https://doi.org/10.5194/egusphere-2026-2172
Preprint. Discussion started: 24 April 2026

West Antarctic Ice Retreat Temporarily Halted with Transient Rheology in Future Climate Projections

Allie N. Coonin[1], B Parazin[2], Harriet C.P. Lau[1], Natalya Gomez[2]

[1]Department of Earth, Environmental, and Planetary Sciences, Brown University, 167 Thayer St., Providence, RI 02912, USA
[2]Department of Earth and Planetary Sciences, McGill University, 3450 University St., Montreal Quebec, Canada H3A 0E8

Correspondence to: Allie N. Coonin (allie_coonin@brown.edu)

Abstract. Projections of sea-level change and Antarctic Ice Sheet (AIS) stability under anthropogenic climate change hinge upon accurately describing physical feedbacks that link ice dynamics (marine and terrestrial) with the gravitational, rotational and deformational response of the solid Earth to ice and ocean loading changes. In turn, the rate of AIS melting can lower the rate of global mean temperature rise, by promoting sea ice growth and amplifying Earth's albedo. The marine West Antarctic Ice Sheet (WAIS) is vulnerable to runaway grounding line retreat. However, the rapid viscoelastic rebound of the bedrock in response to ice retreat has been shown to stabilize its grounding line, aided by the low-viscosity mantle beneath the WAIS. Such bedrock deformation is typically modelled with idealized Maxwell viscoelasticity, despite that rock deformation experiments show that additional "transient" creep mechanisms occur over societally relevant (~decadal-centennial) timescales that are missing from the Maxwell model. Here, we simulate future AIS evolution, coupled with self-consistent solid Earth deformation and sea level change, for various emissions scenarios (RCP 2.6, 4.5, 8.5), incorporating transient deformation. This more complete treatment of solid Earth deformation delays grounding line retreat as compared to Maxwell projections, with differences of tens of kilometres persisting for decades at Pine Island and Thwaites Glaciers. Though transient deformation slows glacier retreat, it is unable to prevent the bulk of ice loss and sea-level rise on longer, centennial timescales. Even still, deviations in AIS meltwater flux with transient deformation could affect the pace of global temperature rise in climate model predictions.

Short Summary. Sea level change and ice sheet stability depend on how Earth's bedrock warps as ice melts. Rock experiments show that traditional models for bedrock deformation leave out important processes relevant for modern ice loss. We simulate the coevolution of the Antarctic ice sheet and global sea level under various climate change scenarios. When more realistic bedrock behavior is considered, Antarctic ice retreat is delayed. Ultimately, this has implications for the rate of global temperature rise.

https://doi.org/10.5194/egusphere-2026-2172
Preprint. Discussion started: 24 April 2026

Main Text

1. Introduction

Predictions of ice sheet and sea-level change in response to various trajectories of atmospheric carbon emissions have demonstrated the potential for dramatic ice retreat in West Antarctica (Deconto & Pollard, 2016; Deconto et al., 2021; Kopp et al., 2017). This vulnerability to extreme ice loss is largely because the bedrock underneath the marine-based West Antarctic Ice Sheet (WAIS) deepens from the margins toward the ice sheet interior, which predisposes the WAIS to runaway retreat via the Marine Ice Sheet Instability (Schoof, 2007; Thomas, 1979; Weertman, 1974). The flux through the grounding line, the location at which the ice sheet begins to float because it is too thin to displace the entire weight of the water column, has strong sensitivity to the thickness of ice at the grounding line (with outflow proportional to ice thickness to the power ~5, Schoof, 2007.) Therefore, on such retrograde bed slopes, even a small perturbation can trigger unstable collapse as the grounding line retreats to a location with deeper bedrock and greater ice thickness. This greater grounding line ice thickness heightens ice loss through the grounding line, promoting continued retreat until the bed begins to slope up or the grounding line becomes pinned on a sill. Grounding line migration is further complicated by time-evolving and highly spatially variable basal conditions due to processes like subglacial water flow and the formation of subglacial landforms, allowing for other possible modes such as irregular oscillations between advance and retreat (Sergienko & Wingham, 2024).

By nature of this dependence on bedrock topography and slope, marine ice sheet retreat is a critical avenue for dynamical feedback between ice sheet evolution and solid Earth deformation and sea level (e.g., Gomez et al., 2010). The redistribution of ice and ocean over Earth's surface in response to an evolving climate will induce gravitational, rotational, and deformational effects on the solid Earth, collectively termed Glacial Isostatic Adjustment (GIA), which modify the timing and pattern of sea level and bedrock elevation change (Mitrovica et al., 2001). Through the Marine Ice Sheet Instability mechanism discussed above, when sea level rises at a marine grounding line (e.g. from far-field ice loss), this will accelerate ice loss across the grounding line and promote grounding line retreat. On the other hand, local ice loss drives local sea level fall due to solid Earth uplift and gravitational drawdown of the sea surface, which slows ice loss and stabilizes the grounding line (Barletta et al., 2018; Gomez et al., 2015; Larour et al., 2019). Changes in bedrock elevation from GIA can also impact ice sheet mass balance through modulation of ice surface temperature, with the potential to reduce surface melting and/or increase the amount of precipitation that falls as snow, aiding in mass accumulation (Zeitz et al., 2022). Studies investigating such feedbacks between solid Earth deformation, sea level, and ice sheet evolution have suggested that the coupling acts to reduce changes in ice volume over timescales of full glacial cycles (Abe-Ouchi et al., 2013; Gomez et al., 2013; Han et al., 2021).

The calculation of gravitationally self-consistent sea-level change due to the redistribution of ice and ocean mass at Earth's surface and consequently, its potential to influence ice sheet evolution, is contingent on the deformational response of the solid Earth. Typically, GIA models assume an idealized linear viscoelastic Maxwell rheology, which deforms by an instantaneous and fully recoverable elastic response and a delayed, irrecoverable viscous response, characterized by the mantle's elastic modulus and viscosity. The viscous response of a mantle with higher viscosity will be delayed longer. For such deformation, the

https://doi.org/10.5194/egusphere-2026-2172
Preprint. Discussion started: 24 April 2026

characteristic timescale of viscoelastic deformation is known as the so-called Maxwell time, τ_M (defined simply by the ratio between a material's viscosity to its elastic modulus). Intuitively, any surface loading changes will induce viscoelastic deformation over timescales $\approx \tau_M$. For rapid changes where loading timescales are $\ll \tau_M$, elastic deformation dominates and oftentimes deformation is modelled with an entirely elastic mantle. For ice mass changes associated with modern climate change, this is often the case since τ_M for the bulk mantle ranges between approximately 500 to 10,000 years (K. Hansen et al., 2021; Spada et al., 2012; Whitehouse et al., 2012). In contrast, the full viscoelastic response is modelled in the case of GIA over ice age cycles (with timescales of 1000s to 10,000s of years). In locations like West Antarctica, however, the underlying mantle is characterized by relatively low mantle viscosity with $\tau_M \approx 10$ to 100 years (Barletta et al., 2018; Lloyd et al., 2020; Lucas et al., 2024), and such an assumption of mantle elasticity cannot be made. And thus, even for some modern cases, the viscoelastic deformation must be accounted for. To account for both Maxwell viscoelasticity and the large geographical variations in mantle viscosity, recent studies developed coupled models of future Antarctic ice sheet and sea level evolution that incorporate lateral variations in Earth's viscosity structure (Gomez et al., 2024; van Calcar et al., 2025). While they assume Maxwell viscoelastic Earth rheology, Gomez et al. (2024) demonstrated that the consideration of 3D Earth structure could reduce the Antarctic global mean sea level (GMSL) contribution by 2500 relative to that predicted with radially symmetric Earth structure by up to 40%.

In this paper, we argue that even Maxwell viscoelasticity is insufficient to characterize solid Earth deformation, especially on modern (decadal to centennial) timescales. Evidence for this largely stems from the rock physics community, where experiments confirm that non-elastic deformation mechanisms are activated even across these timescales (decadal to centennial) and beyond (e.g., Faul & Jackson, 2011; Gribb & Cooper, 1998; McCarthy et al., 2011; Yamauchi & Takei, 2016). The associated strains of such models are non-instantaneous, but recoverable, and we will collectively term such models as transient models (Havlin et al., 2021; Lau et al., 2021). Indeed, by incorporating a variety of transient models, a growing body of literature has demonstrated the importance of moving away from Maxwell viscoelasticity on decadal-centennial ice mass changes in several contexts (e.g. Adhikari et al., 2021; Coonin et al., 2025, Ivins et al., 2023; Lau, 2024).

The elastic, transient viscous, and Maxwell steady state components of strain add together to describe the total deformation response. Hence, if the Earth is more compliant over shorter timescales, regardless of the assumed viscosity structure of the mantle, the magnitude and timing the solid Earth response to ice and ocean load changes and consequently, sea level and topography will differ by as much as meters (Coonin et al., 2025; Lau, 2023). In particular, decadal to centennial timescales of modern ice loss and potentially even more rapid projections of ice loss into the future will activate these transient deformation mechanisms. However, the effect of transient viscous deformation in coupled simulations of future Antarctic ice evolution has yet to be investigated.

