

JGR Earth Surface

RESEARCH ARTICLE

10.1029/2025JF008982

Key Points:

- Bedrock topography in Antarctica has changed by up to ~400 m from the Last Glacial Maximum to present day
- Specifics of the reconstructions of the ice-sheet bed and surface elevation affect subglacial hydrological flow paths
- GIA effects should be accounted for in reconstructions of paleo subglacial hydrology

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

L. Pan,
linda.pan@princeton.edu

Citation:

Pan, L., MacKie, E. J., Mitrovica, J. X., Jamieson, S. S. R., Sergienko, O. V., Ackert, R. P., Jr., & McColl, K. A. (2026). Impacts of glacial isostatic adjustment on Antarctic subglacial water routing since the Last Glacial Maximum. *Journal of Geophysical Research: Earth Surface*, 131, e2025JF008982. <https://doi.org/10.1029/2025JF008982>

Received 10 NOV 2025

Accepted 21 APR 2026

Impacts of Glacial Isostatic Adjustment on Antarctic Subglacial Water Routing Since the Last Glacial Maximum

Linda Pan^{1,2} , Emma J. MacKie³ , Jerry X. Mitrovica² , Stewart S. R. Jamieson⁴ , Olga V. Sergienko¹ , Robert P. Ackert Jr.⁵, and Kaighin A. McColl^{2,6} 

¹Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, NJ, USA, ²Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA, USA, ³Department of Geological Sciences, University of Florida, Gainesville, FL, USA, ⁴Department of Geography, Durham University, Durham, UK, ⁵Climate Change Institute, University of Maine, Orono, ME, USA, ⁶School of Engineering and Applied Sciences, Harvard University, Cambridge, MA, USA

Abstract The bedrock beneath the Antarctic Ice Sheet has experienced widespread viscoelastic deformation as a response to ice-sheet changes from the Last Glacial Maximum (LGM) to present day. The combined changes of the ice sheet and the bedrock most likely had impacted subglacial water routes. Using the evolution of bedrock elevation simulated with two coupled ice-sheet and glacial isostatic adjustment (GIA) models, we explore changes to the subglacial water routes from the LGM to the present day. We explore the sensitivity of our results to bed roughness by repeating the calculations using 10 topographic realizations, and estimate the relative impacts of changes in the bedrock elevation and the ice surface slope. Our results show that bedrock elevation changes of up to ~400 m likely led to a large enough change in tilt of the bedrock, such that subglacial water routing during the last deglacial phase likely differed significantly from patterns inferred at present day. The impact of GIA on subglacial flow paths is thus non-negligible and should be accounted for in reconstructions of ancient subglacial hydrology and studies of past sediment provenance.

Plain Language Summary The bedrock beneath the Antarctic Ice Sheet deforms in response to the ice sheet growing and retreating, and this adjustment leads to changes in the hydrological system beneath the ice sheet. We reconstruct how the bedrock elevation beneath the Antarctic Ice Sheet changed from the peak of the last ice age cycle to the present day and investigate how this change alters the hydrological system beneath the ice sheet. We also consider the sensitivity of the results to different ice histories and uncertainties in the bedrock topography. We find that the bedrock elevation changes by up to ~400 m and that the hydrological system beneath the ice sheet evolved significantly with this adjustment.

1. Introduction

It has been shown that subglacial hydrology is important for ice sheet dynamics, as it impacts ice flow, which, in turn, modulates ice discharge across the grounding line (e.g., Bell, 2008; Dow, 2023). For instance, it has been observed that the acceleration of ice velocity on a glacier in East Antarctica coincided with the discharge of a large volume of subglacial water (Stearns et al., 2008). Previous studies have also shown that glacial isostatic adjustment (GIA; the gravitational, rotational, and deformational response of the Earth in response to the movement of mass between ice sheets and oceans) can impact ice sheets through the stabilizing effect of sea-level fall around a melting ice sheet and the uplift due to the reduced load (e.g., Albrecht et al., 2024; Gomez et al., 2024; Whitehouse et al., 2019). However, the direct impact of GIA on subglacial hydrology has not previously been explored, and this paper investigates these impacts.

The bedrock evolution in Antarctica due to GIA is uncertain. This is because reconstructions of the Antarctic Ice Sheet (AIS) during the Last Glacial Maximum (LGM, ~26 ka; Clark et al., 2009) based on global models of the GIA process and constrained to fit a broad suite of geophysical observables have inferred ice volumes in the range of 7–30 m greater than at present day in units of equivalent global mean sea level (GMSL) (Argus et al., 2014; Ivins & James, 2005; Lambeck et al., 2014; Nakada et al., 2000; Peltier, 2004). The higher end values in this range have come, in large part, from GIA studies that have inferred ice volumes based on relative sea level constraints at globally distributed sites including in the far-field of ancient ice cover (i.e., Barbados, Sunda Shelf, etc.; Lambeck et al., 2014; Peltier, 2004). In contrast, estimates near the lower end of the range were obtained in studies combining GIA modeling and local glaciological and geological constraints across Antarctica (9 ± 1.5 m;

© 2026. The Author(s).

This is an open access article under the terms of the [Creative Commons Attribution License](https://creativecommons.org/licenses/by/4.0/), which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

Whitehouse et al., 2012) and coupled ice sheet-GIA sea level modeling (~6–8 m; Gomez et al., 2013, 2018). These latter studies have significantly reduced estimates of the residual, present-day uplift rates due to GIA over Antarctica and, consequently, led to lower estimates of recent ice mass flux from the region (Shepherd et al., 2012). Thus, there is a high degree of uncertainty in the size of the AIS at the LGM. This uncertainty in excess ice volume of the AIS at the LGM translates to an uncertainty in bedrock evolution from LGM to present day. This has important implications for reconstructions of Antarctic bedrock elevation and its gradients. In addition, significant topographic variability is unresolved in the present-day observations of the AIS bedrock elevation. The widely used data set BedMachine Antarctica, for example, has uncertainties of up to a few hundreds of meters (Morlighem et al., 2020). Both these uncertainties in bed topography could have significant effects on calculations of subglacial hydrology.

In this paper, we investigate how GIA and topographic uncertainty influence the pattern of subglacial drainage in Antarctica since the LGM. We begin by reconstructing LGM bedrock topography using two published GIA models calculated from coupled ice sheet-GIA models to account for the uncertainty in AIS size. These models are characterized by excess ice volumes at the LGM ranging from ~6 to 15 m in units of equivalent GMSL change. We use these GIA model results to compute the evolution of subglacial flow paths since the LGM. We then consider the sensitivity of our results to unresolved topographic variability by repeating the calculations using 10 different topographic realizations that capture the uncertainty in our knowledge of the subglacial landscape and its features at a range of scales.

2. Methods

2.1. Reconstructions of Paleo Sea Level

One of the two sea level calculations discussed here is taken from Gomez et al. (2018). Their calculation was based on a 3-D Antarctic ice sheet model coupled to a 3-D GIA model. The ice sheet model is described in detail in Pollard and DeConto (2012). This model adopts a combination of the shallow ice approximation and the shallow shelf approximation, along with a parametrization of flux across the grounding line from Schoof (2007) (limitations of this parameterization are discussed in Sergienko (2022) and Sergienko and Wingham (2024)). In this model, basal sliding is represented by a power-law sliding law that uses a prescribed basal sliding coefficient. The ice history outside of the Antarctic region was adopted from the ICE-5G ice model (Peltier, 2004). The 3-D Earth model was taken from Hay et al. (2017), which was based on a multi-step scaling of seismic velocity anomalies (An et al., 2015; Heeszel et al., 2016) to density variations, temperature variations, and ultimately to a 3-D viscosity field. The spherically averaged structure of the model is characterized by a lithospheric thickness of 96 km, and upper and lower mantle viscosities of 5×10^{20} Pa s and 5×10^{21} Pa s, respectively. Figures 1a and 1b shows maps of the lithospheric thickness variation in the model and lateral variations in mean viscosity from the base of the lithosphere to a depth of 400 km. The average lithospheric thickness within West Antarctica is 65 km, and 200 km in East Antarctica. The viscosity beneath West Antarctica in the model has a minimum value of $\sim 10^{18}$ Pa s, reflecting the tectonic rift setting of the region. In contrast, the shallow mantle region beneath East Antarctica is generally of significantly higher viscosity than the background average of 5×10^{20} Pa s, consistent with the cratonic setting of the region (though there are isolated zones close to the Wilkes, Aurora, and Recovery Basins, where the mantle viscosity is approximately one order of magnitude lower than the spherical background average of 5×10^{20} Pa s). The GIA calculations within the coupled model of Gomez et al. (2018) (henceforth G18) were performed using the finite volume GIA software SeaKon described in Latychev et al. (2005).

