M2 (~3.3 Ma) indicate expansion of the Greenland, Iceland, and Scandinavian ice sheets (e.g. Kleiven et al. 2002), consistent with coupled climate-ice sheet simulations suggesting 40-60 m of GMSL drawdown (Tan et al. 2017; Dolan et al. 2015, Berends et al. 2019). Terrestrial records from Alaska and northwest Canada reveal a robust Cordilleran Ice Sheet and Brooks Range glaciation during the late Gauss polarity Chron (3.05 - 2.60 Ma, Barendregt and Duk-Rodkin, 2011, Hidy et al. 2013, Sanchez-Montez et al. 2020), while rare early Pleistocene (~2.4 Ma) dates on LIS glacial tills at 39^{o}N (Balco and Rovey, 2010) do not preclude less extensive Laurentide advances prior to 2.6 Ma.

Taken together, these data suggest that North America's gradual cryospheric expansion from 3.5 through 2.6 Ma (Mudelsee and Raymo, 2005) and into the Pleistocene likely had significant impacts on sea level. If episodes of this expansion aligned with episodes of Antarctic mass loss, the muted GMSL fluctuations recorded in oxygen isotope records from the period could be obscuring large ice sheet fluctuations, as likely occurred for the Greenland and Antarctic Ice Sheets (Raymo et al., 2006; de Boer et al., 2017; Grant et al., 2019).

Implications for future climate projections

It has been general practice to assume that when past GMSL is above present, the LIS is gone and that only the GrIS and AIS are influencing the Earth system, including by changing sea level. For the LIG, this assumption was not enforced by Kopp and colleagues (2009), whose ice sheet ensemble permitted Laurentide melt until ~126 ka, but has been the standard assumption since then. For instance, Dyer et al. (2021) and Dumitru et al. (2023) used an ensemble of GIA models produced using ice sheet scenarios in which the Laurentide disappears by 128 ka. Similarly, Dutton and Lambeck (2012) assume that the Laurentide is not present when peak LIG GMSL occurs.

However, the assumption does not hold for key past warm periods: the LIS was likely present during the the early portion of the LIG, MIS-11, and possibly other warm periods, and therefore may have masked loss from the other polar ice sheets. This means that the AIS may be more sensitive to past warming than previously interpreted (Raymo et al., 2006, Gilford et al. 2020). AIS sensitivity to past warming is important to know because some AIS models that run into the future get tested by their ability to reproduce the past. AIS models that can reproduce both present dynamics and peak Plio/Pleistocene mass loss as inferred from proxies are considered more credible (Golledge et al., 2021); some models that cannot hit these targets are tuned until they can (Deconto and Pollard, 2016; Deconto et al. 2021).

The assumption of LIS absence from prior interglacials has influenced future projections in two ways. First, some AIS models that project future AIS mass loss (e.g. Deconto and Pollard, 2016; Deconto et al. 2021) have been tuned to hit LIG mass loss targets based on sea-level reconstructions that assumed that the Laurentide was absent. Second, forward simulations of LIG cryospheric evolution use climate forcing that itself assumes pre-LIG Laurentide termination. For instance, Clark et al. (2020) fed their LIG AIS models atmospheric and oceanic boundary conditions produced with an Earth System model itself forced by ice geometries from the last deglaciation (based on ICE5G, Peltier, 2004), which reach present day conditions before the LIG begins.

Including Laurentide persistence during past interglacials would have several effects on future climate projections. The most obvious effect comes from the math used to determine AIS melt based on peak GMSL. Both for the LIG (e.g. Dutton et al., 2015a, 2015b, Fig. 3a) and for earlier warm periods (Dumitru et al., 2019; Richards et al. 2023), AIS melt is routinely calculated as the residual when peak GrIS melt, mountain glacier melt, and thermosteric expansion are subtracted from peak interglacial GMSL – a technique hereafter referred to as the 'subtraction method' (e.g. Dutton et al., 2015). The math of the subtraction method hinges on simultaneous peak melt contributions, which likely did not occur either during the LIG (Rohling et al., 2019) or during the Pliocene (de Boer et al., 2017; Halberstadt et al., 2024). Nevertheless, AIS melt contribution assessments produced using the subtraction method generally do not account for the time-dependence of the AIS/GrIS tradeoff, in part because of uncertainties about individual ice sheet timings, in part because differences between the early- vs. late-LIG GrIS contribution may be modest (<2 meters GMSL equivalent) and smaller than uncertainties from other sources.