Inspired by the coupled ice sheet and sea-level dynamics study of Gomez et al. (2024) discussed above, which incorporated Maxwell viscoelastic deformation, here we modify their approach by considering transient viscoelastic deformation. While Gomez et al. (2024) showed that laterally varying properties clearly play an important role in coupled global sea level–Antarctic ice sheet evolution, such models with 3D earth structure require significantly greater computational power and we do not take this route, instead opting for 1D (i.e., depth dependent only) mantle viscoelastic structure. Not only is this computationally more feasible, but it also

https://doi.org/10.5194/egusphere-2026-2172
Preprint. Discussion started: 24 April 2026

allows us to isolate the effect that transient deformation alone has in modulating the solid Earth's response to modern timescales of ice loss. In this study, we explore the consequences of incorporating more realistic solid Earth rheology, namely transient rheology, in coupled ice sheet-sea level dynamics. We examine the effect of transient solid Earth rheology on the evolution of the Antarctic ice sheet for various emissions scenarios (RCPs 2.6, 4.5, and 8.5; IPCC, 2014), namely because we expect that transient deformation will be more sensitive to the rates of ice volume changes than a typical Maxwell model over the relevant timescales (decades to centuries).

2. Methods

2.1 Coupled ice sheet-sea level modelling

We run forward simulations of Antarctic Ice Sheet evolution using the PSU 3D ice sheet shelf model (Pollard & Deconto, 2012; Pollard et al., 2015) coupled with solving the 1D gravitationally self-consistent sea-level equation, accounting for gravitational, deformational and rotational effects from glacial isostatic adjustment using the algorithm outlined in Kendall et al. (2005). Within this algorithm, the calculation of deformation routinely adopts Maxwell viscoelastic Earth rheology (Gomez et al., 2015; Han et al., 2022; Pollard et al., 2017), but has more recently been adapted to consider the effects of transient viscoelastic solid Earth rheology (Lau, 2024). To the authors' best knowledge, transient rheology has only been considered in coupled ice sheet–sea level modelling once before and only very recently, where Caron et al. (2025) modify the coupled Ice Sheet–Sea-Level System Model (ISSM) to incorporate the Extended Burgers viscoelastic model (Faul & Jackson, 2015) for solid Earth deformation. Here, we take this further and consider a realistic climate scenario which we describe below.

Required inputs for the ice sheet model are the bedrock topography, basal sliding coefficients, geothermal heat flux, sea-level, and – as just mentioned – air temperature and precipitation outputs from a climate model of the RCP climate projections (IPCC, 2014) as in Gomez et al. (2024) and Deconto et al. (2021). Required inputs for the sea level model include the initial bedrock topography, a prescribed loading history, and the Love numbers corresponding to the chosen radially varying viscoelastic Earth model (see Fig. S2; Kendall et al., 2005). Love number theory is a Green function approach to determining the viscoelastic deformation of the solid Earth and the Earth's gravity field, given a surface load history. The ice sheet and sea-level models communicate via offline coupling with a timestep of 10 years. That is, under the prescribed climate forcing, the ice sheet model runs with the specified internal time-stepping (here set to ~18 days as in DeConto et al., 2021; Fig. S4) until the coupling time is reached. At this point, the associated ice volume changes are then fed into the sea-level model to calculate changes in sea-level and bedrock topography. These fields are sent back to the ice model, thereby impacting ongoing ice sheet evolution. The coupling time step of 10 years was chosen to balance resolution with computation time, since sensitivity tests for the coupling time step showed minimal differences for the choice of 25-, 10-, or 2-year coupling time steps (see Fig. S3). Forward calculations of global sea-level change are performed to spherical harmonic degree 512 (~80 km resolution), and a spatial resolution of 10 km is used within the ice sheet model. Unfortunately, finer spatial resolutions are computationally infeasible for continental-scale calculations (Gomez et al., 2024). To isolate the effects of the choice of solid Earth rheology on Antarctic Ice Sheet evolution, we hold ice volume and extent constant over the

https://doi.org/10.5194/egusphere-2026-2172
Preprint. Discussion started: 24 April 2026

remainder of the globe, hence any changes in GMSL are the result of Antarctic Ice Sheet changes only.

2.2 Ice sheet dynamics

The dynamic ice component is a hybrid ice sheet-shelf model employing the shallow ice and shallow shelf approximations for ice flow (which account for vertical shearing and longitudinal stretching respectively), ensuring computational feasibility for continental-scale simulations (Pollard & DeConto, 2012). A modified version of the Schoof (2007) parametrization for ice flux through the grounding line is adopted, allowing for evolving grounding line position according to the Marine Ice Sheet Instability (MISI) and self-consistency with the basal shear stress condition at the grounding line (Pollard & DeConto, 2012; Schoof, 2007). Surface mass balance is calculated by a positive-degree day scheme using RCP temperature and precipitation forcings. Sub-ice oceanic melting and calving at ice shelf edges are additional considerations in the ice sheet mass balance. Calving, though still poorly understood, is an important consideration for tidewater glaciers and ice shelves because floating ice can stabilize grounded ice upstream by means of buttressing at the grounding line (Gudmundsson, 2013; Sergienko, 2025). We consider two endmembers to describe ice loss through calving – a parametrization based on the large–scale stress field of the ice sheet where calving is related to the thickness of the ice shelf and is proportional to the positive divergence of floating ice velocity for thicker ice shelves (Nick et al., 2010) and the highly debated Marine Ice Cliff Instability (MICI), which is a physical treatment to account for hydrofracturing due to surface melt and failure of vertical cliff faces (Bassis et al., 2021; Golledge & Lowry, 2021; Pollard et al., 2015). The main results presented in this paper reflect the former, though we explore a possible scenario of accelerated retreat due to the MICI (see Section 4.2).

2.3 Solid Earth Structure and Rheology

While we focus on West Antarctica in the Main Text, we consider two distinct 1D Earth models to represent the geological dichotomy of the Antarctic continent, where East Antarctica is characterized by cold cratonic structure and West Antarctica is characterized by thin lithosphere underlain by relatively warm mantle. For both models, however, we assume the elastic and density properties based on the Preliminary Reference Earth Model (Dziewonski & Anderson, 1981). The elastic properties of the mantle are much less sensitive to temperature differences than the viscous properties, where the steady state, or Maxwell, viscosities differ by orders of magnitude. In accordance with East Antarctic structure, we assume a steady state viscosity profile (hereafter referred to as η_H, as in higher steady state viscosity model), which is comprised of a 96 km-thick lithosphere, an upper mantle viscosity of $10^{20}\ Pa \cdot s$, and a lower mantle viscosity of 5×10^{21} Pa s (> 670 km depth). To reflect West Antarctic mantle structure, we assume a reduced steady state viscosity model (hereafter referred to as η_L) with a 50 km-thick lithosphere overlying a zone with reduced viscosity down to 400 km depth with a viscosity of 10^{19} Pa s, a viscosity of 2×10^{20} Pa s for the remainder of the upper mantle, and a lower mantle viscosity (> 670 km depth) of 3×10^{21} Pa s. To be clear, in order to model the entire continent self-consistently in a way that captures the East-West dichotomy, we would require a 3D model of GIA (as in Gomez et al., 2024). As mentioned, this is computationally expensive and we emphasize that our approach (i.e., to run full simulations with two distinct 1D Earth models) is a

https://doi.org/10.5194/egusphere-2026-2172
Preprint. Discussion started: 24 April 2026

reasonable approximation to model each side of the continent, since our focus, as we shall see, will be on deformation in the direct vicinity of each region.

With these mantle properties, we calculate the viscoelastic Love numbers using the methodology outlined in Lau (2024). We do this for both a Maxwell viscoelastic rheology – which we will treat as our reference calculation – and for a transient viscoelastic rheology, adopting the empirical law of Yamauchi and Takei (2016) for both 1D Earth models. The Yamauchi and Takei (2016) transient rheology model accounts for the observed weakening across timescales spanning the elastic to steady state and can conveniently be scaled to a particular reference Maxwell model (see SM-1 for more details on these models). We compare the coupled ice sheet-sea level modelling results for simulations with the same steady state Earth structure but with Maxwell versus transient viscoelastic solid Earth rheology to assess the impact of including transient viscoelastic deformation on sea level and ice sheet evolution for the prescribed climate forcing between 1950 to 2500 (RCP 2.5, RCP 4.5, RCP 8.5; IPCC, 2014). An Earth with transient solid Earth rheology will be more sensitive to the pace of ice melting over timescales smaller than typical Maxwell relaxation times, so, given that our planet's actual trajectory of radiative forcing is unknown, we explore multiple climate change scenarios and also modify the rate of ice loss in each climate scenario further by invoking the rapid ice loss via MICI.

2.4 Calculating Antarctic Global Mean Sea Level Contribution

Mass balance can be used to estimate the GMSL contribution associated with the simulated co-evolution of ice sheet and sea-level change. In consideration of the effects of transient Earth deformation on predictions of the Antarctic contribution to GMSL, we neglect steric changes and adopt the modified volume above floatation (VAF) method described in Equation (1) of Gomez et al. (2024), which is applicable for cases where there are minimal changes in ice sheets and/or shorelines outside of Antarctica. This formulation accounts for water expulsion from regions of Antarctica below sea level to the remainder of the ocean. While globally, the ice mass lost will be equal to the mass gained by the ocean, in this paper we consider the Antarctic GMSL contribution to be the global average sea level rise in the rest of the world due to Antarctic ice loss and the gravitational, rotational, and deformational feedbacks from GIA. We present the deviations in GMSL predictions, uplift, ice volume, and marine grounding line dynamics in West Antarctica due to the inclusion of transient Earth deformation in the following section.