The second GIA model that we consider is from Albrecht et al. (2024), which is also from a 3-D ice sheet model (PISM; Bueler & Brown, 2009; Winkelmann et al., 2011) coupled to a 3-D GIA model (VILMA; Bagge et al., 2021). We will refer to this model as A24. The PISM ice model also adopts a combination of the shallow ice approximation and the shallow shelf approximation, but the grounding line position is computed based on the simulated ice-flow and thickness distribution and the flotation condition. The production of subglacial water is simulated via an energy conservation scheme, and the basal friction is controlled by a saturated and pressurized subglacial till. The 3-D Earth structure is taken from Bagge et al. (2021), and is characterized by a lower bound of 1×10^{19} Pa s. It was created based on the SL2013SV seismic tomography model (Schaeffer & Lebedev, 2013) for depths up to 200 km, and the 2010 update of Grand (2002) for depths below 200 km. At depths below 870 km, lateral variations are omitted. The radial viscosity profile features a substantial viscosity increase with depth at 410 km, and the lithospheric thickness is defined as the minimum depth with viscosity greater than $10^{23.5}$ Pa s. In

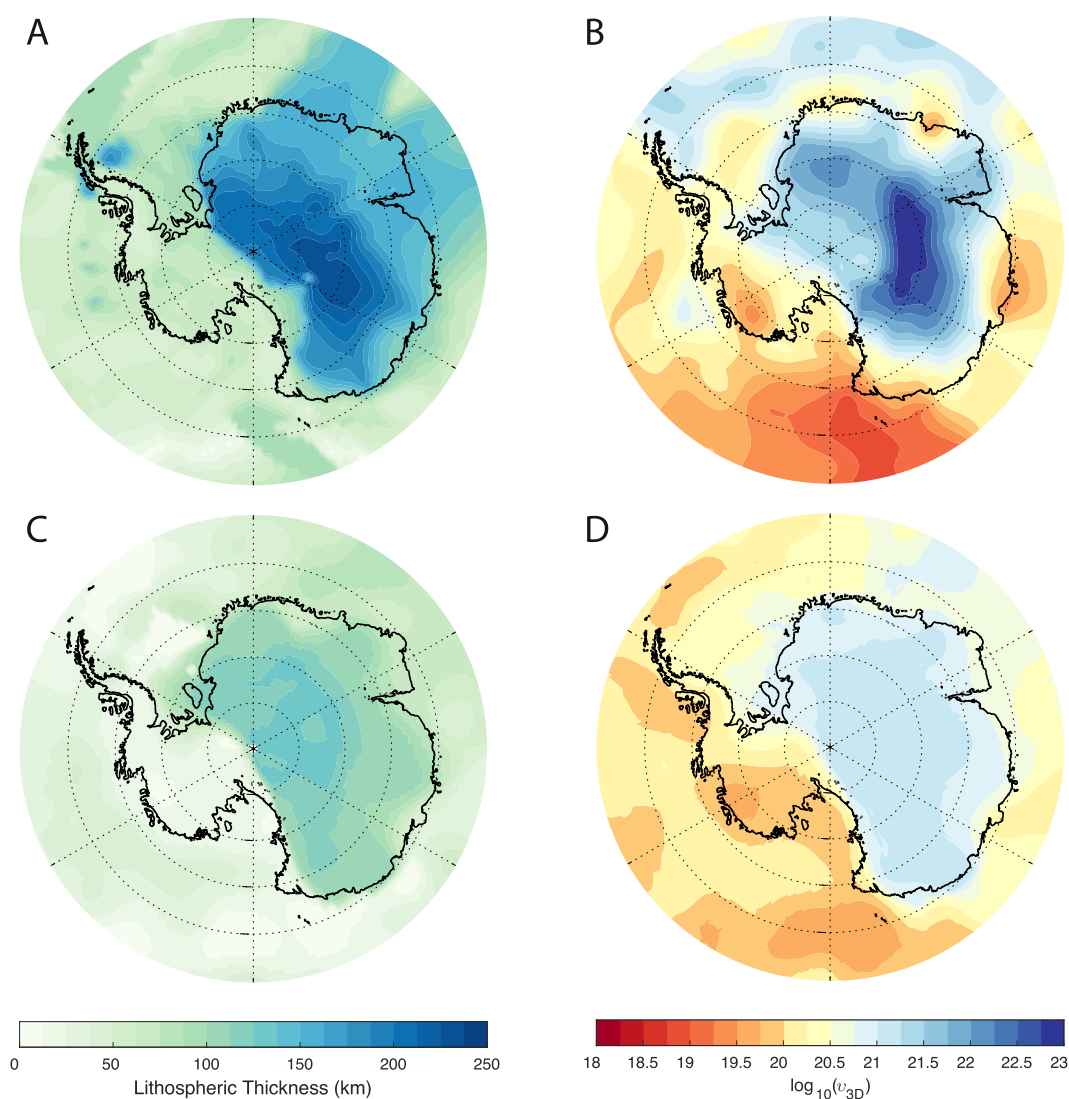


Figure 1. 3-D Viscoelastic Earth Models in G18 and A24. (a) Lithospheric thickness (km) and (b) logarithm of the viscosity (averaged from the base of the lithosphere to a 400 km depth) of the Earth model adopted in the coupled ice sheet—GIA simulations of Gomez et al. (2018). (c) and (d) as in (a) and (b), but for the Earth model adopted in the coupled ice sheet—GIA simulations in Albrecht et al. (2024).

West Antarctica, the lithospheric thickness ranges from 10 to 20 km, while it peaks at 125 km in East Antarctica (Figure 1c). The minimum average viscosity in the upper mantle in West Antarctica is $\sim 10^{19.5}$ Pa s, while the upper mantle viscosity in East Antarctica is higher, $\sim 10^{21}$ Pa s (Figure 1d). As in the G18 model, the thinner lithosphere and lower viscosity upper mantle in West Antarctica is reflective of the tectonic rift setting, while the thicker lithosphere and more viscous upper mantle in East Antarctica is reflective of the cratonic setting.

The differences between the two models include their spatial resolution (20 km in G18 vs. 16 km in A24), different treatments of basal sliding, different treatments of the ice flux across the grounding line, and different Earth models. When considered together, these model differences translate into very different representations of the bed elevation.

We note that both GIA calculations considered in this study have been derived from coupled ice-sheet/GIA models. The feedbacks between the bedrock deformation and the ice-sheet evolution simulated by these coupled models are critical for reconstructions of subglacial flow paths because the gradient of the hydraulic potential that drives flow of subglacial water is more sensitive to the ice surface slopes than to the bed slope (Shreve, 1972).

Other GIA models were specifically developed to fit relative sea level data (e.g., Peltier et al., 2015), and do not necessarily reconstruct realistic ice sheets. These GIA models typically simulate a distribution of ice thickness as opposed to a bed elevation and ice surface elevation (e.g., Ivins & James, 2005). Thus any roughness in the chosen bed topography would map into roughness at the ice surface. Furthermore, for models that do include a bed topography, the resulting ice surface is typically unrealistic, with unphysical artifacts (e.g., Peltier et al., 2015).