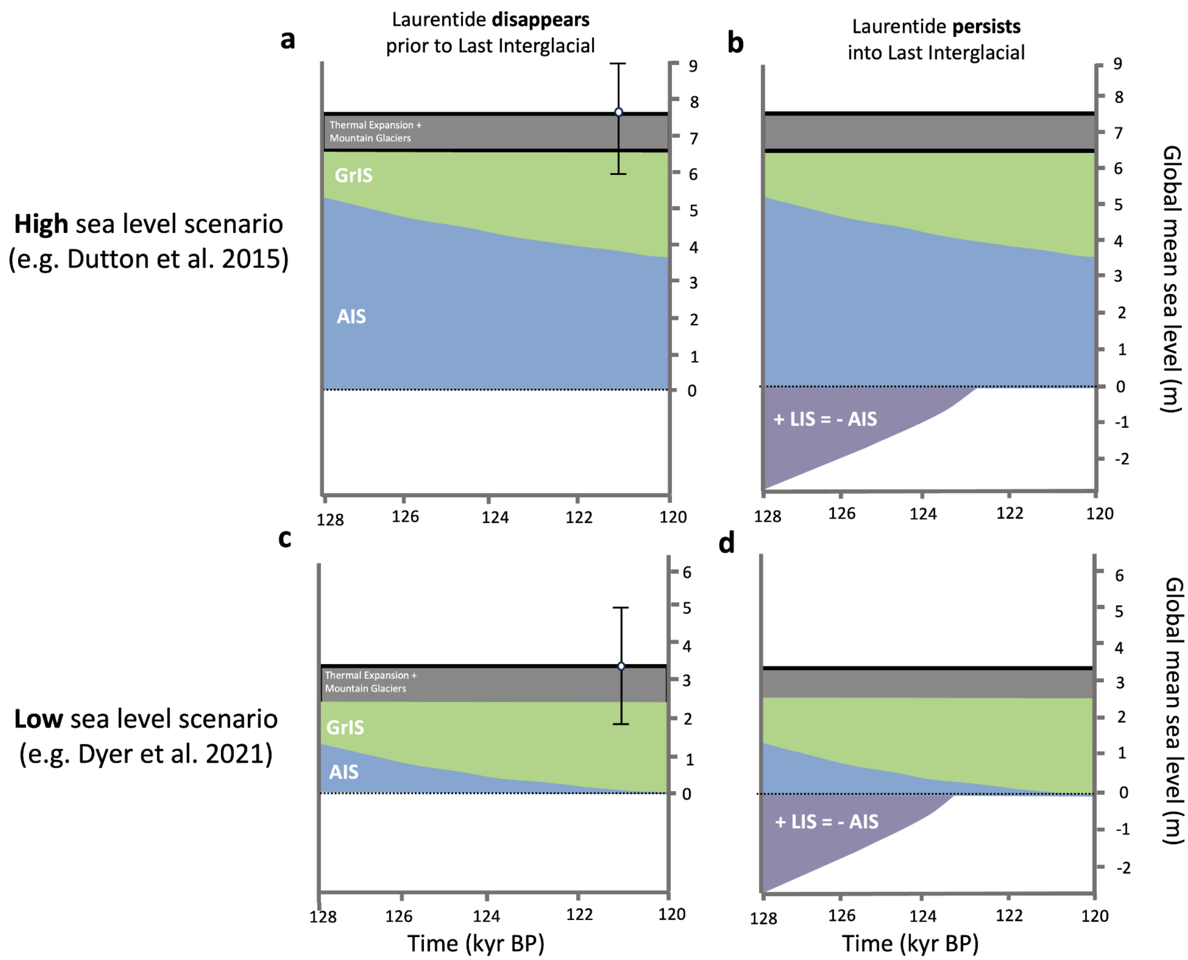

Figure 3. Schematic diagram of effect that Laurentide Ice Sheet (LIS) persistence into the Last Interglacial (LIG) would have on LIG sea level budget. (a/b [c/d]) Scenarios with high [low] peak GMSL estimates in which the Laurentide (a[c]) disappears prior to the LIG or (b[d]) persists into the interglacial. Black lines with uncertainty bars indicate examples of peak LIG GMSL (e.g. 7.6 m ± 1.7, Dutton et al. 2015). Blue/green envelopes mark Antarctic/Greenland Ice Sheet (AIS/GrIS) contribution; purple envelope shows extra AIS contribution possible with >3 meters of Laurentide Ice Sheet (LIS) volume in the early LIG (e.g. Zhou et al., 2022, Creel and Austermann, 2024). Grey bar marks combined contribution of thermal expansion and mountain glaciers, estimated at ~1 meter following Dutton et al. (2015). Colored area below the y = 0 axis is equal to the persistent LIS contribution. Note these illustrative scenarios assume constant GMSL from 128 to 120 ka so as to emphasize the effect of LIS persistence; paleo-constraints allow for GMSL variation during the LIG.

LAST INTERGLACIAL

With three ice sheets during interglacials, however, pinning down the timing of each ice sheet's maximum contribution to sea level becomes crucial—both for top-down assessment of ice volumes based on modeled GMSL and for bottom-up assessment of GMSL via ice volume histories. For instance, if peak AIS melt occurred early in an interglacial, Laurentide persistence would require more AIS melt to reach the same peak GMSL. This effect, illustrated schematically in Fig. 3 for the LIG, applies regardless of peak GMSL estimate. With a higher peak GMSL estimate such as the 7.6 ± 1.7 meter LIG GMSL estimate of Dutton et al. (2015), Laurentide persistence could enable an Antarctic contribution of >8 meters (Fig. 3b) if we assume that the excess contribution did not come from Greenland, which approaches the maximum likely AIS