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Grounding-Line Retreat and Sea-Level Feedback in Pine Island Glacier: A Century-Scale Perspective

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Grounding-Line Retreat and Sea-Level Feedback in Pine Island Glacier: A Century-Scale Perspective

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Abstract: A vital component of the global climate system is the Antarctic Ice Sheet (AIS). West AIS's major outlet is Pine Island Glacier (PIG), which has been rapidly thinned as well as accelerated recently. As per numerous studies, PIG is undergoing irreversible retreat and acceleration. Yet, there is a lack of studies on the coupled feedback mechanism between the ice sheets and Sea Level (SL) in the PIG. Therefore, this research aims to examine the feedback mechanism between AISs as well as SL, specifically focusing on PIG evolution over a period of 100 years by utilizing datasets like MEaSUREs BedMachine Antarctica, Version 3, MEaSUREs Annual Antarctic Ice Velocity Maps, Version 1, along with ISMIP6 Antarctica Results. The study uses the Icepack framework. The study finds that the high stress zones of basal and driving shear stresses are near the Grounding Line (GL) and central flowline. Transect-based projection shows that there is an ice loss near the GL and downstream areas, and dynamic thickening in upstream zones. A surge in accumulation rate leads to a reduction in SL Equivalent (SLE).

Keywords: *Antarctic Ice Sheet, Sea Level, Pine Island Glacier, Coupled Feedback, and Ocean-Induced Melting.*

1. INTRODUCTION

The major potential source, as well as an uncertain contributor to global SL Rise (SLR) is the AIS (Noble et al., 2020). The solid Earth, as well as the oceans along with the atmosphere, employs a sturdy influence on the AIS's dynamics (Whitehouse et al., 2019). Currently, the West AIS has retreated as well as diluted at hastening rates in the Amundsen Sea Embayment (ASE); also, it is foretold to endure this trend. Glaciers that discharge ice to ASE are misplacing mass at cumulative rates, driven by improved oceanic melting under the floating ice shelves that confine (buttress) their flow. Ongoing mass loss of Thwaites along with PIG is a concern (Joughin et al., 2021; Braddock et al., 2022). PIG, which has donated more to global mean SLR when weighed against any other glacier in Antarctica, is one amongst the largest ASE glaciers. Recently, the glacier has lost in a glut of a trillion tons of ice, or else the equivalent of 3 mm (SLR) (Reed et al., 2024; Rydt et al., 2021). PIG dismisses in a melting ice shelf, as well as ocean circulation, along with temperature, are concerned in the retreat as well as its contribution to PIG and nearby glaciers' SLR (Webber et al., 2017). For instance, the abridged ice load about the ice margin permits bedrock to rebound in ice sheet retreat, shallowing the bathymetry along with minimizing ice flux in the GL. Below the ice sheets, bedrock topography's deformation has key feedback on longer-term ice evolution, in which ice fluxes thru the GL are delicate to bathymetry (Pollard et al., 2017).

In places where thick, marine-terminating GLs have lost their strengthening ice shelves, ice (wastage rate) is functional at the GL in places in which vertical ice cliffs are tall enough to generate stresses, which surpass the ice yield strength (Kopp et al., 2017). For constant basal properties, significant variations in glacier flow velocity can only be caused by tidal forcing and transmission of dynamical perturbation (Gillet-Chaulet et al., 2016). In the past, numerous researchers have examined the AISs' SL contribution. The ice loss is conquered by the obliging as opposed to an internal instability in sturdy ocean warming scenarios. (Levermann et al., 2020) found that the Antarctic ice dynamic contribution's uncertainty due to atmospheric warming was increasing. The ice loss owing to basal ice shelf melting was 10.2mm, with a likely range between 5.2 as well as 21.3mm from 1992 to 2017. (Albrecht et al., 2024) conducted a coupled ice sheet-solid Earth simulation for two glacial cycles. In West Antarctica, in a glacial climate related to the far-field SL lower stand, the authors found the ice sheet's GL advanced up to the continental shelf edge, dominated

by a self-amplifying GIA. In a separate study, the author (Kachuck et al., 2020) highlighted that an effective equilibrium betwixt PIG's retreat as well as the reply of a weak viscoelastic mantle reduced the ice mass lost by 30% for 150 years with no bed formation.