2.2. Constructions of the Bed Roughness

Subglacial water routes estimated from the bed elevation and the ice surface slope can be highly sensitive to uncertainties related to the topographic variability (MacKie et al., 2021; Zuo et al., 2020), which is unresolved in the present-day observations of the AIS bedrock elevation and is not included in areas where bed topography is interpolated between measurements. As such, relying solely on existing bed digital elevation models (DEM) would produce a biased estimate of changes in the hydrological paths over time. To assess the sensitivity of the evolution of subglacial flow paths to the bed roughness, we compute 10 realizations of each bed DEM, in which random correlated noise was added to the present day, G18, and A24 LGM bed topographies, while preserving the ice surface height (i.e., ice thickness is calculated as ice surface height minus (bed height + noise); see Figure S1 in Supporting Information S1). This creates a ten-member ensemble of each of the three topographies (present day, G18, A24) for assessing the sensitivity of the evolution of subglacial flow to uncertainties in the bed elevations.

Each random noise perturbation is added such that its characteristics are statistically appropriate to the radar-derived bed topography. The added noise is derived from random Gaussian fields constructed by computing the residual between radar measurements of topography and BedMachine (Müller et al., 2022). The statistics of the residual topography are then used to generate random Gaussian noise. This yields an ensemble of realistic roughness fields.

The radar bed measurements are acquired from Frémand et al. (2023) and gridded to a 1 km resolution. To capture a range of possible bed topographies, the residuals between the constructed bed DEMs and the bedrock elevation inferred from the radar measurements are computed at the Thwaites and Pine Island glaciers in West Antarctica, and at the Denman Glacier in East Antarctica. These sites were chosen to capture a range of geographic settings. The spatial variability of the residuals is then analyzed (MacKie et al., 2023; Mälicke, 2022; Matheron, 1963) to approximate the residual roughness between BedMachine Antarctica and bed elevation measurements (see Text S1 in Supporting Information S1 for greater detail). Each of the 10 fields of roughness generated is added to the respective bed topographies (BedMachine at present day, and the reconstructed topographies from the two coupled models at the LGM), to therefore produce 10 topographic realizations for each of the 3 bed elevation models (present day, and the two LGM reconstructions). We note that the GIA models provide a change in topography relative to the present day bedrock elevation, and thus the Gaussian noise fields carry over to its LGM reconstructions.

2.3. Reconstructions of Subglacial Flow Paths

Subglacial flow paths are calculated based on the present-day ice sheet bed topography data set BedMachine Antarctica (Morlighem et al., 2020) and the two LGM reconstructions of bed topography computed using the G18 and A24 GIA simulations for sea-level change from LGM to present day. In each case, we compute the hydraulic potential gradient, ϕ (Shreve, 1972):

$$\nabla\phi = \rho_w g \nabla h + \rho_i g \nabla H \quad (1)$$

where ρ_w and ρ_i are the density of water and ice respectively, g is the surface gravitational acceleration, h is the bed elevation, and H is ice thickness. We note that, in this formulation, the water pressure is assumed to be equal to the ice overburden pressure. The present-day and LGM subglacial hydropotential gradients (Equation 1) are then used in Antarctic Mapping Tools (Greene et al., 2017) and TopoToolbox (Schwanghart & Scherler, 2014) to calculate the number of upstream cells based on flow direction, thus obtaining subglacial water flow paths.

We also assess the sensitivity of reconstructed subglacial water flow paths to unresolved topographic roughness by repeating each calculation of subglacial flow paths 10 times, in each case with a different topographic realization computed by adding a field of noise to their respective topographies (see Figure S1 in Supporting

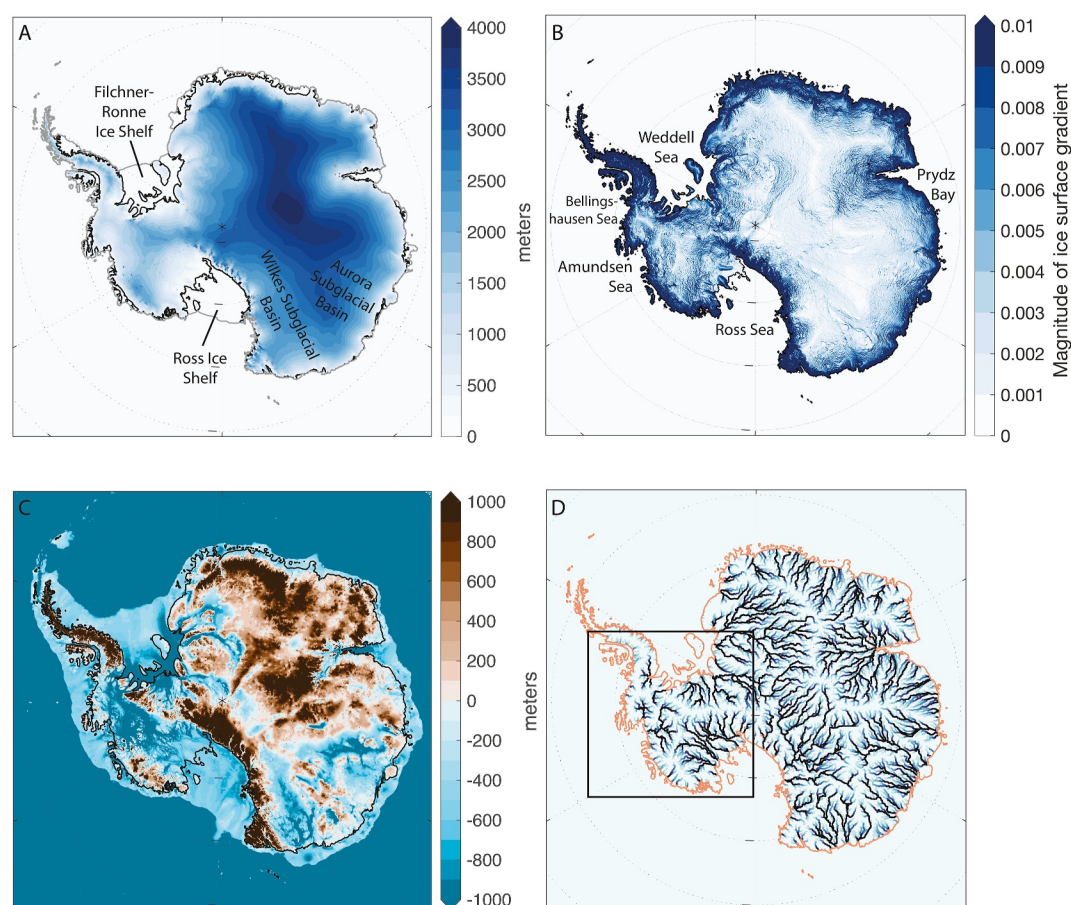


Figure 2. Present-Day Antarctic Ice Sheet and Bedrock Characteristics. (a) Ice surface elevation (m), (b) the magnitude of ice surface gradient (m m^{-1}), (c) bedrock elevation (m), and (d) inferred subglacial water flow paths across Antarctica. The box in (d) shows the area considered in Figures 4 and 7. Ice thickness, surface slope and bedrock topography are taken from BedMachine Antarctica (Morlighem et al., 2020). The black contour in panels (a)–(c) and orange contour in (d) correspond to the present day grounding line. The gray contour in panel (a) shows the edge of floating ice. Routing paths are computed as described in the text.

Information S1 for a visual representation of the steps taken). Specifically, the simulations are prescribed an arbitrary but consistent threshold value of water flow accumulation that defines whether or not a subglacial drainage pathway would be present at a given location, resulting in a field of 0 and 1 s. These fields (10 of them for 10 topographic realizations) are then added together to form a heat map in order to assess levels of consistency in the computed flow paths such that, in the result, values represent the frequency of flow path occurrence across the ensemble.

3. Results

3.1. Changes in Subglacial Flow Paths From LGM to Present Day

Figure 2 shows maps of present-day ice height, surface slope, bed topography, as well as subglacial drainage pathways computed following the procedure discussed above. While subglacial hydrology is significantly more sensitive to surface slope than the bed slope (Shreve, 1972), the magnitude of the former is significantly smaller (except for at the ice margins) relative to the magnitude and scale of variability in the latter (Figure 2b). The routing calculation yields major outflow into the Ross, Ronne and Amundsen Sea sectors of West Antarctica, as well as ocean-ward of the Wilkes and Aurora Subglacial Basins and Prydz Bay (Figure 2d).