contribution as assessed by most sources (Fig. 1c). With a lower peak GMSL estimate, such as the 1.2 - 5.3 meter (95% credible interval) maximum LIG GMSL of Dyer et al., (2021), Laurentide persistence could permit an early-LIG Antarctic contribution of ~4-5 meters. Furthermore, in the lower peak GMSL scenarios of Dyer et al. (2021) and Dumitru et al. (2023), Laurentide disappearance prior to the LIG would require only minimal (<2 meters) AIS contribution, which disagrees with most sources (Fig. 1c). In summary, any persistence of LIS ice into the LIG would require an increased contribution from another ice sheet, in this case, most likely the AIS. Hence the presence of land-based ice in North America may be masking the true sensitivity of the AIS.

Laurentide persistence into the LIG could also affect AIS and GrIS dynamics via climate mechanisms. Increased AIS melt could have occurred with a persistent LIG Laurentide via an oceanic teleconnection (Clark et al., 2020). Abundant oceanographic evidence suggests that pulses of cold glacial water, likely of Laurentide origin, may have affected North Atlantic circulation into the early LIG (Winkelstern et al., 2017; Zhang et al. 2021). North Atlantic circulation modifications of this kind would have warmed the Southern Ocean via the classic Bipolar Seesaw (Broecker, 1998). Southern Ocean warming in turn likely influenced Antarctica by encouraging the intrusion of circumpolar deep water onto the Antarctic continental shelf (Wang et al., 2022). This mechanism may have driven AIS change throughout the Penultimate deglaciation and into the early LIG (Clark et al., 2020). A persistent Laurentide might also have affected GrIS melt via a climate mechanism, since LIS topography appears to raise Northern Hemisphere air temperatures by encouraging atmospheric stationary waves that increase poleward energy flux over Greenland via perturbations to the jet stream (Liakka and Lofverstrom, 2018).