3. Results

Figure 1 shows the initial ice configuration for all simulations (1950 CE; Fig. 1a) and the change in ice thickness between 1950 and 2500 CE across West Antarctica the η_L steady state viscosity with Maxwell solid Earth rheology, our reference case (Fig. 1b.i RCP 2.6; Fig. 1b.ii RCP 4.5; Fig. 1b.iii RCP 8.5). We note that in all map figures, the unshaded region is that in which the background viscoelastic structure is appropriate (e.g., for an unshaded Western Antarctic region, the simulation adopted the η_L steady state profile). Projected ice loss under RCP 8.5 in West Antarctica is drastic, with ice thickness losses as large as 2 km and near-complete collapse of the Filchner-Ronne and Ross ice shelves (grey fill in Fig. 1a to reduced extent in Fig 1b.iii). While floating ice does not impact GMSL, loss of ice shelves can reduce buttressing of upstream grounded ice, leading to reductions in grounded ice volume and consequently, GMSL rise. In addition to loss of floating ice, grounded ice margins of the WAIS undergo notable retreat (Fig.

https://doi.org/10.5194/egusphere-2026-2172
Preprint. Discussion started: 24 April 2026

1b; compare grey contour of initial grounded ice margins and solid black contour outlining final grounded ice margins in the Maxwell model). Grounded ice loss is particularly severe in the Amundsen Sea Embayment (ASE), which encompasses the swiftly deglaciating Pine Island (transect A-A'; Fig. 1a) and Thwaites Glacier (transect B-B'; Fig. 1a). The near-complete collapse of the ASE in RCP 8.5 disconnects the grounded ice of the Antarctic Peninsula from the remainder of the continent. The starting point of the glacier transects (circle markers A, B) are located along the initial grounded ice margins. Small yellow areas along the Maxwell model in the ASE region indicate places where the final grounded ice margins in the transient model extend further outward than those within the Maxwell model. There is noticeably less grounding line retreat in the ASE under the more moderate emissions scenarios, RCPs 2.6 and 4.5, however, if the parametrization of MICI is applied within the coupled model, the ice loss exceeds that of RCP 8.5 without MICI for both RCP 2.6 and 4.5, resulting in near-total collapse of the ASE and the interior of the WAIS (see SM-6).

https://doi.org/10.5194/egusphere-2026-2172
Preprint. Discussion started: 24 April 2026

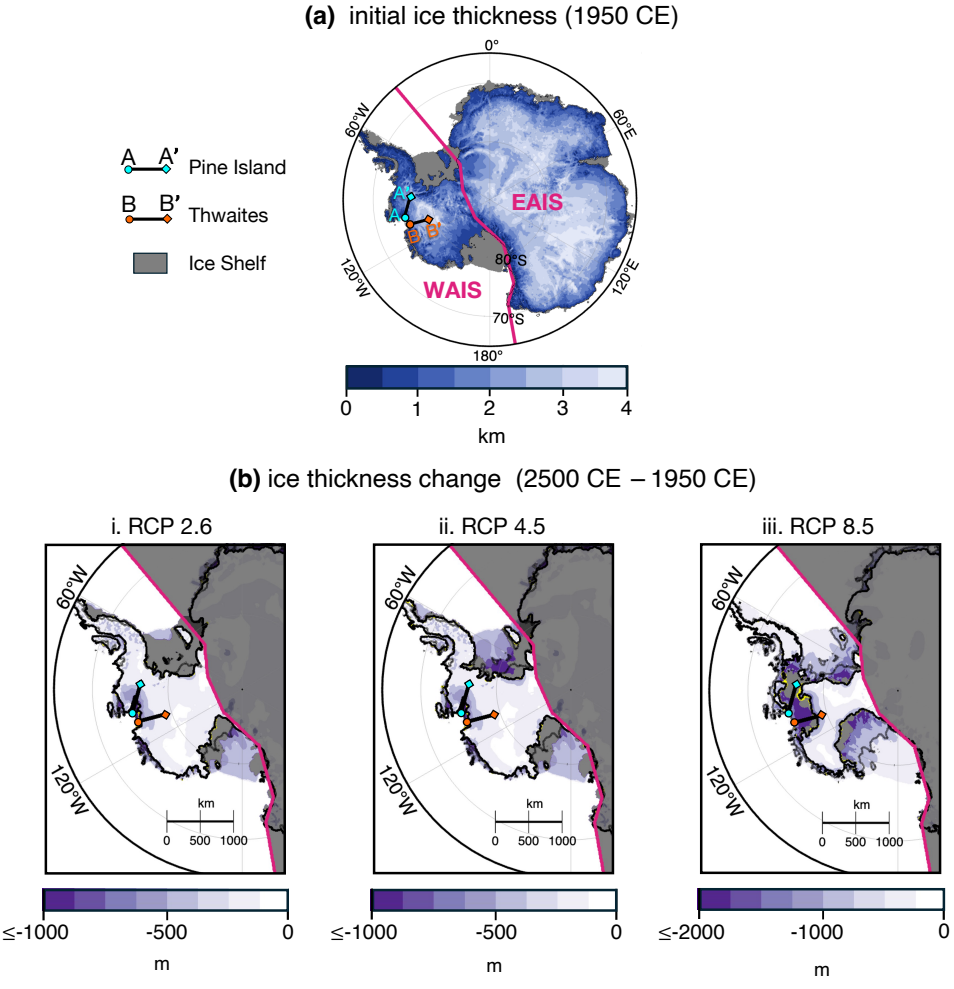

Figure 1. Maxwell Model Ice Thickness Change: (a) initial ice sheet configuration and ice shelf extent at 1950 CE. (b) total change in ice thickness from 1950 CE to 2500 CE in West Antarctica with the η_L Maxwell Earth model for RCP 2.6 (b.i), RCP 4.5 (b.ii), and RCP 8.5 (b.iii). Solid contours outline initial (dark grey) and final (black) grounded ice extent in the Maxwell model. The final grounded ice extent in the transient model is contoured in yellow, indicating areas of additional grounded ice extent in the transient model, compared to the maxwell model (b.iii). Pink line indicates division between East Antarctica and West Antarctica used in this study. Transects A-A' (cyan markers) and B-B' (orange markers) cut through Pine Island and Thwaites glaciers, respectively. Solid grey fill in (b) indicates final ice shelf extent.

Once more, the Maxwell model results presented in Fig. 1 serve as a reference for solid Earth–ice sheet feedbacks without accounting for transient Earth deformation. We compare the effect of including transient Earth deformation on bedrock elevation and ice thickness relative to the reference Maxwell model at 2500 CE in Fig. 2. Regardless of the choice of solid Earth rheology, the largescale patterns of solid Earth deformation consist of uplift across West

https://doi.org/10.5194/egusphere-2026-2172
Preprint. Discussion started: 24 April 2026

Antarctica and subtle subsidence with pockets of uplift around marine outlet glaciers in East Antarctica. However, the magnitudes of vertical displacement are greater in the transient models for nearly the entirety of the continent, compared to that of the Maxwell model. Under RCP 8.5, the ASE is uplifted by an additional ~25 m when accounting for transient Earth deformation (~10 m for RCPs 4.5 and 2.6; Fig. 2c,e).

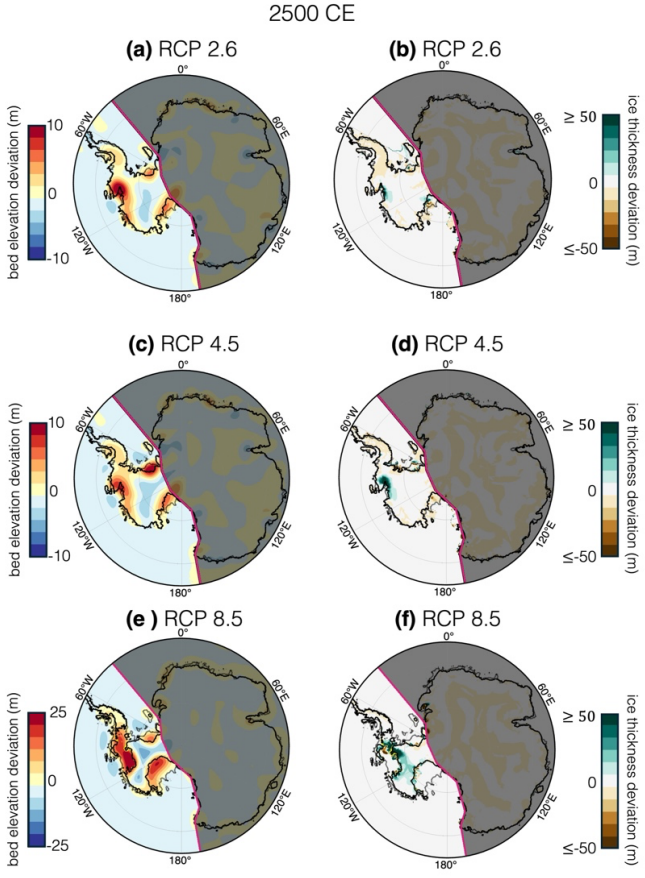

Figure 2. Bedrock and Ice Thickness Deviation (Transient minus Maxwell) (a),(c),(e) Difference between bedrock elevation of transient and Maxwell Earth rheology simulations at 2500 CE in West Antarctica for (a) RCP 2.6 and (c) RCP 4.5, and (e) RCP 8.5 respectively. (b),(d),(f) Difference between final ice thickness of transient and Maxwell Earth rheology simulations at 2500 CE in West Antarctica for (b) RCP 2.6 and (d) RCP 4.5, and (f) RCP 8.5 respectively.