The simulated topography changes from LGM to present day based on the G18 model is shown in Figure 3a. This map highlights the variation in bedrock topography associated with the local GIA process. The reconstructed

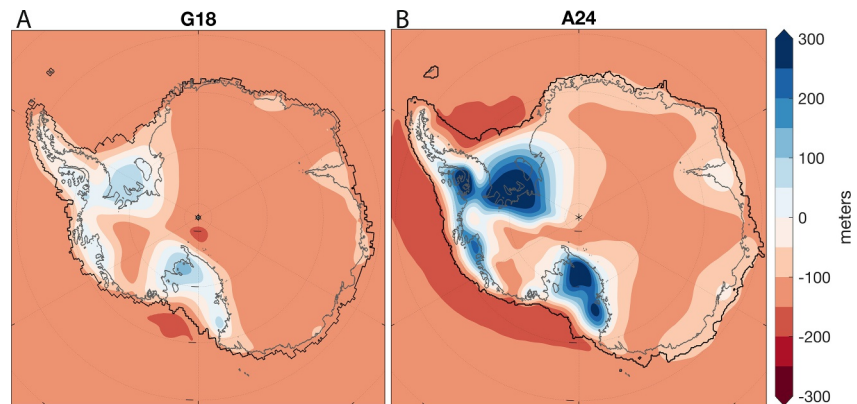


Figure 3. Change in the bed elevation (m) from LGM to Present-Day. (a) Change in topography (present day minus LGM topography) calculated from the G18 model (Gomez et al., 2018). (b) As in (a), but computed with the A24 model (Albrecht et al., 2024). Black contours show the extent of the ice sheet at the LGM for each model, while gray contours show the present-day grounding line.

bedrock elevation is characterized by three local peaks of post-glacial uplift in West Antarctica: ~ 115 m near the grounding line of the Ross Ice Shelf, ~ 93 m landward of the Filchner-Ronne Ice Shelf, and ~ 50 m along the Amundsen Sea coastline. In the interior of West Antarctica, a peak subsidence of ~ 130 m is predicted within Marie Byrd Land, at the periphery of the three zones of uplift. Thus, as an example, an up-toward-the-coast tilt of magnitude ~ 250 m is predicted over a distance of ~ 900 km from Marie Byrd Land to the Ross Sea coastline since the LGM due to GIA. More subdued tilting of bedrock is predicted over East Antarctica.

The bedrock elevation reconstructed with the A24 model (Figure 3b) is broadly similar to the results of the G18 model (Figure 3a). The A24 results are characterized by uplift in the same areas as those evident in the G18 model results: the Ross Ice Shelf, the grounding line of the Filchner-Ronne Ice Shelf, the Bellingshausen Sea, and the Amundsen coast. However, the magnitude of uplift obtained with the A24 model is much larger. Over the Ross Ice Shelf and the Bellingshausen Sea, the uplift peaks at ~ 400 m, and over the present-day grounding line of the Filchner-Ronne Ice Shelf the peak is ~ 350 m. The subsidence outside the West Antarctic Ice Sheet and in Marie Byrd Land reaches ~ 200 and ~ 150 m, respectively. Thus, the results for the A24 GIA model are characterized by a greater magnitude of topographic deflection than the G18 model, and therefore a greater regional tilt.

Figure 4 shows reconstructions of subglacial flow paths in the boxed area in Figure 2d in West Antarctica at present day, and the two cases mentioned above that are based on reconstructions of topography at the LGM. As

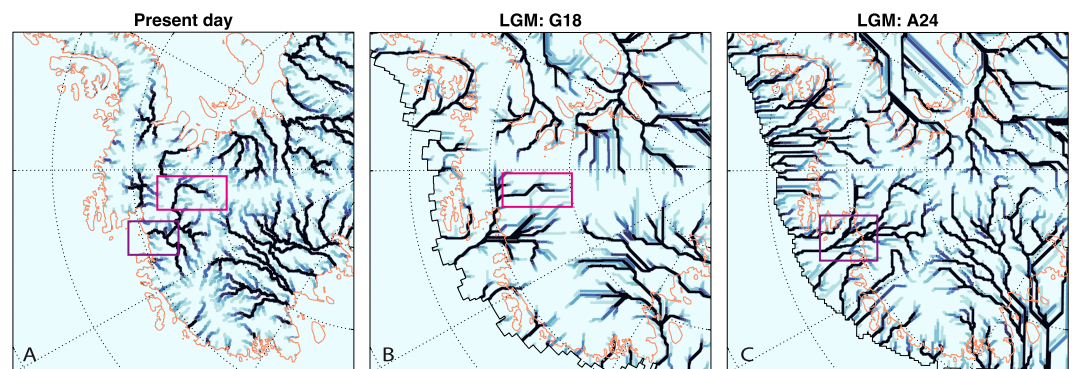


Figure 4. Subglacial Flow Paths in West Antarctica. (a) Present-day subglacial flow paths as shown in Figure 2d, but focused on the West Antarctic region. (b) Reconstructed LGM subglacial flow paths in West Antarctica computed from the G18 model (Gomez et al., 2018). (c) As in (b), but computed with the A24 model (Albrecht et al., 2024). The black contours in frames (b) and (c) correspond to the location of the grounding line at the LGM for the associated model, while the orange contour in all three frames shows the present day grounding line. Pink and purple boxes highlight areas where LGM paths differ from present day paths.

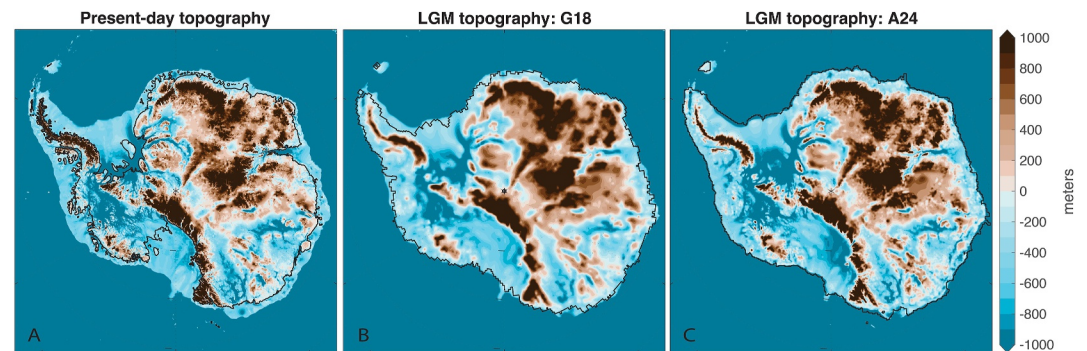


Figure 5. Bedrock elevation (m) at (a) present day, (b) the LGM using the G18 model (Gomez et al., 2018), and (c) the LGM using the A24 model (Albrecht et al., 2024). The black contours correspond to the location the grounding line. Note that the colors are saturated.

Figures 4a–4c show, flow paths at the LGM across the two ice models as well as between these reconstructions and the present-day flow paths are different. For example, the results based on ice history G18 show a significantly less dense path structure than the analogous results for A24. This is likely due to the lower resolution of both the bed topography and the G18 model. Moreover, a detailed inspection shows that the reconstructed flow paths in Figures 4b and 4c have less sinuosity when compared to the present day flow paths. This is most likely due to the smoothness of the bed topography and ice surface in the LGM reconstructions (Figures 5 and 6), an aspect that we will explore in more detail in the following section. The differences between flow paths calculated with G18 and A24 demonstrate that reconstructions of subglacial flow paths are highly dependent on the reconstruction of both bed topography and ice sheet surfaces.

At the LGM, the hydrological systems under the Pine Island and Thwaites glaciers differ from the present day hydrological systems in both the G18 and A24 models. In G18, one of the paths that flows toward the Thwaites glacier at present day instead flows toward the Pine Island glacier at the LGM (Figures 4a and 4b, pink boxes). In the A24 model, the flow paths that converge on the Thwaites glacier at present split off into two outlets at the present-day grounding line, and only converge further out toward the ocean at the LGM (Figures 4a and 4c, purple boxes). Another difference can be seen at the Siple Coast ice streams, where the overall direction of the flow paths has shifted in the A24 reconstruction, relative to the present day flow paths.