Whether through climate teleconnections or the changed sea level budget of a three ice sheet interglacial, LIS persistence into the LIG would favor LIG AIS melt scenarios on the high side of the range (3.5 - 7.4 m GMSL) used by Deconto et al. (2021) to tune their projections of future AIS melt. We quantify the impact of Laurentide persistence on future projections using the Bayesian approach of Gilford et al. (2020). Gilford and colleagues built a Gaussian process emulator of future AIS projections, then conditioned these projections on the peak LIG Antarctic contributions of Kopp et al., (2009), Deconto and Pollard (2016), Rohling et al. (2019), Edwards et al. (2019), and others to demonstrate the influence that shifts in these paleoclimate targets could have on future projections. We extend the explorations of Gilford et al. (2020) to include Laurentide persistence during the LIG (Figure 4). Under a low sea level scenario in which peak LIG GMSL is below ~5.3 meters (Dyer et al., 2021), no Laurentide volume on land during peak LIG GMSL leads to future projections with highest likelihood of <0.2 m of Antarctic contribution by 2100 and no likelihood of a contribution >0.65 m (Figure 4a). By contrast, with 6 meters of

Laurentide volume concurrent with peak Antarctic melt, the range of possible AIS contributions by 2100 increases to include ~0.83 m. That probability distribution is virtually identical to the projected AIS contribution under a high LIG sea level scenario (7.6 ± 1.7, Dutton et al., 2015) with no Laurentide grounded ice volume (Figure 4b). Under this higher sea level scenario, Laurentide volume of 6 meters during peak GMSL elevates the highest probability in AIS melt exceeding 0.7 meters by 2100 and precludes AIS projections below ~0.25 meters.

These scenarios were produced assuming that the GrIS contributes 2 ± 1.5 m during peak GMSL and that thermosteric expansion and mountain glacier (TMG) melt together contribute 1 ± 0.2 m (Dutton et al., 2015). Sensitivity tests of these variables (not shown) reveal that though the 21st century AIS projections vary depending on the absolute values of GrIS and TMG contribution, the trend towards higher AIS projections with more LIS persistence remains unchanged regardless of assumed GrIS and TMG contribution.