3.1 Slowdown of grounding line retreat

Fig. 3 compares the relative pace of grounding line retreat in Maxwell versus transient models under RCP 8.5 (IPCC, 2014) at Pine Island (vertical lines, Fig. 3a,c) and Thwaites Glaciers (Fig.

https://doi.org/10.5194/egusphere-2026-2172
Preprint. Discussion started: 24 April 2026

3b,d). Along both glacier transects, the transient and Maxwell models are similar until around 2300 CE, after which, there is observable deviation in the relative pace of grounding line retreat. Though, regardless of the rheology, the grounding line tends to become pinned along bumps in the bedrock or locations where the slope changes from retrograde to prograde, grounding line retreat at both glaciers in the transient model is delayed by decades or more relative to the Maxwell model. For every time slice in Fig. 3, the grounding line in the Maxwell model has retreated further upstream than in the transient model, with deviations in grounding line position greater than 30 km (RCP 8.5).

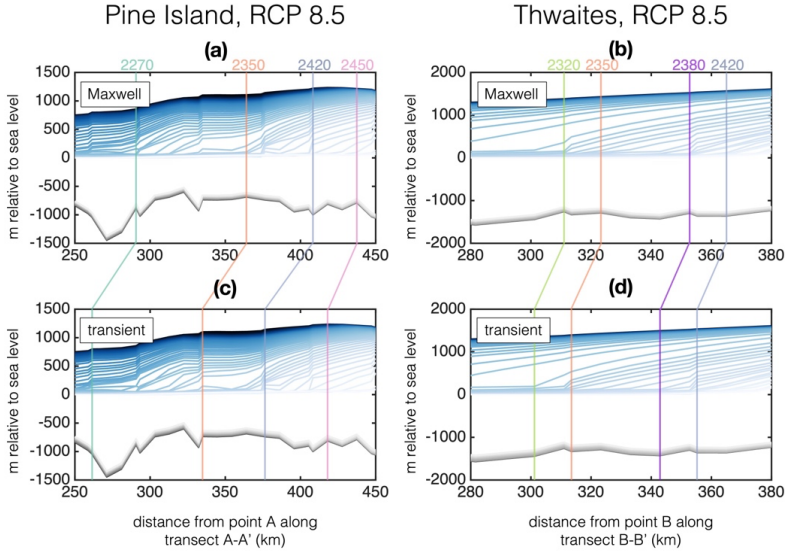

Figure 3. RCP 8.5 Grounding Line Retreat at Pine Island and Thwaites Glacier (a),(c) Evolution of bedrock surface (dark grey to light grey) and ice sheet surface (dark blue to light blue) elevation across Pine Island Glacier (Transect A-A', Figure 1a) considering Maxwell (a) vs. transient (c) viscoelastic solid Earth deformation. **(b),(d)** As in (a) and (c) but for Thwaites Glacier (Transect B-B', Fig. 1a). Connecting lines plotted in distinct colours indicate grounding line position at the indicated times within the simulation. At each illustrated time slice in the figure, the transient Earth simulation has undergone less retreat than the reference simulation considering only Maxwell viscoelastic deformation. All results shown adopt η_L steady state profile.

Fig. 4 demonstrates a similar progression at Pine Island glacier for RCPs 2.6 and 4.5, with more grounding line retreat at a given time within the Maxwell simulation than the transient simulation. In fact, the total distance of grounding line retreat by the year 2500 along the Pine Island glacier transect in the transient model is less than that of the Maxwell model (by ~10 km and 20 km for RCPs 2.6 and 4.5, respectively). In the last ~150 years of the coupled ice sheet-sea level evolution, grounding line retreat is significantly delayed in the transient model compared to the Maxwell model at Pine Island Glacier in all RCPs (Supplementary Movies 2-4). The same is true at Thwaites Glacier in RCP 8.5, though in the more moderate emissions scenarios there is little to no deviation in Thwaites Glacier grounding line retreat with transient rheology (Supplementary Movie 1). We emphasize that the marine outlet glaciers of the WAIS are broad spatial features, and we only show the grounding line migration through time along the transects

https://doi.org/10.5194/egusphere-2026-2172
Preprint. Discussion started: 24 April 2026

304 described in Fig. 1 in the cross-sections (Figs 3 and 4). The deviations in the spatial pattern of
305 retreat of marine outlet glaciers are more complex, as illustrated by the areas where the grounded
306 ice margins vary between the transient and Maxwell models off-transect in Figs 1 and 2 (yellow
307 fill).
308

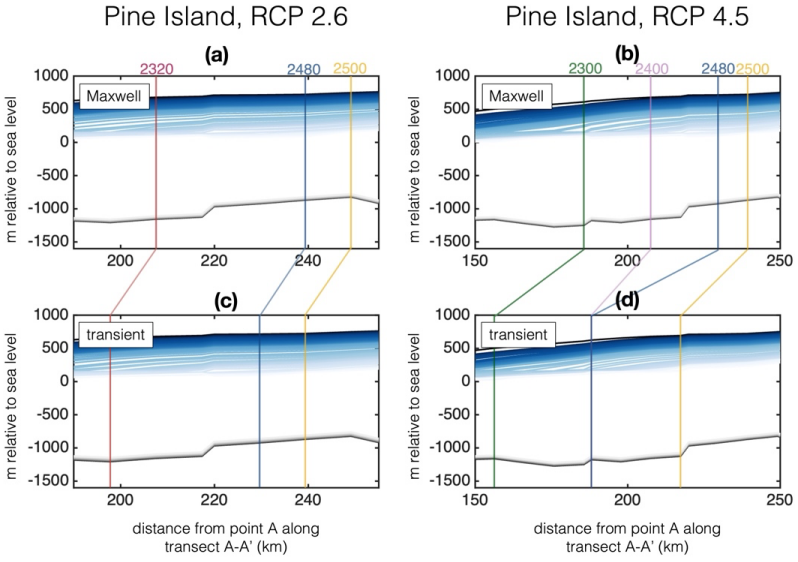

Figure 4. Grounding Line Retreat at Pine Island Glacier in RCP 2.6 and RCP 4.5 (a),(c) Evolution of bedrock surface (dark grey to light grey) and ice sheet surface (dark blue to light blue) elevation across Pine Island Glacier (Transect A-A', Fig. 1a) under RCP 2.6 considering Maxwell (a) vs. transient (c) viscoelastic solid Earth deformation. **(b),(d)** As in (a) and (c) but for RCP 4.5 climate forcing. At each time slice for either glacier transect, the transient Earth simulation has undergone less retreat than the reference Maxwell Earth rheology simulation. All results shown adopt the low steady state viscosity profile, to mirror West Antarctic Earth structure.

https://doi.org/10.5194/egusphere-2026-2172
Preprint. Discussion started: 24 April 2026

309 Moving to a continent-scale view of the predicted deformation and sea-level change, Fig.
310 5 displays maps of the absolute value of bedrock uplift rate in the Maxwell model (left panels)
311 and the deviation in uplift rate between the transient and Maxwell models (right panels) in West
312 Antarctica at 2300 CE (here, uplift rate is defined as the radial displacement of the solid Earth
313 surface over a change in time step.)
314

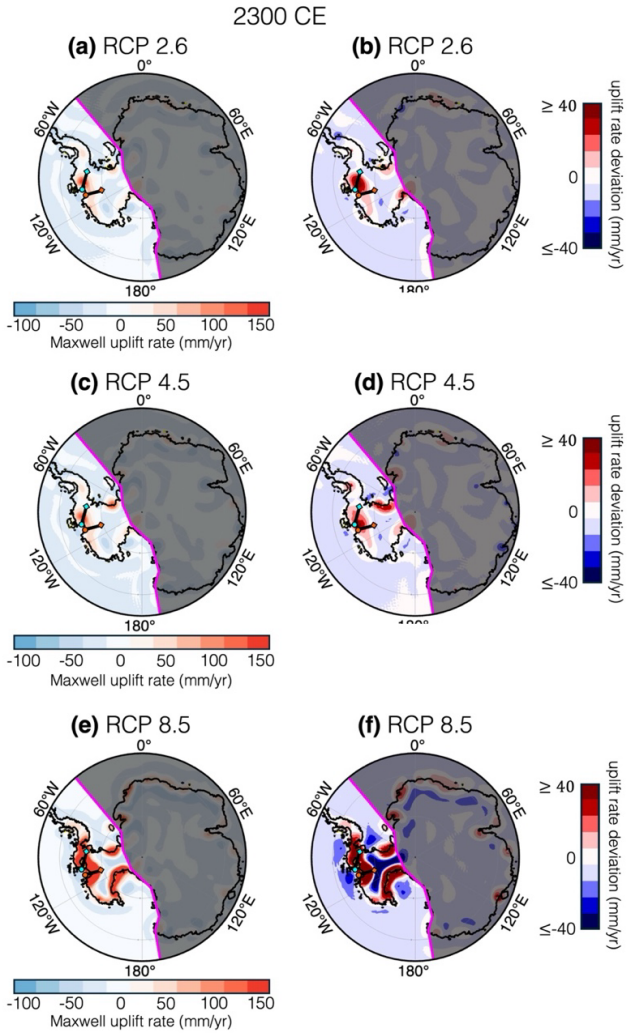

Figure 5. Vertical Bedrock Displacement Rate Deviation (Transient–Maxwell) (a),(c),(e) Uplift rate in mm/yr in the reference Maxwell simulation with low steady state viscosity profile for RCP 2.6, 4.5, and 8.5, respectively. **(b),(d),(f)** Difference in uplift rate (transient minus Maxwell) with the low steady state viscosity profile for RCP 2.6, 4.5, and 8.5, respectively. Pine Island and Thwaites transects marked as in Fig. 1a (bounded by cyan and orange markers, respectively).

https://doi.org/10.5194/egusphere-2026-2172
Preprint. Discussion started: 24 April 2026

Across all RCP scenarios, the rate of bedrock uplift at the Thwaites and Pine Island grounding lines in the Maxwell model (proximate to the orange- and cyan-filled circles, respectively in Fig. 5), are on the order of magnitude of observed bedrock uplift rates in the ASE (Lucas et al., 2024; SM-4). When transient deformation is included, the modelled rates of bedrock uplift exceed that of the Maxwell model by an additional 10 to 40 mm/yr (Fig. 5b,d,f).