Likewise, (Siahaan et al., 2022) performed a coupling betwixt the UK Earth system as well as BISICLES ice sheet to examine Antarctic ice-climate connections under 2 climate change scenarios. The augmented snowfall dominated the grounded ice's mass budge, causing an ensemble mean Antarctic contribution to 22mm (fall) (global mean SL) by 2100 in the Shared Socioeconomic Pathway (SSP5-8.5). Another author (Barnes & Gudmundsson, 2022) compared Thwaites and PIGs and the neighbouring regions' mass loss. Key qualitative geographical alterations in the relation betwixt sliding parameters as well as the modelled reaction to changes in forcing were detected. The Weertman, Tsai, as well as regularised Coulomb laws displayed comparable actions in changing things the sliding exponent (m) as well as the friction coefficient (C) values. In the view of (Lowery et al., 2025), near the PIG ice shelf GL, basal melting melted a channel's western flank 50% more when weighed against eastern flank. (Liu et al., 2022) found that PIG's ice flow velocity was augmented from 2.3 km/year in 1973 to 4.5 km/year in 2020. Ice shelf rifting as well as calving's acceleration, correlated with the destruction of shear margins. Even though interactions betwixt ice sheets as well as the solid Earth have been planned within the GIA field, there is a lack of studies on the coupled feedback mechanism between AISs as well as SL. The research aim is to explore the coupled feedback between AISs and SL, particularly focusing on the PIG evolution over a 100-year projection period. The objectives of the research are,

- To investigate the behavior of PIG at different forcings to elucidate its impact on glacier stability and ice discharge.
- To examine the basal and driving shear stress for understanding the dynamics as well as the motion of ice in the ice-freezing PIG.
- To evaluate the changes in the ice sheet as well as SLR of PIG over the next 100 years.

The latter part of the research is divided into a few sections: Section 2 describes the research methodology adopted in this study. The results are analyzed and given in Section 3. In Section 4, the discussion is provided by comparing the findings of the current study with existing studies. Lastly, the study settles with finding summary, their limitations, as well as future research directions.

2. METHODOLOGY

2.1. Data Collection

The datasets used in the study were MEaSUREs BedMachine Antarctica, Version 3, MEaSUREs Annual Antarctic Ice Velocity Maps, Version 1, along with ISMIP6 Antarctica Results. MEaSUREs BedMachine Antarctica provided the data related to bed topography, surface elevation, ice thickness, and GL positions. MEaSUREs Annual Antarctic Ice Velocity Maps provided the velocity data. ISMIP6 Antarctica Results were used to understand the modeling framework and parameterizations required for ice sheet dynamics.

2.2. Visualization of PIG

Mesh generation for PIG followed the standard workflow implemented within the Icepack framework, which builds upon Firedrake and provides established tools for glacier and ice-shelf domain construction. While Icepack tutorials commonly demonstrate mesh generation through fully scripted geospatial processing pipelines, in this study, we adopted an equivalent Icepack-supported approach by directly utilizing the glacier outline available within the Icepack dataset repository and associated utilities. The outline of PIG is shown in Figure 1.

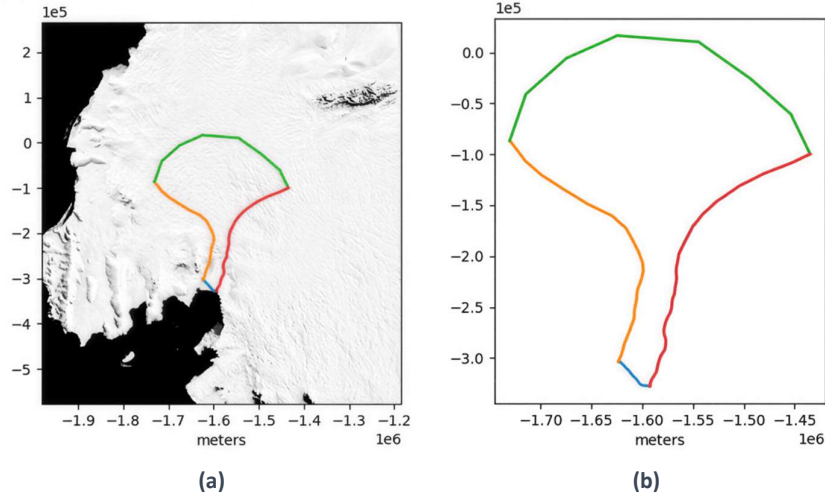


Figure 1: Outline of PIG

This approach ensures consistency with previously validated Icepack domain definitions while allowing the generation of a stable and high-quality computational mesh suitable for high-resolution simulations of PIG dynamics. The resulting mesh preserves the essential geometric characteristics of the glacier domain and is fully compatible with subsequent dynamical simulations performed in this study. The generated mesh of PIG is shown in Figure 2.