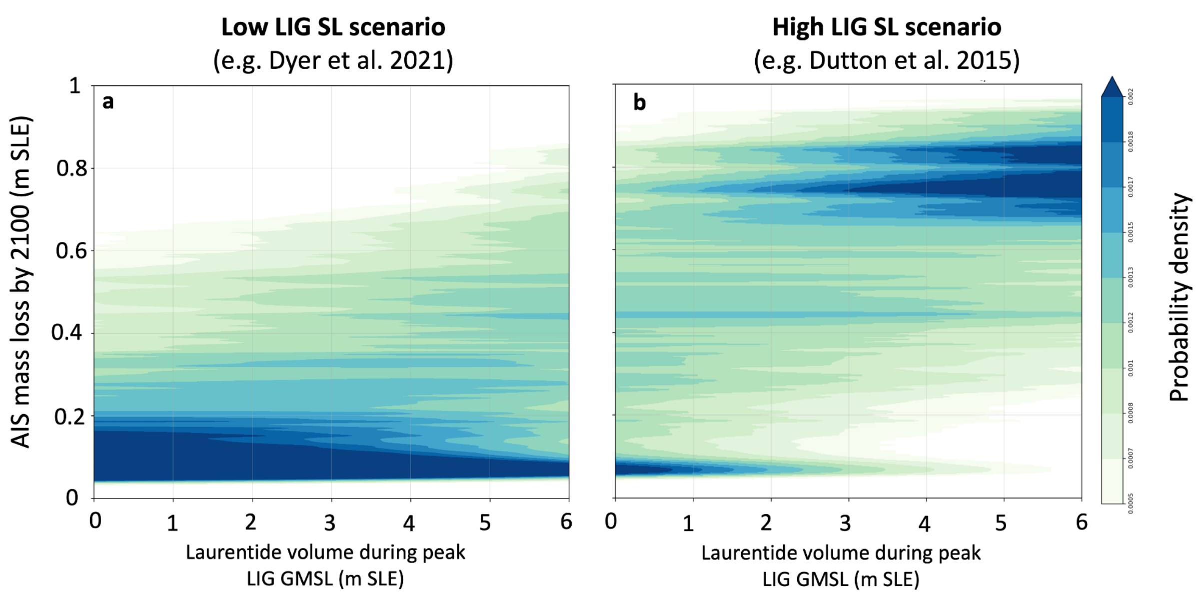

Figure 4. Influence of Last Interglacial (LIG) Laurentide Ice Sheet persistence on projections of future Antarctic Ice Sheet (AIS) mass loss. (a/b) Projections of AIS mass loss by 2100 under a high emissions scenario (RCP8.5) for Laurentide Ice Sheet of up to 6 meters GMSL equivalent for (a) low—1.2 - 5.3 meters, 95% credible interval, Dyer et al. (2021)—and (b) high—μ=7.6, σ=1.6, Dutton et al. (2015)—LIG GMSL scenarios. Projections follow Dutton et al. (2015) in assuming that during peak GMSL, thermosteric and mountain glaciers contribute 1 ± 0.2 meters and the Greenland Ice Sheet contributes 2 ± 1.5 meters. Calculations are performed using the Gaussian Process emulation framework of Gilford et al. (2020).

EARLIER WARM PERIODS

During MIS-11, protracted Laurentide deglaciation would have expanded the LIS peripheral bulge and delayed peripheral bulge relaxation throughout the interglacial. Delayed peripheral bulge relaxation could have reduced the amount that the Bahamas and Bermuda subsided during early MIS-11, lessening the GIA correction that Raymo and Mitrovica (2012) applied to the Bermudan and Bahamian sea-level indicators. This, in turn, would increase peak GMSL assessed from those indicators to higher than the 6 to 13 m range they infer. On the other hand, the effect of a delayed LIS disappearance on local sea level in South Africa, the subject of Roberts et al. (2012) and Chen et al. (2014), could be to reduce the amount of local sea level fall, which would reduce the 8.5 - 11 m GMSL highstand inferred from those data. It is difficult to know exactly the effect that those two opposing corrections would have on a joint inversion for MIS-11 GMSL, and quantifying it with GIA modeling is outside the scope of this study. Still, because GIA effects grow larger with proximity to ice sheets, it is likely that the positive correction to the Bahamas and Bermuda data would outweigh the negative South Africa correction. If so, LIS persistence would push peak MIS-11 GMSL towards the upper end of the 6 - 13 m range, which would imply large GrIS and AIS contributions, as recent findings from both poles suggest occurred (Christ et al,. 2024).

Concerning the Pliocene, the tenet that the full LIS was absent during Pliocene warm periods is likely well-founded. Nevertheless, assumptions about synchrony between Antarctica and the Greenland and/or Cordilleran Ice Sheets during the MPWP can undermine the use of Pliocene sea level and ice sheet reconstructions in future projections. For example, in assessing peak MPWP GMSL, Richards et al. (2023) follow de Boer et al. (2017) in assuming that the GrIS's peak MPWP contribution was 5 ± 1 meters GMSL equivalent. However, the modeled AIS and GrIS contributions in de Boer et al. (2017) are asynchronous: their peak AIS mass loss occurs 50 kyr after peak GrIS mass loss, and peak Antarctic mass loss occurs when the GrIS contribution is ~2 m. Assuming that the MPWP GrIS and AIS volume minimum occurs simultaneously leads Richards et al. (2023) to revise the future Antarctic mass loss projections of Deconto et al. (2020) down from 0.36 ± 0.16 m to 0.07 ± 0.02 m for 2100 and from 9.94 ± 2.97 m to 5.17 ± 3.53 m for 2300. In fact, the two ice sheets were likely antiphase in the mid-Pliocene (Dolan et al., 2011). This asynchrony would have resulted in larger Antarctic melt with lower GMSL (Halberstadt et al., 2024) and would imply that the high end future projections in Deconto et al. (2021) should not be discounted.

Moving forward

Paleoclimatic investigations fall along a spectrum between the view that present Earth system events and processes adequately represent the past, and the view that some past events and processes have no present analogue (Rudwick, 2014). Though paleoclimatic research has often treated past interglacials as similar to our current two ice sheet world—if not in climate forcing then at least in ice sheet configuration (Raymo and Mitrovica, 2012; Dendy et al. 2017)— we argue that this framing needs revision. During the Holocene, the Laurentide persisted for ~3,500 years after the Northern Hemisphere reached peak interglacial warmth (Dalton et al., 2023). This delay is unsurprising: in idealized simulations, large ice sheets lag several thousand years behind insolation and surface air temperature throughout the Quaternary (Binjanta and van der

Wal, 2008). Had later Laurentide advances not scraped North America clean of traces of ice sheet persistence during earlier warm periods, this feature of ice house Earth might be part of the accepted paradigm. As it is, the evidence of Pleistocene interglacial persistence is subtler than the Holocene evidence. It is hard to ignore the Holocene moraine belts that rib Canada. It is easier to overlook marine sedimentary evidence of interglacial Laurentide proglacial lake outburst floods, cratonic erosion, freshwater plumes, and iceberg rafting.