3.2 Deviation in global mean sea level contribution

The spatial pattern of global sea-level change is largely unaffected by transient solid Earth rheology outside of Antarctica. The total amount of GMSL rise from the Antarctic Ice Sheet (AIS) as a whole is dominated by the contribution from the WAIS, since majority of the ice loss occurs in marine-grounded areas. Fig. 6 shows the transient–Maxwell deviation in GMSL rise contributed by the WAIS over the course of the simulation, for all emissions scenarios. Examining the deviation in the total WAIS GMSL contribution throughout the simulation (Fig. 6, right vertical axis), we see that transient deformation causes the cumulative GMSL rise from the WAIS to be smaller than that of the Maxwell model by several centimetres (~2 cm in RCP 2.6, ~3 cm in RCP 4.5, and ~5 cm in RCP 8.5). This is despite that the incremental WAIS GMSL contribution over a given model time step is sometimes larger in the transient model (red fill, Fig. 6). The WAIS GMSL contribution is reduced on the order of centimetres in the transient model relative to the Maxwell model, regardless of which steady state viscosity profile is used (compare solid vs. dashed continuous lines in Fig. 6). Even so, the percent reduction in both WAIS and AIS GMSL

https://doi.org/10.5194/egusphere-2026-2172
Preprint. Discussion started: 24 April 2026

334 contribution with transient deformation is ~5% or less for all times in the simulation; see SM-5 for
335 absolute and percent deviations in WAIS GMSL contribution).

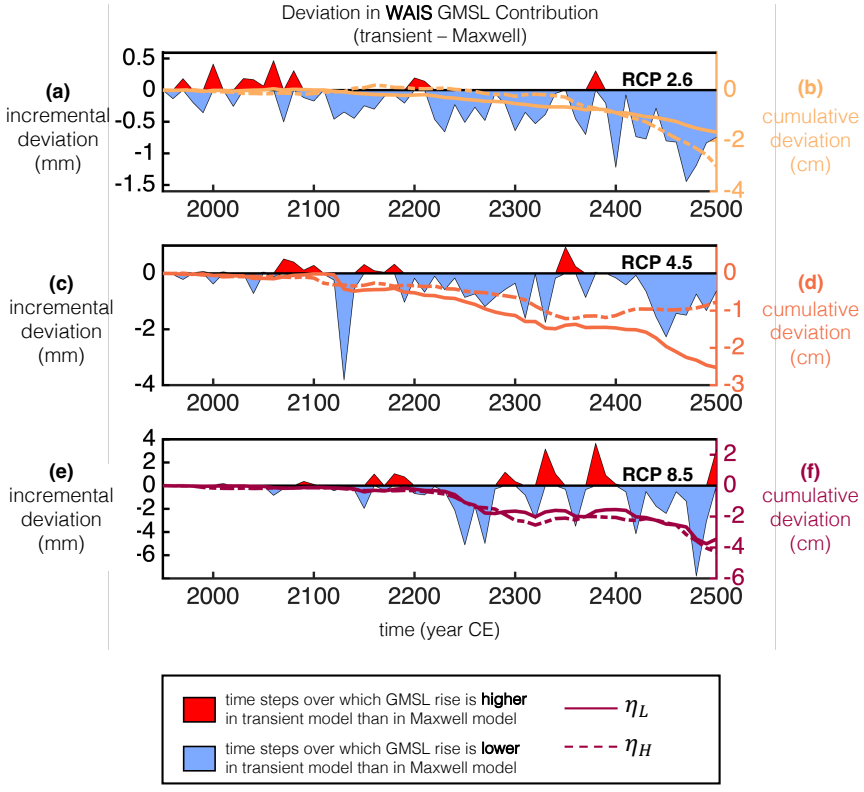

Figure 6. Deviation in WAIS GMSL Contribution (a),(c),(e) Blue and red infilled lines indicate the associated Transient – Maxwell deviation in incremental GMSL contribution in millimetres from the WAIS over each time step in the simulations for RCP 2.6 (a), 4.5 (c) and 8.5 (e) forcings with steady state profile η_L. **(b),(d),(f)** Continuous lines indicate Transient – Maxwell deviation cumulative WAIS GMSL contribution in centimetres throughout the simulations using the η_L steady state profile (solid lines) and the η_H steady state viscosity (dashed lines) for RCP 2.6 (b), 4.5 (d) and 8.5 (f) forcings. For all RCP scenarios, the cumulative transient-Maxwell GMSL deviation is negative (reduction of total WAIS contribution to GMSL.)

336 **4. Discussion and Conclusions**

337 We simulate coupled Antarctic ice sheet–sea level dynamics with a 1D, radially varying
338 GIA model (Gomez et al., 2010; Han et al., 2022; Kendall et al., 2005) and 3D ice sheet-shelf
339 model (Pollard & Deconto, 2012; Pollard et al., 2015) subject to the RCP 2.6, 4.5, and 8.5
340 emissions trajectories (IPCC, 2014). Our results show that transient rheology has a stabilizing
341 effect on the WAIS by providing an additional (and earlier) strain contribution to solid Earth
342 rebound in response to ice loss, thereby slowing and/or reducing the absolute extent of grounding
343 line retreat. We observe differing sensitivities of grounding line retreat to transient deformation

https://doi.org/10.5194/egusphere-2026-2172
Preprint. Discussion started: 24 April 2026

between Pine Island Glacier and Thwaites Glaciers, likely because of the distinct roughness and bathymetry profiles of the bedrock along the selected glacier transects. Overall, the local effects of transient rheology are stabilizing to the WAIS via counteraction of the Marine Ice Sheet Instability (MISI). We note that the stabilizing effects of transient deformation are only temporary across WAIS grounding zones; over a timescale of centuries, both Maxwell and transient simulations converge to similar magnitudes of grounding line retreat. That is, drastic ice loss still occurs regardless of the assumed solid Earth rheology, but the pathway there varies. This becomes the case for all RCP scenarios when rapid ice loss via the Marine Ice Cliff Instability (MICI) is accounted for in the coupled ice sheet-sea level simulations (see Section 4.2). Although transient deformation cannot counteract the magnitude of projected global sea level rise, the delayed trajectory of grounding line retreat with transient deformation on the glacier-to-glacier scale aids in the interpretation of observations of change in the WAIS. Moreover, predicted AIS discharge rates will play a role in understanding the global climate feedbacks associated with the delivery of freshwater to the Southern Ocean (Gorte, 2023; Sadai et al., 2025).

4.1.1 Local feedback mechanisms and impact on global mean sea level

As the WAIS shrinks throughout the simulation, water mass is added to the ocean and sea level is lowered in the near field, due to both solid Earth uplift and reduced gravitational attraction of the remaining ice load to the ocean. The counterpart of this local sea-level fall is increased sea-level rise in the far field (Mitrovica et al., 2001). While ultimately, the contribution of transient deformation to bedrock uplift prolongs the inevitable retreat and therefore integrated GMSL rise (Gomez et al., 2015; Gomez et al., 2024), earlier in the simulations, the opposite is true, i.e., our transient simulations show more incremental GMSL in the first few time steps. We interpret this early opposing trend to be enhanced far field sea level rise due to increased water expulsion in the transient simulations relative to the Maxwell (Fig 6; red fill). Despite this, there is a net reduction in GMSL rise from Antarctica. The ability for solid Earth uplift to counteract the MISI (or MICI) in West Antarctica builds with time as the simulation progresses, owing to the time delay between the loading change and the associated strain contribution from non-elastic deformation (see continuous lines, Fig. 6). We note that the magnitude of GMSL reduction from transient deformation is small and likely within the uncertainty in dynamic ice sheet model projections due to factors like basal conditions and implementation of ice sheet-shelf physics (Bamber et al., 2022).