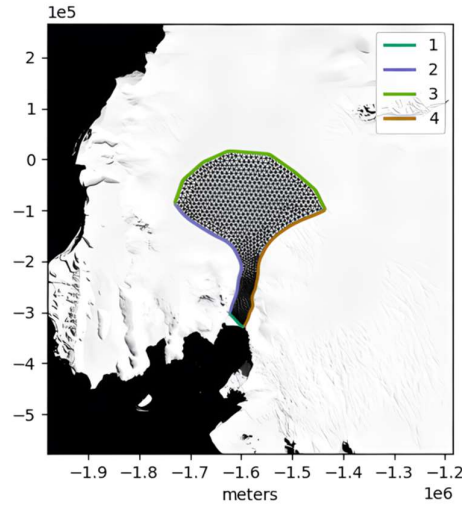


Figure 2: Mesh of PIG

The .msh file was given to Firedrake to form the computational domain. The Firedrake comprised a stack of specialized components, which implemented a set of multi-layered abstractions to offer automated finite element computation as of a higher-level specification. The triangular elements were processed to capture high-resolution details of the GL. The data from the dataset (MEaSURES BedMachine Antarctica, Version 3) were added to the computational mesh to characterize the bed topography, surface elevation maps, as well as ice thickness. Surface velocity data (V_x and V_y) as of the dataset, MEaSURES Annual Antarctic Ice Velocity Maps, were used for ice velocity field initialization. In Figure 3, the bed topography, surface elevation maps, ice thickness, as well as velocity are shown.

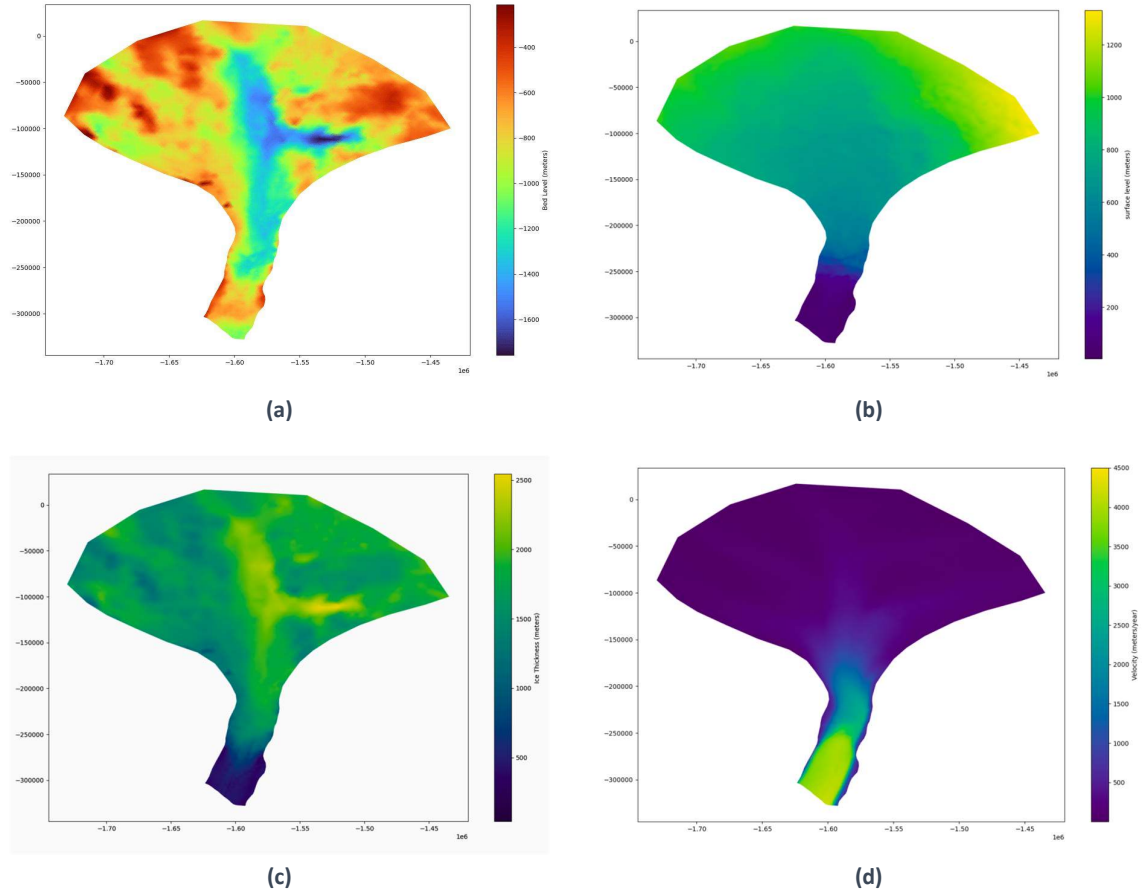


Figure 3: (a) Bed topography, (b) surface elevation maps, (c) ice thickness, and (d) velocity of PIG

2.3. Smoothing Function

The Laplacian regularization technique was used for surface smoothing to mitigate the small-scale noise in the surface elevation data. A regularization parameter ' α ' was used to control smoothing. The diagnostic plots of average percent change in surface elevation and total surface roughness are given in Figure 4.