3.2. The Relative Importance of Ice Surface Slope and Bed Topography

We then assess the sensitivity of modeled subglacial flow paths to uncertainties in bed topography. Figure 7 shows the combined subglacial flow paths computed with 10 topographic realizations at present day and at the LGM. A comparison of the three panels shows that the reconstructed LGM flow paths are more sensitive to topographic roughness than the present-day calculations. This is likely due to a combination of the smoother LGM bedrock topographies in the reconstructions, which is in part controlled by the resolution of the coupled ice sheet and GIA model, as well as the smoother ice surface at the LGM (see Figure 6). The A24 model has both a smoother ice surface (Figure 6) and a rougher bed topography (Figure 5) when compared to G18, but since the A24 ice is thicker, it is overall less sensitive to topographic roughness.

We also note that for the LGM reconstructions, and especially the A24 model, drainage exits at the grounding line can vary significantly due to topographic uncertainty. This is possibly due to the larger ice thickness in the A24 model, when compared to G18, which translates to a steeper ice surface slope at the ice margins (Figure 6d). Due to the steeper ice surface slope, water that has been diverted by topographic noise would then follow a route more dictated by the ice surface. This is in comparison to G18, where the ice surface slope may be less dominant and therefore topographic noise would only lead to smaller diversions.

In order to evaluate the impacts on subglacial hydrology of changes in ice surface slope and changes in bedrock topography separately, we calculated flow paths at the LGM using present day ice surface elevation but LGM bed topography reconstructed using the G18 and A24 models (Figure 8). The reconstructed flow paths with LGM topography (Figures 8b and 8c) are visually much more similar to the present-day subglacial flow paths than the equivalent shown in Figures 4b and 4c. This visual comparison is confirmed by the calculation of correlation

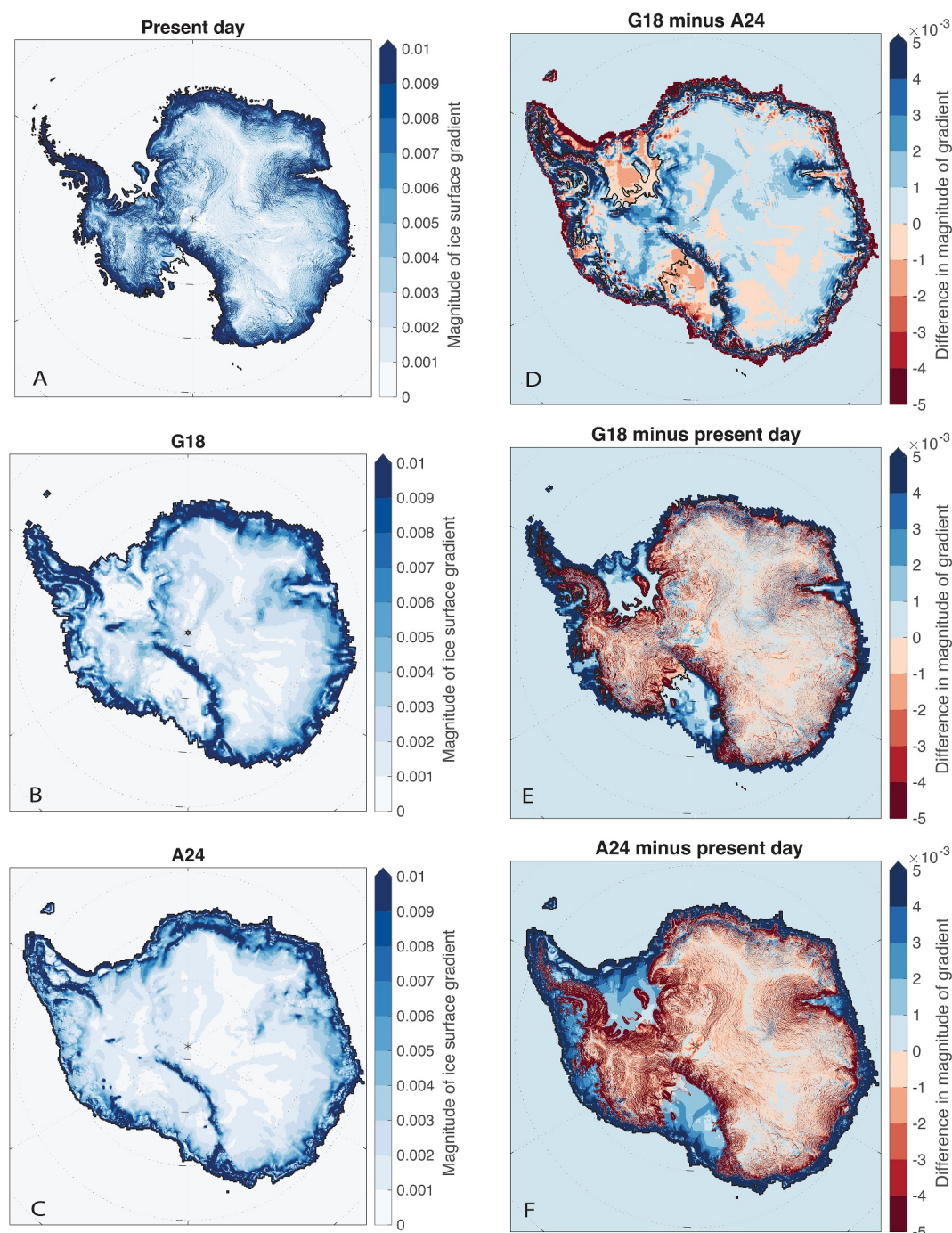


Figure 6. Magnitude of ice surface gradients (m m^{-1}). (a) Present day. (b) At LGM from the G18 model (Gomez et al., 2018). (c) As in (b), but taken from the A24 model (Albrecht et al., 2024). (d) Difference between panels (b) and (c). (e) Difference between panels (b) and (a). (f) Difference between panels (c) and (a).

coefficients. After defining each location as having flow or not, as was done for Figures 7 and 9, we compute the correlation coefficient between the LGM and present day flow paths. In Figure 4, when LGM flow paths are computed with LGM ice reconstructions, the correlation coefficient between present day (Figure 4a) and the G18 flow paths (Figure 4b) is 0.149, and the correlation coefficient between present day (Figure 4a) and the A24 flow paths (Figure 4c) is 0.204. When the LGM flow paths are instead calculated with the same ice surface as present day flow paths (Figure 8), the correlation coefficient between present day (Figure 8a) and the G18 flow paths

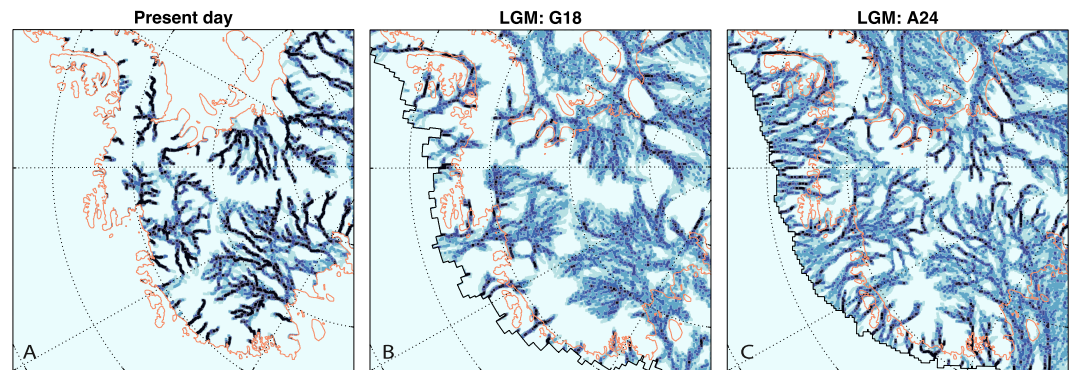


Figure 7. Sensitivity of computed subglacial flow paths to realistic topographic roughness. Each panel is computed by stacking computed subglacial flow paths calculated from 10 different topographic realizations. The darkest blue corresponds to locations where 6 or more of the 10 models have flow. (a) Sensitivity of computed present-day flow paths to topographic noise, computed from present-day topography and ice thickness from BedMachine Antarctica (Morlighem et al., 2020). (b–c) Sensitivity of reconstructed subglacial flow paths to topographic noise, computed at the LGM using (b) the G18 model (Gomez et al., 2018), and (c) the A24 model (Albrecht et al., 2024). The orange contour in all frames corresponds to the location of the present day grounding line, while the black contour in (b) and (c) correspond to the grounding line of the associated LGM reconstruction.