4.1.2 Sensitivity to steady state viscosity

As aforementioned, transient deformation affects the magnitude and timing of the solid Earth response to loading changes, causing an apparent softening of Earth's mechanical properties over relevant loading timescales and an effective reduction in time delay for viscous deformation. In the Yamauchi and Takei (2016) rheological model, a given transient Earth model is scaled to the assumed steady state viscosity profile and will therefore have a different sensitivity to the timescale of the forcing than another transient Earth model scaled to a different steady state viscosity profile. While we have chosen to focus our discussion on results based on Earth structure characterized by the low (η_L) steady state viscosity profile, thought to be representative of the hot structure beneath West Antarctica (Lloyd et al., 2020), there remains substantial uncertainty in the absolute viscosity structure. Indeed, a lower Maxwell viscosity

https://doi.org/10.5194/egusphere-2026-2172
Preprint. Discussion started: 24 April 2026

mantle beneath West Antarctica is also consistent with GPS measurements of uplift rates. It is unclear, however, whether these inferred low viscosities are representative of the long-term viscosity as opposed to a transient deviation from a higher, steady state viscosity activated by modern loading changes (Lau et al., 2021; Nield et al., 2025), or even some combination (see SM-4, Fig. S5).

Given the uncertainty in steady state mantle viscosity, we also considered the coupled ice sheet-sea level evolution of the WAIS with the high steady state viscosity profile for RCP 2.6, RCP 4.5, and RCP 8.5 in West Antarctica. We find similar delayed trajectories of grounding line retreat and magnitudes of the reduction in WAIS GMSL contribution with transient deformation for both the low- and high steady state viscosity simulations (compare solid vs. dashed lines in Fig. 6). For the low steady state viscosity profile, the WAIS GMSL contribution at 2500 is reduced by 1.9% under RCP 8.5 (2.1% with high steady state viscosity profile), 4.1% under RCP 4.5 (1.7 % with high steady state viscosity profile), and 3.1% under RCP 2.6 (5% with high steady state viscosity profile). These results suggest that the stabilizing effect of transient deformation on grounding line retreat need not be unique to West Antarctica, given the subglacial topography of some East Antarctic glaciers (Pritchard et al., 2025). There are several marine-terminating outlet glaciers through which East Antarctica loses considerable ice mass, and they have been suggested to exhibit considerable grounding line retreat (Favier et al., 2016; Jones et al., 2015; Picton et al., 2023; Stokes, 2022).

4.2 Impact of the Marine Ice Cliff Instability

Though there is no consensus in physical treatment of calving, the Marine Ice Cliff Instability (MICI) has been suggested to exacerbate both East and West Antarctic ice loss through rapid cliff failure and the subsequent reduction in buttressing of upstream grounded ice (Bassis et al., 2021; Bassis & Walker, 2012; Deconto et al., 2021; Golledge & Lowry, 2021; Pollard et al., 2015). The transient Earth deformation response will be sensitive to such rapid loading changes, and viscoelastic behaviour will occur on timescales that can better compete with that of ice loss, thereby affecting the ice dynamics. We explore the potential effects of MICI on ice sheet-sea level projections with transient Earth deformation (see SM-7; Supplementary Movies 5-6). We find exacerbated deviations in grounding line position at a given time due to transient Earth deformation in MICI simulations of RCP 2.6 and RCP 4.5. This reflects the expedited rate of ice loss becoming sufficient to activate a larger transient deformation response. Under RCP 8.5, however, when rapid ice loss via calving is invoked, there is minimal deviation in the grounding line position between the transient and Maxwell models, precisely because the background climate forcing is already sufficiently rapid to trigger the transient deformation response;

https://doi.org/10.5194/egusphere-2026-2172
Preprint. Discussion started: 24 April 2026

regardless of rheology, the solid earth uplift cannot keep pace with the ice sheet retreat, unlike in the more moderate climate scenarios.

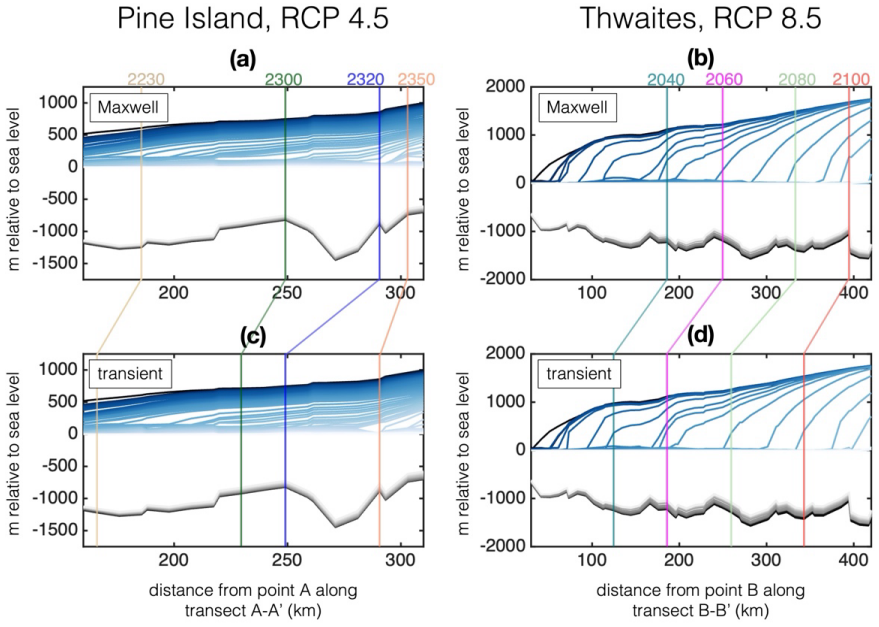

Figure 7. Deviation in Grounding line retreat with MICI Timeline of grounding line retreat across Pine Island and Thwaites Glaciers. Analogous to Fig. 2, instead using the coupled ice sheet-sea level simulations of RCP 4.5 with the inclusion of rapid ice calving via the MICI. Ice sheet (dark blue to light blue) and bedrock surface (dark grey to light grey) evolution at Pine Island Glacier **(a,c)** and Thwaites Glacier **(b,d)** for Maxwell and transient Earth models, respectively.

Fig. 7 is analogous to Fig. 2, illustrating grounding line retreat at Pine Island and Thwaites Glaciers for Maxwell versus transient Earth models, but with RCP 4.5 climate forcing and the additional consideration of MICI (implemented in the model via the algorithm described in DeConto & Pollard, et al. 2016 and DeConto et al., 2021). Fig. 7b,d demonstrates deviations in the Maxwell and transient model grounding line positions of between ~50-70 km at a given time in the simulation at Thwaites Glacier. While eventually the transient model catches up with the grounding line retreat in the Maxwell model by ~2130 CE, the trajectory is delayed. In the Maxwell model under RCP 4.5 with MICI included, Pine Island Glacier has nearly fully collapsed by 2380 CE (Fig. 7a). It takes another ~30 years for the glacier to fully retreat in the transient model. Given that understanding and modelling of calving processes is currently under active development in the literature, these results should be viewed as a preliminary sensitivity test of the role of transient deformation in modulating ice retreat through calving processes. Though we focus on West Antarctica, subglacial basins of East Antarctica are also prone to rapid retreat with MICI (Deconto et al., 2021). We see greater ice retention by upwards of 50 metres within the Wilkes, Aurora, and Recovery subglacial basins in the transient Earth rheology simulations as early as 2050 CE for all RCP simulations including MICI (see SM-6, Fig. S12).

https://doi.org/10.5194/egusphere-2026-2172
Preprint. Discussion started: 24 April 2026

Ultimately, the transient models with MICI catch up to the ice levels in the Maxwell simulations with MICI after 2300 CE in East Antarctica (apart from a small region in the Wilkes Subglacial Basin under RCP 8.5; Fig. S12). Given that Greenland, like East Antarctica, is predominantly grounded above sea level and has cratonic mantle structure, we should also expect a delay in ice retreat with transient Earth deformation.

4.3 Moving to more realistic Earth rheology

Although there is strong consensus in the rock physics community that transient viscous deformation occurs over a range of timescales from the elastic end-member to the steady state viscous regime, the exact nature of empirically-derived parametrizations of transient rheology varies between laboratories (Faul & Jackson, 2015; Havlin et al., 2021; Lau & Holtzman, 2019; Yamauchi & Takei, 2016). These transient models have differing sensitivities across the full spectrum of loading timescales, and therefore predictions of sea level and ice sheet coevolution with transient deformation will bear the uncertainty in the choice of transient model (as well as the assumed trajectory of climate forcing).

Furthermore, Lau et al. (2025) model the GIA response to static ice loading changes under future projections, accounting for lateral variations in both steady state mantle viscosity and transient rheology (Yamauchi and Takei et al. 2016, as applied here though only to 1D Earth models), but without consideration of dynamic ice sheet-sea level feedback. They find that deviations in near field sea level from transient solid Earth deformation are on the order of or larger than the effects of 3D Earth structure, suggesting that transient Earth rheology is an important consideration in modelling modern and future marine grounding line dynamics. Though the two distinct 1D steady state viscosity profiles used in this study are consistent in terms of the magnitude of GMSL reduction in the transient Earth model relative to that of the reference Maxwell model, future coupled ice sheet-sea level modelling studies should incorporate laterally varying Earth structure (as in Gomez et al., 2024) in conjunction with transient deformation behaviour, since East Antarctica and West Antarctica evolve simultaneously and there is potential for covariance across the regions within the context of solid Earth-ice sheet feedbacks (Gomez et al., 2018; Gomez et al., 2024; Lucas et al., 2024; van Calcar et al., 2025). Moreover, this study considers the effects of complex time-dependent deformation in the linear viscoelastic regime. There is also evidence for transient dislocation creep mechanisms at these intermediate timescales (L. N. Hansen et al., 2021). Accordingly, stress-dependence and transient deformation behaviour could also be considered together in regions of high background stress (e.g., Lau et al. 2021).