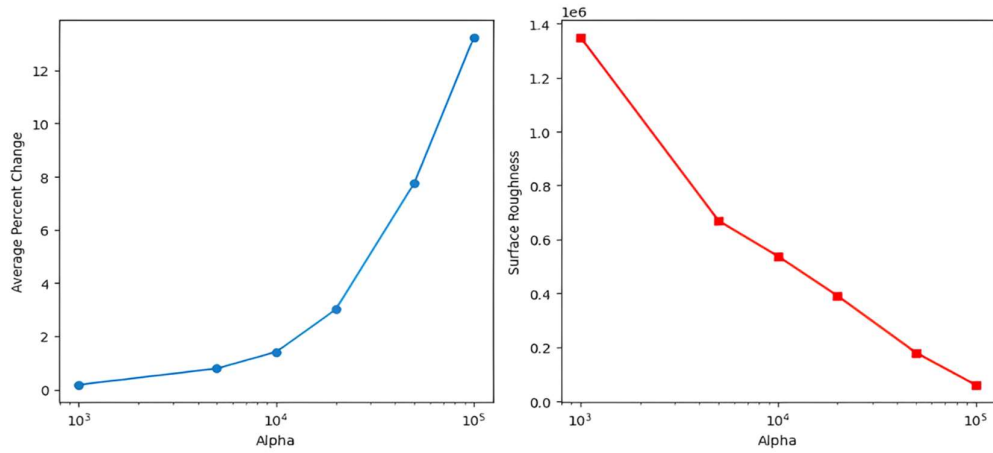


Figure 4: Average percentage change while smoothing v/s alpha and Surface Roughness v/s alpha

Based on visual inspection and quantitative diagnostics, $\alpha = 10^4$ was chosen for this study as it achieved a reasonable trade-off between geometric fidelity and numerical smoothness, presenting only 7.765% average change while significantly reducing surface roughness. Figure 5 shows the post-smoothing plots of ice sheet thickness, surface level, and elevation boundaries of PIG.