(Figure 8b) is 0.296, and the correlation coefficient between present day (Figure 8a) and the A24 flow paths (Figure 8c) is 0.241.

This increased similarity between LGM and present day flow paths when the ice surface is constant suggests that, as expected, ice surface slope exerts a strong influence on subglacial flow paths, and the less sinuous flow paths in Figures 4b and 4c are largely a consequence of the smoother modeled LGM ice surfaces (Figure 6). From this, we can infer that the increased sensitivity of LGM flow paths to topographic noise at the bed is also a result of the smoother ice surface (Figure 9).

There are, however, significant differences in Figures 8b and 8c compared to Figure 8a, highlighted in the yellow and red boxes in Figure 8. First, flow paths around the Siple Coast ice streams suggest a reorganization with LGM topography relative to present day topography, with some changes in flow path length and directions (red boxes). Second, upstream of the Filchner-Ronne ice shelf, a subglacial flow path that connects to the flow paths coincident with the Thwaites glacier at present day, connects instead to a flow path that exits at the Filchner-Ronne ice shelf in the LGM reconstructions (yellow boxes). These changes in subglacial flow paths even with an unchanging ice surface demonstrate that the changes in subglacial flow paths from LGM to present day seen in

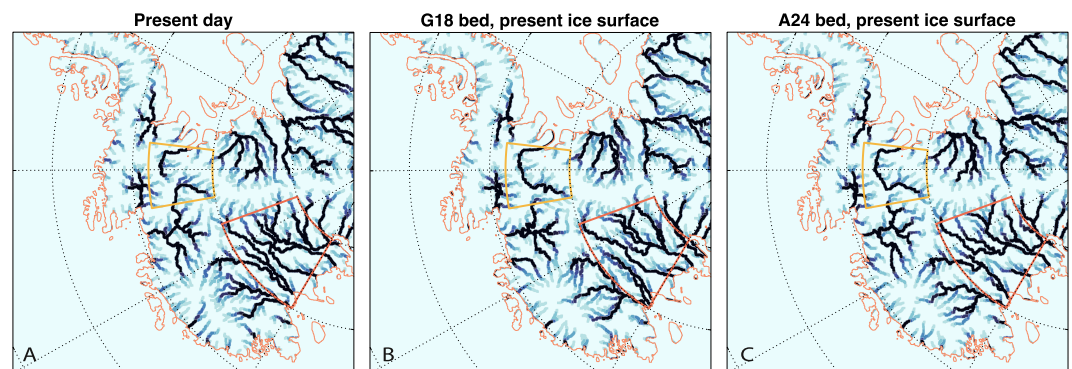


Figure 8. Calculated Subglacial Flow Paths with present-day ice surface. (a) Present-day flow paths computed from present-day bedrock topography and ice surface slope from BedMachine Antarctica (Morlighem et al., 2020)—reproduced from Figure 4a. (b) Flow paths calculated using present day ice surface from BedMachine Antarctica and LGM bedrock topography from the G18 model (Gomez et al., 2018). (c) As in (b), but with LGM bedrock topography from the A24 model (Albrecht et al., 2024). Red and yellow boxes in both panels highlight two areas where subglacial flow paths in (b) and (c) have changed relative to (a).

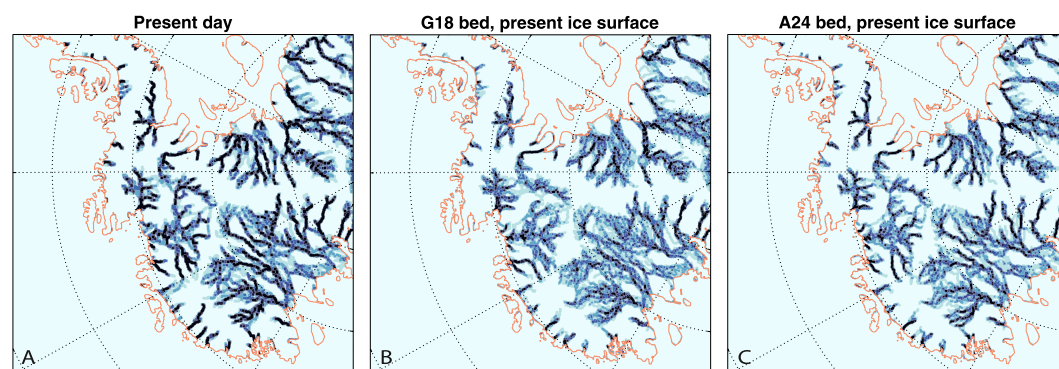


Figure 9. Sensitivity of flow paths to topographic noise with unchanged ice surface. (a) Sensitivity of computed present-day flow paths to topographic noise, computed from present-day topography and ice thickness from BedMachine (Morlighem et al., 2020). Reproduced from Figure 7a. (b) Sensitivity of computed flow paths to topographic noise, computed from present day ice surface and G18 bed topography at the LGM (Gomez et al., 2018). (c) As in (b), but bed topography is from the A24 model (Albrecht et al., 2024).

Figure 4 are not purely a result of changes in ice surface slope, but that changes in bedrock topography due to GIA also contribute to establishing flow paths.

4. Discussion

Our analysis indicates that areas in which subglacial paths are rerouted in our results tend to be adjacent to areas of large uplift in the GIA models (Figure 3), and consequently coincide with large changes in the basal slope. For instance, in Figure 4, large changes in flow paths occur in the Pine Island and Thwaites glaciers catchments, as well as the catchment areas of the Siple Coast ice streams. These results suggest that a number of processes impact the ice discharge through the fast-flowing ice streams into the oceans, such as changes in the bed elevation, subglacial hydrology and their interactions with the ice flow.

Our models suggest that, assuming sediment is being transported along the subglacial drainage pathways, GIA-driven changes in these flow paths may therefore also be reflected in sediment records. Thus it may be worthwhile to investigate whether our modeled hydrological shifts can be correlated to changes in sediment provenance during post-LGM retreat, as reflected in offshore cores (e.g., Kirshner et al., 2012). For instance, we found that the modeled hydrological systems under the Pine Island and Thwaites glaciers differ from the present day hydrological systems in both the G18 and A24 models. This finding is consistent with marine sediment core data from Pine Island Bay which suggests that the meltwater conditions and sediments provenance shifted during the late Holocene (Kirshner et al., 2012; Witus et al., 2014).

A more detailed investigation into Pine Island Bay, and other regions with sediment provenance studies, could provide more insight into how the subglacial hydrological system evolved and how this may be reflected in the geological record. Future work on this topic should also investigate whether reconstructed flow channels correspond with any existing offshore paleo channels (e.g., Napoleoni et al., 2020).

Comparing the modeling results to sediment provenance studies and offshore paleo channels would provide a test of the ability of geophysical modeling to capture important aspects of the evolving hydrological system and provide further insight into the impact of the ongoing GIA process on bed topography, the associated subglacial hydrological system, and, most importantly, the feedback of this intimately coupled system on the future evolution of the AIS.