Nevertheless, now that this subtler evidence has accumulated, the paleoclimate community should treat Laurentide persistence during at least a portion of Quaternary interglacials as more likely than not, rather than an anomalous occurrence during the Holocene. Adopting this model for interglacials would better orient the paleoclimate community to the reality that the erosive power of ice sheets—which can exceed that of fluvial processes by an order of magnitude (Wilner et al. 2024)—may have been underestimated, and this underestimation may have biased the geoscientific grasp on differences between the most recent glacial cycle and earlier cycles.

To close, we propose concrete research directions to help the paleoclimate community pivot towards the paradigm of North American ice sheet persistence during Pleistocene interglacials. First, recent ocean and atmosphere simulations have modeled the LIG using ice configurations in which the Laurentide disappeared by ~127 ka largely because the Paleoclimate Modeling Intercomparison Project (PMIP) endorsed this timing (Otto-Bleisner et al., 2017; Kageyama et al. 2018, Menviel et al. 2019) and made the recommended ice histories available. The next PMIP, for which planning is underway, should consider revising the ice history for the penultimate deglaciation to match current proxy-based understandings – i.e. an 8.2 ka-sized Laurentide ice body persisting past ~126 ka (Zhou et al., 2022). And whether or not the PMIP protocols are revised, future work that uses the existing PMIP protocols should employ the recommended LIG ice sheet geometries from Menviel et al. (2019) rather than adopting pre-industrial configurations (*sensu* Guarino et al. 2020), as lingering early-LIG Laurentide and Eurasian ice sheet remnants likely cooled Northern Hemisphere climate (Hirose et al., 2025).

Second, the continuing spread of estimates for LIG ice sheet contributions to GMSL attests to the limits of inferring ice volume changes from sea level data and other indirect proxies. Direct nearfield evidence of the timing and magnitude of ice sheet extents and volumes has no substitute. Promising results from lake drilling (e.g. Briner et al. 2007, Miller et al. 2022), paleo-permafrost studies (e.g. Coulombe et al. 2024), marine sediment cores (e.g. Dong et al., 2017; Parker et al., 2022, 2023), and marine geophysics (e.g. Polyak et al. 2007, Dove et al. 2014) indicate that these and other proxies may hold the key to confident reconstruction of Quaternary Laurentide persistence during past warm periods. They also hold the key to understanding how Laurentide and Eurasian ice sheet volumes during peak glacials, which influence their respective likelihoods of enduring into subsequent interglacials, depend on the sequence of ice sheet nucleation during early glacials (Colleoni et al. 2016). Additional near-field data from Antarctica, either from sedimentary (Iizuka et al., 2023) or genomic (Lau et al., 2022) sources, would yield further knowledge advances. Future efforts should aim at collecting more of these data.

Third, ice simulations require validation by collections of geologic proxies that are standardized, assigned robust uncertainties, and have unified age models. Production of such databases has slowed even as funding agencies increasingly support science that uses legacy data. Encouraging production of more such databases will enable intercomparison of data, which will support future work to characterize North American ice sheet dynamics during past interglacials.

Lastly, we advocate caution in comparing past to future warm periods. The differences we trace between past and present interglacials undermine attempts to connect paleo-GMSL estimates to long-term future GMSL commitment—as was done in the Intergovernmental Panel on Climate Change's Sixth Assessment report (Fox-kemper et al., 2021). By contrast, past LIS masking of AIS sensitivity implies that the potential for the AIS to retreat more rapidly under future warming scenarios may be systematically underestimated. In that light, the paleoclimate community should focus attention on quantifying rates, amounts, and timings of individual ice sheet mass loss during past warm periods, as progress on this front will advance understanding of how Earth's remaining ice sheets may respond to warming.

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