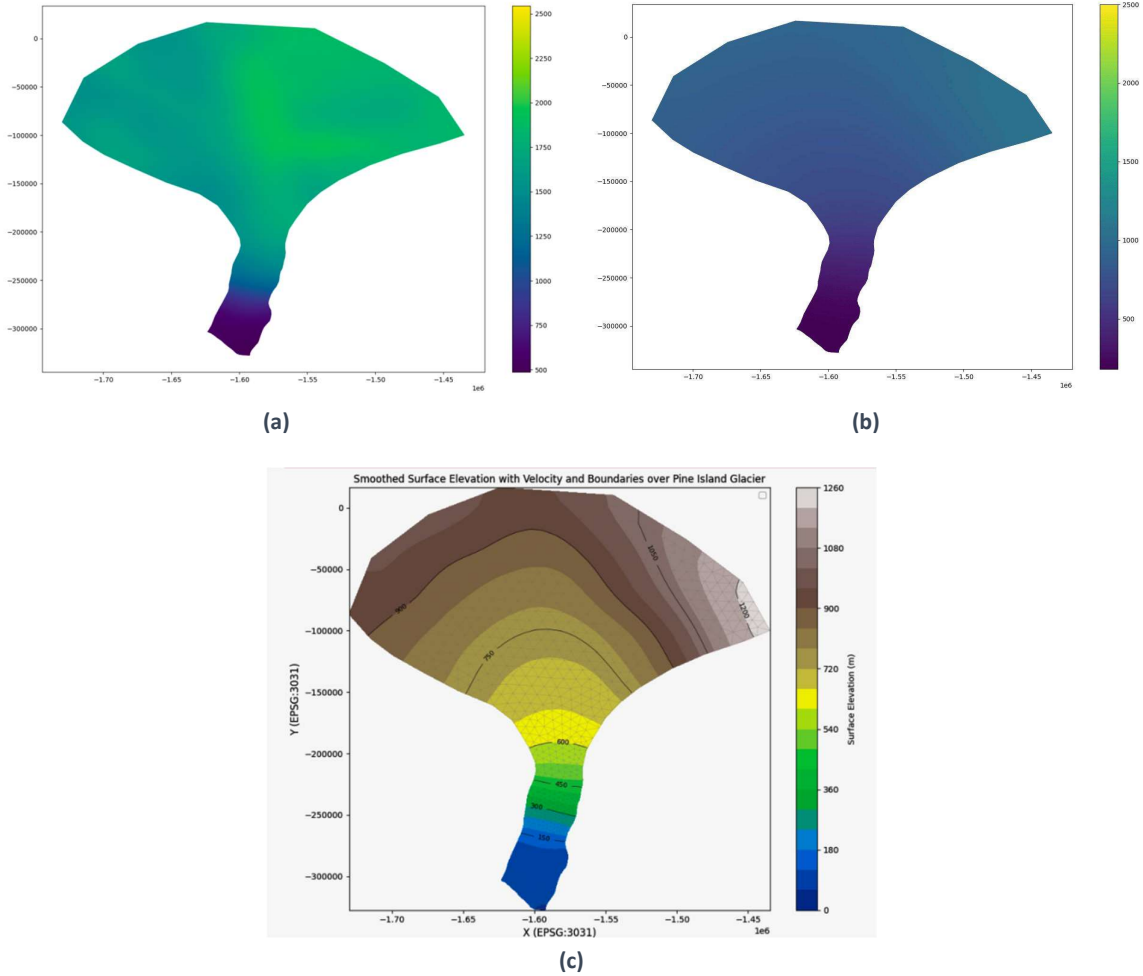


Figure 5: Post-smoothing plots of (a) ice sheet thickness, (b) surface level, and (c) elevation boundaries

2.4. Basal Shear Stress and Driving Shear Stress

The basal shear stress (τ_b) was calculated by employing the Weertman sliding law, which is given as,

$$\tau_b = \beta^2 |u|^{1/m}$$

Where, m is $1/3$, β depicts the friction coefficient, as well as u signifies the horizontal velocity. The driving stress (τ_d) is calculated as,

$$\tau_d = \rho_i g h |\nabla s|$$

Here, ρ_i signifies the ice density, g depicts gravitational acceleration, h implies ice thickness, as well as $|\nabla s|$ signifies the surface slope magnitude.

2.5. Velocity Computation Using a Custom Basal Friction Law in Icepack

The basal shear stress (τ_b) was calculated based on effective pressure N , which in turn was derived from the difference between the ice overburden pressure ($\rho_i g h$) as well as the sub-glacial water pressure ($\rho_w g \max(0, -(s - h))$). The formula for yield stress was $\tau_c = N / 2$. Regularization was applied using a velocity scale ($u_c = (\tau_c / C)^m$). The basal velocity magnitude was $u_b = \sqrt{u \cdot u}$. The expression for the returned basal shear stress was $\tau_b = \tau_c [(u_c^{1/m+1} + u_b^{1/m+1})^{m/(m+1)} - u_c]$. Figure 6 shows the modeled ice velocity field and the velocity difference between the modeled and observed fields.

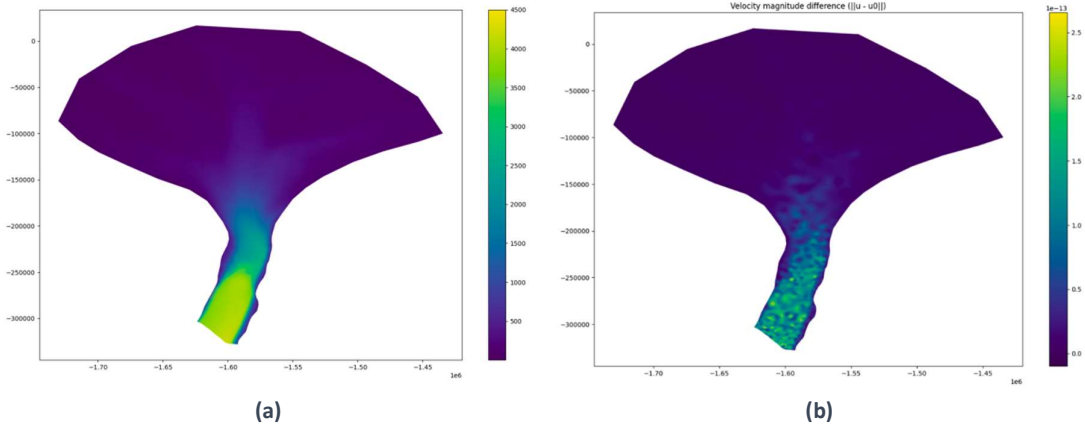


Figure 6: Plots of (a) modeled ice velocity field and (b) velocity difference between the modeled and observed fields

3. RESULTS

3.1. Basal and Driving Shear Stress

3.1.1. Basal Shear Stress

It is a critical factor used to regulate PIG dynamics. The high and low stress zones were identified near the GL as well as tributary junctions and beneath fast-flowing streams and near the ice shelf, correspondingly. The basal shear stress in PIG and its log-based distribution are given in Figure 7. Figure 7(b) demonstrated that the glacier bed of PIG attained moderate stress values ranging from 10 to 30 kPa, and extremely high stress zones acted as pinning points.