5. Conclusions

In this study, ice sheet models (Albrecht et al., 2024; Gomez et al., 2018) were used to reconstruct ancient Antarctic bed topography, and estimate the hydraulic potential at the LGM. As shown in Pan et al. (2021), the low viscosity and thin lithosphere beneath the West Antarctic Ice Sheet contribute to particularly rapid postglacial rebound, and thus changes to bedrock topography occur quickly and are of large amplitude. The reconstructions of bedrock topography were used to calculate the degree to which the GIA process may have impacted subglacial

hydrological flow paths from the LGM to present day. The sensitivity of our results to uncertainties in bedrock topography was explored by repeating our calculations with 10 different topographic realizations generated by adding roughness of spatial scale and amplitude consistent with estimates from the radar measurements across the AIS.

Our results show that the reconstructed flow paths at the LGM are relatively sensitive to topographic roughness at the bed of the ice sheet due to the smoother ice surface and bedrock topography in the LGM reconstructions. We also find that the impact of GIA on subglacial flow paths is non-negligible, but highly dependent on the reconstruction of both bed topography and ice sheet surface slopes. Both these conclusions highlight the necessity of properly accounting for topographic uncertainties in reconstructions of subglacial hydrology. Overall, it is important for GIA to be accounted for in reconstructions of ancient subglacial hydrology as subglacial water may influence the evolution of the overlying ice sheet. If models of past ice behavior are to be used to understand modern and future behavior, then it is important to understand the history of ice loading and water drainage, and recognize the sensitivity to adopted surface and bedrock slopes.

Acronyms

GIA	Glacial isostatic adjustment
LGM	Last Glacial Maximum
AIS	Antarctic Ice Sheet
GMSL	Global mean sea level

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Availability Statement

All data and code necessary to reproduce the results in this paper are available at the associated Zenodo repository (Pan et al., 2025). The ice histories adopted in this study are available in Gomez et al. (2018) and Albrecht et al. (2024). Calculations of subglacial flow paths were done with Antarctic Mapping Tools (Greene et al., 2017) and TopoToolbox (Schwanghart & Scherler, 2014).

Acknowledgments

L.P. is supported by the Fonds de recherche du Québec–Nature et technologies, Natural Sciences and Engineering Research Council of Canada, and Harvard University. E.J.M. is supported by NSF award 2324092. J.X.M. is supported by Harvard University and the MacArthur Foundation. R.P.A.Jr. and J.X.M. are supported by NSF Office of Polar Programs (1744927). L.P. and O.S. are supported by Award NA23OAR4320198 from the National Oceanic and Atmospheric Administration, U.S. Department of Commerce. The statements, findings, conclusions, and recommendations are those of the authors and do not necessarily reflect the views of the National Oceanic and Atmospheric Administration, or the U.S. Department of Commerce. We thank Ann Pearson for the helpful discussions.

References

- Albrecht, T., Bagge, M., & Klemann, V. (2024). Feedback mechanisms controlling Antarctic glacial-cycle dynamics simulated with a coupled ice sheet–solid Earth model. *The Cryosphere*, 18(9), 4233–4255. (TC). <https://doi.org/10.5194/tc-18-4233-2024>
- An, M., Wiens, D. A., Zhao, Y., Feng, M., Nyblade, A., Kanao, M., et al. (2015). Temperature, lithosphere–asthenosphere boundary, and heat flux beneath the Antarctic Plate inferred from seismic velocities. *Journal of Geophysical Research: Solid Earth*, 120(12), 8720–8742. <https://doi.org/10.1002/2015jb011917>
- Argus, D. F., Peltier, W. R., Drummond, R., & Moore, A. W. (2014). The Antarctica component of postglacial rebound model ICE-6G_C (VM5a) based on GPS positioning, exposure age dating of ice thicknesses, and relative sea level histories. *Geophysical Journal International*, 198(1), 537–563. <https://doi.org/10.1093/gji/ggu140>
- Bagge, M., Klemann, V., Steinberger, B., Latinović, M., & Thomas, M. (2021). Glacial-isostatic adjustment models using geodynamically constrained 3D Earth structures. *Geochemistry, Geophysics, Geosystems*, 22(11), e2021GC009853. <https://doi.org/10.1029/2021GC009853>
- Bell, R. E. (2008). The role of subglacial water in ice-sheet mass balance. *Nature Geoscience*, 1(5), 297–304. <https://doi.org/10.1038/ngeo186>
- Bueler, E., & Brown, J. (2009). Shallow shelf approximation as a “sliding law” in a thermomechanically coupled ice sheet model. *Journal of Geophysical Research*, 114(F3). <https://doi.org/10.1029/2008JF001179>
- Clark, P. U., Dyke, A. S., Shakun, J. D., Carlson, A. E., Clark, J., Wohlfarth, B., et al. (2009). The Last Glacial Maximum. *Science*, 325(5941), 710–714. <https://doi.org/10.1126/science.1172873>
- Dow, C. F. (2023). The role of subglacial hydrology in Antarctic ice sheet dynamics and stability: A modelling perspective. *Annals of Glaciology*, 63(87–89), 1–6. <https://doi.org/10.1017/aog.2023.9>
- Frémand, A. C., Fretwell, P., Bodart, J. A., Pritchard, H. D., Aitken, A., Bamber, J. L., et al. (2023). Antarctic Bedmap data: Findable, accessible, interoperable, and reusable (FAIR) sharing of 60 years of ice bed, surface, and thickness data. *Earth System Science Data*, 15(7), 2695–2710. <https://doi.org/10.5194/essd-15-2695-2023>
- Gomez, N., Latychev, K., & Pollard, D. (2018). A coupled ice sheet–sea level model incorporating 3D Earth structure: Variations in Antarctica during the last deglacial retreat. *Journal of Climate*, 31(10), 4041–4054. <https://doi.org/10.1175/jcli-d-17-0352.1>
- Gomez, N., Pollard, D., & Mitrovica, J. X. (2013). A 3-D coupled ice sheet–Sea level model applied to Antarctica through the last 40 ky. *Earth and Planetary Science Letters*, 384, 88–99. <https://doi.org/10.1016/j.epsl.2013.09.042>