Transient solid Earth deformation is unable to thwart the inevitable Antarctic ice loss and sea level rise predicted in this coupled model of ice sheet-sea level-solid Earth interactions. However, transient deformation has the potential to slow the pace of ice retreat and influence the rate at which freshwater discharge from the Antarctic Ice Sheet is delivered to the ocean. All-the-while, many studies from the atmospheric and oceanic modelling community (e.g. Sadai et al. 2020) have shown that freshwater outflux from the AIS can delay global temperature rise, concurrently with increasing sea level rise, by driving the expansion of sea ice. Earth's albedo, or reflectivity of the surface against solar radiation, is highly sensitive to sea ice extent and this feedback has been shown to reduce predictions of global mean temperature between 0.3 and 1°C by 2100 CE (Sadai et al., 2025). If we predict AIS evolution and contribution to sea-level rise within the framework of transient solid Earth rheology, it remains unclear how the deviations from Maxwell model predictions will impact ocean and atmospheric processes such as sea ice

https://doi.org/10.5194/egusphere-2026-2172
Preprint. Discussion started: 24 April 2026

growth and ocean circulation. Regardless, transient viscoelastic deformation is a more realistic description of viscoelastic rock deformation behaviour. We demonstrate that transient earth deformation delays AIS retreat, which controls the rate of freshwater discharge, thus it should be a consideration in predicting and interpreting the response of the entire climate system.

Code Availability

All codes used in this study are publicly available from previously published studies. The sea level model component of the coupled Ice Sheet-Sea Level model can be accessed at https://github.com/hollyhan/1DSeaLevelModel_FWTW. The dynamic ice sheet model component can be accessed at https://www.frdr-dfdr.ca/repo/dataset/de1bb752-6778-4c5c-8293-2abaddf93a89

Data Availability

The model outputs for ice sheet and sea level change, as well as the driver scripts for the simulations will be made available in a repository prior to acceptance of the manuscript.

Author Contribution

A.N.C. developed the project. A.N.C. conducted the modelling with guidance from B.P. and N.G. Results were analyzed by A.N.C. with guidance from B.P., N.G., H.C.P.L. The paper was written by A.N.C. with feedback by B.P., H.C.P.L., N.G.

Competing interests

The authors declare they have no conflict of interest.

Acknowledgements

We thank N. Gomez for providing access and computation time on the Digital Resource Alliance of Canada cluster and look forward to helpful feedback from the Editor and Reviewers.

Financial Support

This work was supported by the David and Lucile Packard Foundation and NSF grant EAR 2311897.

References

Abe-Ouchi, A., Saito, F., Kawamura, K., Raymo, M. E., Okuno, J. I., Takahashi, K., & Blatter, H. (2013). Insolation-driven 100,000-year glacial cycles and hysteresis of ice-sheet volume. *Nature*, *500*(7461), 190-193. https://doi.org/10.1038/nature12374

Bamber, J. L., Oppenheimer, M., Kopp, R. E., Aspinall, W. P., & Cooke, R. M. (2022). Ice Sheet and Climate Processes Driving the Uncertainty in Projections of Future Sea Level Rise: Findings From a Structured Expert Judgement Approach. *Earth's Future*, *10*(10). https://doi.org/10.1029/2022ef002772

Barletta, V. R., Bevis, M., Smith, B. E., Wilson, T., Brown, A., Bordoni, A., Willis, M., Khan, S. A., Rovira-Navarro, M., Dalziel, I., Smalley, R., Kendrick, E., Konfal, S., Caccamise, D. J., Aster, R. C., Nyblade, A., & Wiens, D. A. (2018). Observed rapid bedrock uplift in

https://doi.org/10.5194/egusphere-2026-2172
Preprint. Discussion started: 24 April 2026

Amundsen Sea Embayment promotes ice-sheet stability. *Science*, *360*(6395), 1335-1339. https://doi.org/10.1126/science.aao1447

Bassis, J. N., Berg, B., Crawford, A. J., & Benn, D. I. (2021). Transition to marine ice cliff instability controlled by ice thickness gradients and velocity. *Science*, *372*(6548), 1342-1344. https://doi.org/10.1126/science.abf6271

Bassis, J. N., & Walker, C. C. (2012). Upper and lower limits on the stability of calving glaciers from the yield strength envelope of ice. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *468*(2140), 913-931. https://doi.org/10.1098/rspa.2011.0422

Caron, L., Ivins, E., Larour, E., Adhikari, S., & Metivier, L. (2025). *Love number computation within the Ice-sheet and Sea-level System Model (ISSM v4.24)*. Copernicus GmbH. https://dx.doi.org/10.5194/egusphere-2024-3414

Coonin, A. N., Lau, H. C. P., & Coulson, S. (2025). Meltwater Pulse 1A sea-level-rise patterns explained by global cascade of ice loss. *Nature Geoscience*, *18*(3), 254-259. https://doi.org/10.1038/s41561-025-01648-w

Deconto, R. M., & Pollard, D. (2016). Contribution of Antarctica to past and future sea-level rise. *Nature*, *531*(7596), 591-597. https://doi.org/10.1038/nature17145

Deconto, R. M., Pollard, D., Alley, R. B., Velicogna, I., Gasson, E., Gomez, N., Sadai, S., Condron, A., Gilford, D. M., Ashe, E. L., Kopp, R. E., Li, D., & Dutton, A. (2021). The Paris Climate Agreement and future sea-level rise from Antarctica. *Nature*, *593*(7857), 83-89. https://doi.org/10.1038/s41586-021-03427-0

Dziewonski, A. M., & Anderson, D. L. (1981). Preliminary reference Earth model. *Physics of the Earth and Planetary Interiors*, *25*(4), 297-356. https://doi.org/10.1016/0031-9201(81)90046-7

Faul, U., & Jackson, I. (2015). Transient Creep and Strain Energy Dissipation: An Experimental Perspective. *Annual Review of Earth and Planetary Sciences*, *43*(1), 541-569. https://doi.org/10.1146/annurev-earth-060313-054732

Faul, U. H., Fitz Gerald, J. D., Farla, R. J. M., Ahlefeldt, R., & Jackson, I. (2011). Dislocation creep of fine-grained olivine. *Journal of Geophysical Research*, *116*(B1). https://doi.org/10.1029/2009jb007174

Favier, L., Pattyn, F., Berger, S., & Drews, R. (2016). Dynamic influence of pinning points on marine ice-sheet stability: a numerical study in Dronning Maud Land, East Antarctica. *The Cryosphere*, *10*(6), 2623-2635. https://doi.org/10.5194/tc-10-2623-2016

Golledge, N. R., & Lowry, D. P. (2021). Is the marine ice cliff hypothesis collapsing? *Science*, *372*(6548), 1266-1267. https://doi.org/10.1126/science.abj3266

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., & Holland, D. (2015). Sea-level feedback lowers projections of future Antarctic Ice-Sheet mass loss. *Nature Communications*, *6*(1), 8798. https://doi.org/10.1038/ncomms9798

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., Nyblade, A., Wiens, D. A., Aster, R. C., & Wilson, T. (2024). The influence of realistic 3D mantle viscosity on

https://doi.org/10.5194/egusphere-2026-2172
Preprint. Discussion started: 24 April 2026

Antarctica's contribution to future global sea levels. *Science Advances*, *10*(31). https://doi.org/10.1126/sciadv.adn1470

Gorte, T., Lovenduski, N. S., Nissen, C., & Lenaerts, J. T. M. (2023). Antarctic Ice Sheet freshwater discharge drives substantial Southern Ocean changes over the 21st century. *Geophysical Research Letters, , 50*. https://doi.org/https://doi.org/10.1029/2023GL104949

Gudmundsson, G. H. (2013). Ice-shelf buttressing and the stability of marine ice sheets. *The Cryosphere*, *7*(2), 647-655. https://doi.org/10.5194/tc-7-647-2013

Han, H. K., Gomez, N., Pollard, D., & Deconto, R. (2021). Modeling Northern Hemispheric Ice Sheet Dynamics, Sea Level Change, and Solid Earth Deformation Through the Last Glacial Cycle. *Journal of Geophysical Research: Earth Surface*, *126*(4). https://doi.org/10.1029/2020jf006040

Han, H. K., Gomez, N., & Wan, J. X. W. (2022). Capturing the interactions between ice sheets, sea level and the solid Earth on a range of timescales: a new "time window" algorithm. *Geoscientific Model Development*, *15*(3), 1355-1373. https://doi.org/10.5194/gmd-15-1355-2022

Hansen, K., Truffer, M., Aschwanden, A., Mankoff, K., Bevis, M., Humbert, A., Van Den Broeke, M. R., Noël, B., Bjørk, A., Colgan, W., Kjær, K. H., Adhikari, S., Barletta, V., & Khan, S. A. (2021). Estimating Ice Discharge at Greenland's Three Largest Outlet Glaciers Using Local Bedrock Uplift. *Geophysical Research Letters*, *48*(14). https://doi.org/10.1029/2021gl094252

Hansen, L. N., Wallis, D., Breithaupt, T., Thom, C. A., & Kempton, I. (2021). Dislocation Creep of Olivine: Backstress Evolution Controls Transient Creep at High Temperatures. *Journal of Geophysical Research: Solid Earth*, *126*(5). https://doi.org/10.1029/2020jb021325

Havlin, C., Holtzman, B. K., & Hopper, E. (2021). Inference of thermodynamic state in the asthenosphere from anelastic properties, with applications to North American upper mantle. *Physics of the Earth and Planetary Interiors*, *314*, 106639. https://doi.org/10.1016/j.pepi.2020.106639

IPCC. (2014). *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]*.