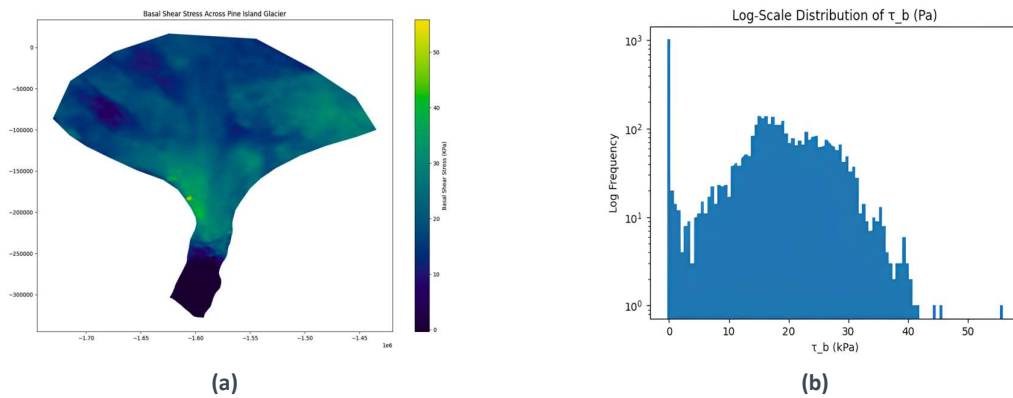


Figure 7: (a) Basal shear stress in PIG and (b) its log-based distribution

3.1.2. Driving shear stress

Driving stress is the gravitational force component parallel to the ice surface that drives glacier and ice sheet flow. It is the primary force responsible for the motion of ice masses. The high and low stresses on the central flow line near the GL as well as upstream along with downstream floating regions, respectively. The findings revealed that the dynamics of PIG were highly impacted by the interaction between surface slope and ice thickness. The driving shear stress in PIG and its log-based distribution are given in Figure 8.

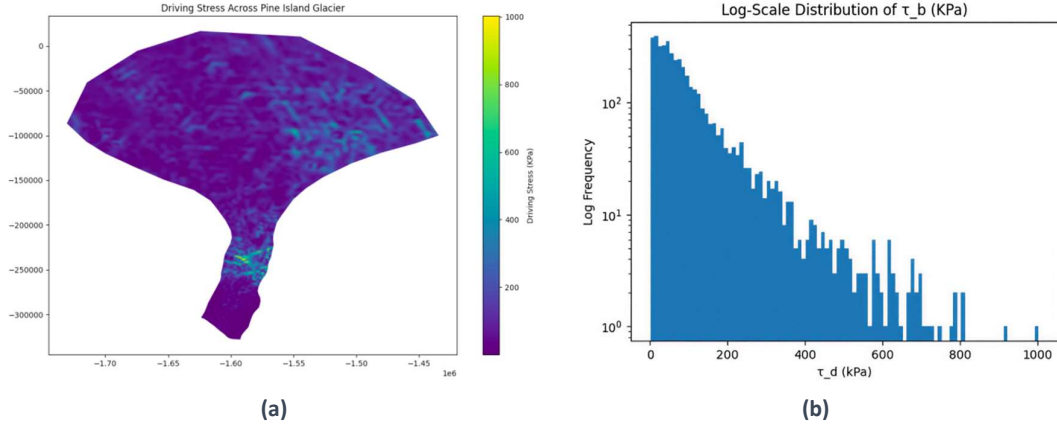


Figure 8: (a) Driving shear stress in PIG and (b) its log-based distribution

3.1.3. Reduced Shear Stress Analysis

The reduced shear stress or residual stress was the difference between the basal and driving shear stress. The spatial distribution and histogram of residual stress are displayed in Figure 9.