- Gomez, N., Yousefi, M., Pollard, D., DeConto, R. M., Sadai, S., Lloyd, A., et al. (2024). The influence of realistic 3D mantle viscosity on Antarctica's contribution to future global sea levels. *Science Advances*, 10(31), eadn1470. <https://doi.org/10.1126/sciadv.adn1470>
- Grand, S. P. (2002). Mantle shear-wave tomography and the fate of subducted slabs. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 360(1800), 2475–2491. <https://doi.org/10.1098/rsta.2002.1077>
- Greene, C. A., Gwyther, D. E., & Blankenship, D. D. (2017). Antarctic mapping tools for Matlab. *Computers & Geosciences*, 104(C), 151–157. <https://doi.org/10.1016/j.cageo.2016.08.003>
- Hay, C. C., Lau, H. C. P., Gomez, N., Austermann, J., Powell, E., Mitrovica, J. X., et al. (2017). Sea level fingerprints in a region of complex Earth structure: The case of WAIS. *Journal of Climate*, 30(6), 1881–1892. <https://doi.org/10.1175/jcli-d-16-0388.1>
- Heeszel, D. S., Wiens, D. A., Anandakrishnan, S., Aster, R. C., Dalziel, I. W. D., Huerta, A. D., et al. (2016). Upper mantle structure of Central and West Antarctica from array analysis of Rayleigh wave phase velocities. *Journal of Geophysical Research: Solid Earth*, 121(3), 1758–1775. <https://doi.org/10.1002/2015jb012616>
- Ivins, E. R., & James, T. S. (2005). Antarctic glacial isostatic adjustment: A new assessment. *Antarctic Science*, 17(4), 541–553. <https://doi.org/10.1017/s0954102005002968>
- Kirchner, A. E., Anderson, J. B., Jakobsson, M., O'Regan, M., Majewski, W., & Nitsche, F. O. (2012). Post-LGM deglaciation in Pine Island Bay, West Antarctica. *Quaternary Science Reviews*, 38, 11–26. <https://doi.org/10.1016/j.quascirev.2012.01.017>
- Lambeck, K., Rouby, H., Purcell, A., Sun, Y., & Sambridge, M. (2014). Sea level and global ice volumes from the Last Glacial Maximum to the Holocene. *Proceedings of the National Academy of Sciences*, 111(43), 15296–15303. <https://doi.org/10.1073/pnas.1411762111>
- Latychev, K., Mitrovica, J. X., Tromp, J., Tamisiea, M. E., Komatitsch, D., & Christara, C. C. (2005). Glacial isostatic adjustment on 3-D Earth models: A finite-volume formulation. *Geophysical Journal International*, 161(2), 421–444. <https://doi.org/10.1111/j.1365-246X.2005.02536.x>
- MacKie, E. J., Field, M., Wang, L., Yin, Z., Schoedl, N., Hibbs, M., & Zhang, A. (2023). GStatSim V1.0: A Python package for geostatistical interpolation and conditional simulation. *Geoscientific Model Development*, 16(13), 3765–3783. <https://doi.org/10.5194/gmd-16-3765-2023>
- MacKie, E. J., Schroeder, D. M., Zuo, C., Yin, Z., & Caers, J. (2021). Stochastic modeling of subglacial topography exposes uncertainty in water routing at Jakobshavn Glacier. *Journal of Glaciology*, 67(261), 75–83. <https://doi.org/10.1017/jog.2020.84>
- Mälicke, M. (2022). SciKit-GStat 1.0: A SciPy-flavored geostatistical variogram estimation toolbox written in Python. *Geoscientific Model Development*, 15(6), 2505–2532. <https://doi.org/10.5194/gmd-15-2505-2022>
- Matheron, G. (1963). Principles of geostatistics. *Economic Geology*, 58(8), 1246–1266. <https://doi.org/10.2113/gsecongeo.58.8.1246>
- Morlighem, M., Rignot, E., Binder, T., Blankenship, D., Drews, R., Eagles, G., et al. (2020). Deep glacial troughs and stabilizing ridges unveiled beneath the margins of the Antarctic ice sheet. *Nature Geoscience*, 13(2), 132–137. <https://doi.org/10.1038/s41561-019-0510-8>
- Müller, S., Schüler, L., Zech, A., & Heße, F. (2022). GSTools v1.3: A toolbox for geostatistical modelling in Python. *Geoscientific Model Development*, 15(7), 3161–3182. <https://doi.org/10.5194/gmd-15-3161-2022>
- Nakada, M., Kimura, R., Okuno, J., Moriwaki, K., Miura, H., & Maemoku, H. (2000). Late Pleistocene and Holocene melting history of the Antarctic ice sheet derived from sea-level variations. *Marine Geology*, 167(1–2), 85–103. [https://doi.org/10.1016/s0025-3227\(00\)00018-9](https://doi.org/10.1016/s0025-3227(00)00018-9)
- Napoleoni, F., Jamieson, S. S. R., Ross, N., Bentley, M. J., Rivera, A., Smith, A. M., et al. (2020). Subglacial lakes and hydrology across the Ellsworth Subglacial Highlands, West Antarctica. *The Cryosphere*, 14(12), 4507–4524. (TC). <https://doi.org/10.5194/tc-14-4507-2020>
- Pan, L., MacKie, E., Mitrovica, J., Jamieson, S., Sergienko, O., Ackert, R., & McColl, K. (2025). Impacts of glacial isostatic adjustment on subglacial water routing since the Last Glacial Maximum—Data [Dataset]. *Zenodo*. <https://doi.org/10.5281/zenodo.17517506>
- Pan, L., Powell, E. M., Latychev, K., Mitrovica, J. X., Creveling, J. R., Gomez, N., et al. (2021). Rapid postglacial rebound amplifies global sea level rise following West Antarctic Ice Sheet collapse. *Science Advances*, 7(18), eabf7787. <https://doi.org/10.1126/sciadv.abf7787>
- Peltier, W. R. (2004). Global glacial isostasy and the surface of the ice-age Earth: The ICE-5G (VM2) model and GRACE. *Annual Review of Earth and Planetary Sciences*, 32(1), 111–149. <https://doi.org/10.1146/annurev.earth.32.082503.144359>
- Peltier, W. R., Argus, D. F., & Drummond, R. (2015). Space geodesy constrains ice age terminal deglaciation: The global ICE-6G_C (VM5a) model. *Journal of Geophysical Research: Solid Earth*, 120(1), 450–487. <https://doi.org/10.1002/2014jb011176>
- Pollard, D., & DeConto, R. M. (2012). Description of a hybrid ice sheet-shelf model, and application to Antarctica. *Geoscientific Model Development*, 5(5), 1273–1295. <https://doi.org/10.5194/gmd-5-1273-2012>
- Schaeffer, A. J., & Lebedev, S. (2013). Global shear speed structure of the upper mantle and transition zone. *Geophysical Journal International*, 194(1), 417–449. <https://doi.org/10.1093/gji/ggt095>
- Schoof, C. (2007). Ice sheet grounding line dynamics: Steady states, stability, and hysteresis. *Journal of Geophysical Research*, 112(F3). <https://doi.org/10.1029/2006JF000664>
- Schwanghart, W., & Scherler, D. (2014). Short communication: TopoToolbox 2—MATLAB-based software for topographic analysis and modeling in Earth surface sciences. *Earth Surface Dynamics*, 2(1), 1–7. <https://doi.org/10.5194/esurf-2-1-2014>
- Sergienko, O. (2022). Marine outlet glacier dynamics, steady states and steady-state stability. *Journal of Glaciology*, 68(271), 946–960. <https://doi.org/10.1017/jog.2022.13>
- Sergienko, O., & Wingham, D. J. (2024). Diverse behaviors of marine ice sheets in response to temporal variability of the atmospheric and basal conditions. *Journal of Glaciology*, 70, e52. <https://doi.org/10.1017/jog.2024.43>
- Shepherd, A., Ivins, E. R., A. G., Barletta, V. R., Bentley, M. J., Bettadpur, S., et al. (2012). A reconciled estimate of ice-sheet mass balance. *Science*, 338(6111), 1183–1189. <https://doi.org/10.1126/science.1228102>
- Shreve, R. L. (1972). Movement of water in glaciers. *Journal of Glaciology*, 11(62), 205–214. <https://doi.org/10.3189/s002214300002219x>
- Stearns, L. A., Smith, B. E., & Hamilton, G. S. (2008). Increased flow speed on a large East Antarctic outlet glacier caused by subglacial floods. *Nature Geoscience*, 1(12), 827–831. <https://doi.org/10.1038/ngeo356>
- Whitehouse, P. L., Bentley, M. J., Milne, G. A., King, M. A., & Thomas, I. D. (2012). A new glacial isostatic adjustment model for Antarctica: Calibrated and tested using observations of relative sea-level change and present-day uplift rates. *Geophysical Journal International*, 190(3), 1464–1482. <https://doi.org/10.1111/j.1365-246X.2012.05557.x>
- Whitehouse, P. L., Gomez, N., King, M. A., & Wiens, D. A. (2019). Solid Earth change and the evolution of the Antarctic Ice Sheet. *Nature Communications*, 10(1), 503. <https://doi.org/10.1038/s41467-018-08068-y>
- Winkelmann, R., Martin, M. A., Haseloff, M., Albrecht, T., Bueler, E., Khroulev, C., & Levermann, A. (2011). The Potsdam Parallel Ice Sheet Model (PISM-PIK)—Part 1: Model description. *The Cryosphere*, 5(3), 715–726. (TC). <https://doi.org/10.5194/tc-5-715-2011>
- Witus, A. E., Branecky, C. M., Anderson, J. B., Szczuciński, W., Schroeder, D. M., Blankenship, D. D., & Jakobsson, M. (2014). Meltwater intensive glacial retreat in polar environments and investigation of associated sediments: Example from Pine Island Bay, West Antarctica. *Quaternary Science Reviews*, 85, 99–118. <https://doi.org/10.1016/j.quascirev.2013.11.021>
- Zuo, C., Yin, Z., Pan, Z., MacKie, E. J., & Caers, J. (2020). A tree-based direct sampling method for stochastic surface and subsurface hydrological modeling. *Water Resources Research*, 56(2), e2019WR026130. <https://doi.org/10.1029/2019wr026130>