Jones, R. S., Mackintosh, A. N., Norton, K. P., Golledge, N. R., Fogwill, C. J., Kubik, P. W., Christl, M., & Greenwood, S. L. (2015). Rapid Holocene thinning of an East Antarctic outlet glacier driven by marine ice sheet instability. *Nature Communications*, *6*(1), 8910. https://doi.org/10.1038/ncomms9910

Kendall, R. A., Mitrovica, J. X., & Milne, G. A. (2005). On post-glacial sea level - II. Numerical formulation and comparative results on spherically symmetric models. *Geophysical Journal International*, *161*(3), 679-706. https://doi.org/10.1111/j.1365-246x.2005.02553.x

Kopp, R. E., Deconto, R. M., Bader, D. A., Hay, C. C., Horton, R. M., Kulp, S., Oppenheimer, M., Pollard, D., & Strauss, B. H. (2017). Evolving Understanding of Antarctic Ice-Sheet Physics and Ambiguity in Probabilistic Sea-Level Projections. *Earth's Future*, *5*(12), 1217-1233. https://doi.org/10.1002/2017ef000663

Larour, E., Seroussi, H., Adhikari, S., Ivins, E., Caron, L., Morlighem, M., & Schlegel, N. (2019). Slowdown in Antarctic mass loss from solid Earth and sea-level feedbacks. *Science*, *364*(6444), eaav7908. https://doi.org/10.1126/science.aav7908

https://doi.org/10.5194/egusphere-2026-2172
Preprint. Discussion started: 24 April 2026

Lau, H. C. P. (2023). Transient rheology in sea level change: Implications for Meltwater Pulse 1A. *Earth and Planetary Science Letters*, *609*, 118106. https://doi.org/10.1016/j.epsl.2023.118106

Lau, H. C. P. (2024). Surface loading on a self-gravitating, linear viscoelastic Earth: moving beyond Maxwell. *Geophysical Journal International*, *237*(3), 1842-1857. https://doi.org/10.1093/gji/ggae149

Lau, H. C. P., Austermann, J., Holtzman, B. K., Havlin, C., Lloyd, A. J., Book, C., & Hopper, E. (2021). Frequency Dependent Mantle Viscoelasticity via the Complex Viscosity: Cases From Antarctica. *Journal of Geophysical Research: Solid Earth*, *126*(11). https://doi.org/10.1029/2021jb022622

Lau, H. C. P., & Holtzman, B. K. (2019). "Measures of Dissipation in Viscoelastic Media" Extended: Toward Continuous Characterization Across Very Broad Geophysical Time Scales. *Geophysical Research Letters*, *46*(16), 9544-9553. https://doi.org/10.1029/2019gl083529

Lloyd, A. J., Wiens, D. A., Zhu, H., Tromp, J., Nyblade, A. A., Aster, R. C., Hansen, S. E., Dalziel, I. W. D., Wilson, T. J., Ivins, E. R., & O'Donnell, J. P. (2020). Seismic Structure of the Antarctic Upper Mantle Imaged with Adjoint Tomography. *Journal of Geophysical Research: Solid Earth*, *125*(3). https://doi.org/10.1029/2019jb017823

Lucas, E. M., Gomez, N., & Wilson, T. (2024). *The impact of regional-scale upper mantle heterogeneity on glacial isostatic adjustment in West Antarctica*. Copernicus GmbH. https://dx.doi.org/10.5194/egusphere-2024-2957

Mitrovica, J. X., Tamisiea, M. E., Davis, J. L., & Milne, G. A. (2001). Recent mass balance of polar ice sheets inferred from patterns of global sea-level change. *Nature*, *409*(6823), 1026-1029. https://doi.org/10.1038/35059054

Nick, F. M., Van Der Veen, C. J., Vieli, A., & Benn, D. I. (2010). A physically based calving model applied to marine outlet glaciers and implications for the glacier dynamics. *Journal of Glaciology*, *56*(199), 781-794. https://doi.org/10.3189/002214310794457344

Nield, G. A., Bentley, M. J., Koulali, A., Clarke, P. J., King, M. A., Wilson, T., & Whitehouse, P. L. (2025). Surface Mass Balance Variability Causes Viscoelastic Solid Earth Deformation in the Antarctic Peninsula. *Geophysical Research Letters*, *52*(12). https://doi.org/10.1029/2025gl114595

Picton, H. J., Stokes, C. R., Jamieson, S. S. R., Floricioiu, D., & Krieger, L. (2023). Extensive and anomalous grounding line retreat at Vanderford Glacier, Vincennes Bay, Wilkes Land, East Antarctica. *The Cryosphere*, *17*(8), 3593-3616. https://doi.org/10.5194/tc-17-3593-2023

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

Pollard, D., Deconto, R. M., & Alley, R. B. (2015). Potential Antarctic Ice Sheet retreat driven by hydrofracturing and ice cliff failure. *Earth and Planetary Science Letters*, *412*, 112-121. https://doi.org/10.1016/j.epsl.2014.12.035

Pollard, D., Gomez, N., & Deconto, R. M. (2017). Variations of the Antarctic Ice Sheet in a Coupled Ice Sheet-Earth-Sea Level Model: Sensitivity to Viscoelastic Earth Properties. *Journal of Geophysical Research: Earth Surface*, *122*(11), 2124-2138. https://doi.org/10.1002/2017jf004371

https://doi.org/10.5194/egusphere-2026-2172
Preprint. Discussion started: 24 April 2026

Pritchard, H. D., Fretwell, P. T., Fremand, A. C., Bodart, J. A., Kirkham, J. D., Aitken, A., Bamber, J., Bell, R., Bianchi, C., Bingham, R. G., Blankenship, D. D., Casassa, G., Christianson, K., Conway, H., Corr, H. F. J., Cui, X., Damaske, D., Damm, V., Dorschel, B.,…Zirizzotti, A. (2025). Bedmap3 updated ice bed, surface and thickness gridded datasets for Antarctica. *Scientific Data*, *12*(1). https://doi.org/10.1038/s41597-025-04672-y

Sadai, S., Condron, A., Deconto, R., & Pollard, D. (2020). Future climate response to Antarctic Ice Sheet melt caused by anthropogenic warming. *Science Advances*, *6*(39), eaaz1169. https://doi.org/10.1126/sciadv.aaz1169

Sadai, S., Karmalkar, A. V., Pollard, D., Dong, Y., Lucas, E., Gomez, N., Deconto, R., & Condron, A. (2025). Antarctic meltwater alters future projections of climate and sea level. *Nature Communications*, *16*(1). https://doi.org/10.1038/s41467-025-64438-3

Schoof, C. (2007). Ice sheet grounding line dynamics: Steady states, stability, and hysteresis. *Journal of Geophysical Research: Earth Surface*, *112*(F3). https://doi.org/10.1029/2006jf000664

Sergienko, O. (2025). Treatment of the ice-shelf backpressure and buttressing in two horizontal dimensions. *Journal of Glaciology*, *71*, 1-40. https://doi.org/10.1017/jog.2024.83

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*, 1-12. https://doi.org/10.1017/jog.2024.43

Spada, G., Ruggieri, G., Sørensen, L. S., Nielsen, K., Melini, D., & Colleoni, F. (2012). Greenland uplift and regional sea level changes from ICESat observations and GIA modelling. *Geophysical Journal International*, *189*(3), 1457-1474. https://doi.org/10.1111/j.1365-246x.2012.05443.x

Stokes, C. R., Abram, N.J., Bentley, M.J. et al. (2022). Response of the East Antarctic Ice Sheet to past and future climate change. *Nature*(608), 275-286. https://doi.org/https://doi.org/10.1038/s41586-022-04946-0

Thomas, R. H. (1979). The Dynamics of Marine Ice Sheets. *Journal of Glaciology*, *24*(90), 167-177. https://doi.org/10.3189/s0022143000014726

van Calcar, C. J., Bernales, J., Berends, C. J., van der Wal, W., & van de Wal, R. S. W. (2025). Bedrock uplift reduces Antarctic sea-level contribution over next centuries. *Nature Communications*, *16*(1), 10512. https://doi.org/10.1038/s41467-025-66435-y

Weertman, J. (1974). Stability of the Junction of an Ice Sheet and an Ice Shelf. *Journal of Glaciology*, *13*(67), 3-11. https://doi.org/10.3189/s0022143000023327

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

Yamauchi, H., & Takei, Y. (2016). Polycrystal anelasticity at near-solidus temperatures. *Journal of Geophysical Research: Solid Earth*, *121*(11), 7790-7820. https://doi.org/10.1002/2016jb013316

Zeitz, M., Haacker, J. M., Donges, J. F., Albrecht, T., & Winkelmann, R. (2022). Dynamic regimes of the Greenland Ice Sheet emerging from interacting melt–elevation and glacial isostatic adjustment feedbacks. *Earth System Dynamics*, *13*(3), 1077-1096. https://doi.org/10.5194/esd-13-1077-2022