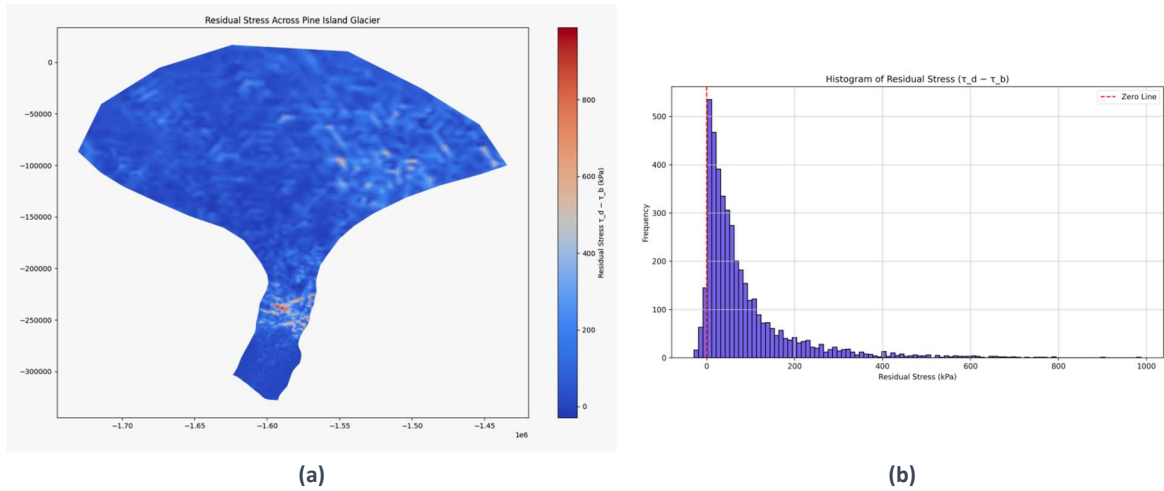


Figure 9: (a) Residual stress in PIG and (b) its histogram

3.2. Evolution of PIG for the Next 100 Years

3.2.1. Transect-based projection and elevation profile analysis of PIG

The Firedrake-based Icepack framework was used to perform the 100-year simulation. The findings showed a subglacial trough between approximately 40 km and 120 km along the transect. This played a crucial role in controlling ice dynamics and potential retreat. However, the ice base elevation did not always coincide exactly with the bed elevation due to subglacial hydrology, numerical approximation, and

model limitations and smoothing. The ice base elevation showed the modeled position of the ice underside after accounting for flow, accumulation, and thickness evolution over the 100-year projection period. The thickest region of PIG along the transect is shown in Figure 10a, and the elevation profile along the transect after the 100-year simulation is shown in Figure 10b.

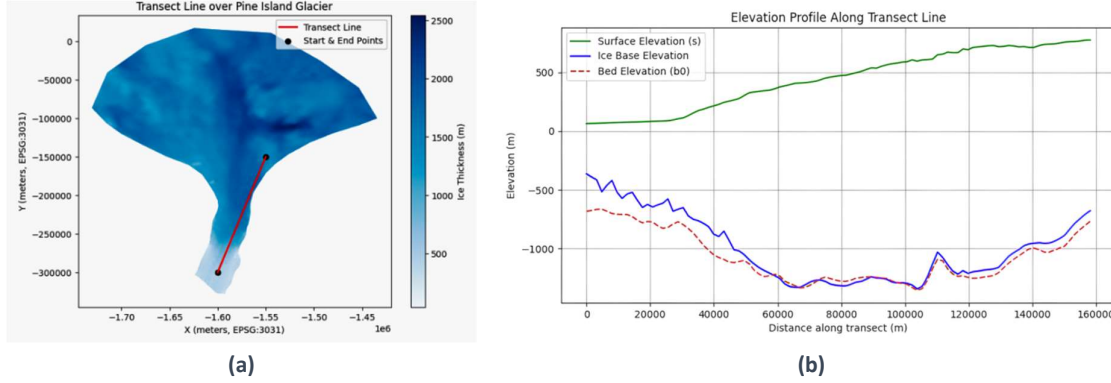


Figure 10: (a) Transect line and (b) Elevation profile

3.2.2. Ice sheet thickness change over 100 years

A 100-year forward simulation was performed to examine the temporal evolution of PIG using a prognostic solver within the ice flow model framework. Figure 11 displays the thickness of ice sheets for PIG over 100 years.

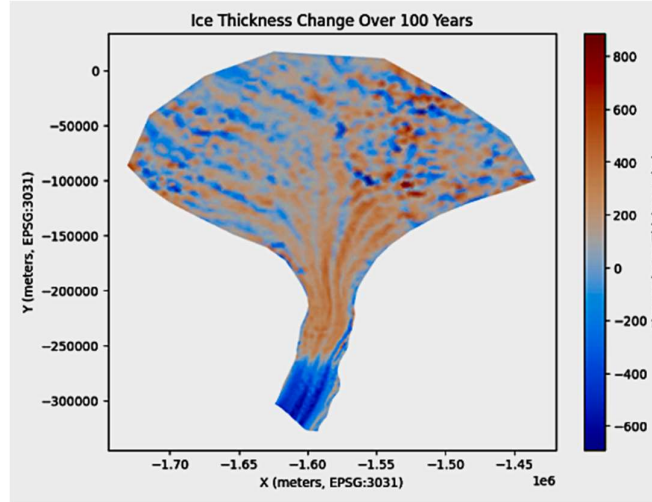


Figure 11: Change in ice thickness

In Figure 12, the red and blue regions indicate the ice thickening and thinning regions, respectively. The result revealed that there was a loss of ice near the GL along with downstream areas and dynamic thickening in upstream areas due to compensatory inflow. The resulting change in binary thickness at the end of 100 years is illustrated in Figure 12.

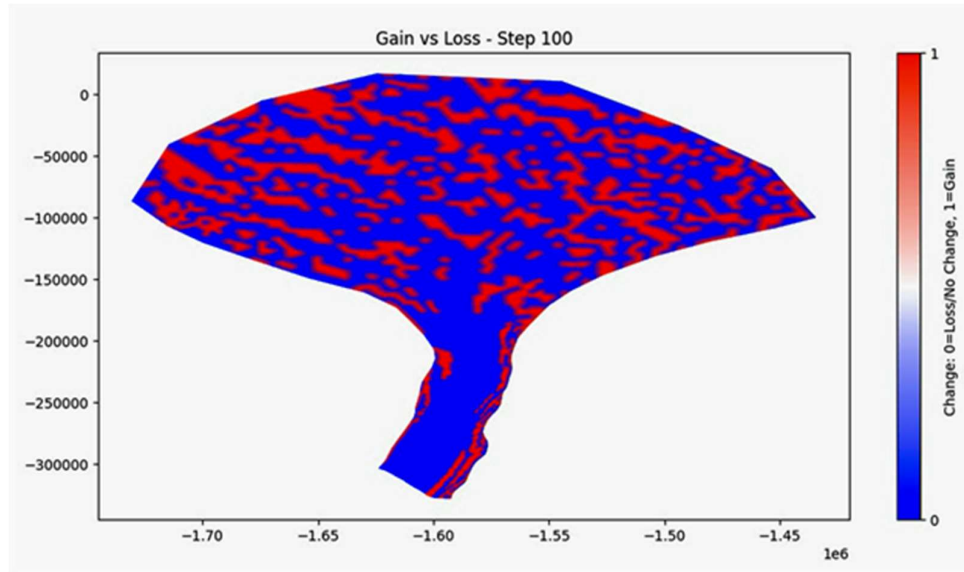


Figure 12: Binary thickness Change at the end of 100 Years

3.2.3. Accumulation rate on projection of sea level rise for 100 years

The relationship between the accumulation rate as well as the SL rise equivalent was examined for the FIG. Net ice volume change, ice mass change, as well as SLE over 100 years for different accumulation rates are given in Table 1.

Table 1: Accumulation rate on the projection of sea level rise

Accumulation rate (m/yr)	Net ice volume change (m ³)	Net ice mass change (Gt)	Sea level equivalent (mm)
0.00	-3.297583×10^{11}	-302.83836	0.8339623
0.20	-1.632895×10^{11}	-149.73643	0.4037736
0.40	3.179387×10^9	2.91550	-0.008
0.60	1.696842×10^{11}	15.556743	-0.433962
0.80	3.361171×10^{11}	308.21936	-0.841509
1.00	5.025859×10^{11}	460.87129	-1.271698

To assess FIG sensitivity to surface mass balance forcing, a set of idealized simulations was performed in which the surface accumulation rate was prescribed uniformly across the glacier domain and held constant over a 100-year projection. Accumulation rates ranging from 0.0 to 1.0 m yr⁻¹ were examined, and the resulting changes in ice volume, ice mass, and SLE are summarized in Table 1.

SLE was computed diagnostically from changes in ice volume beyond floatation, normalized by the global ocean surface area and corrected for the density contrast between ice and seawater, thereby isolating the input of grounded ice to global mean SL.

As shown in Table 1, low accumulation rates (≤ 0.2 m yr⁻¹) result in net grounded ice loss and a positive SL contribution of up to ~ 0.8 mm over the 100-year period. Increasing accumulation progressively reduces ice loss, with a transition to near-zero SL contribution occurring at an accumulation rate of ~ 0.4 m yr⁻¹. For higher accumulation rates (≥ 0.6 m yr⁻¹), FIG gains grounded ice mass, producing a negative SLE of up to ~ 1.2 mm at 1.0 m yr⁻¹.

This experiment represents an idealized sensitivity analysis rather than a realistic climate projection, as accumulation is spatially uniform and temporally constant and ocean-driven basal melting is not dynamically coupled. Nonetheless, the results in Table 1 provide a first-order quantification of the accumulation thresholds required to offset dynamically driven ice loss at PIG. The relationship between the accumulation rate and SL equivalent is shown in Figure 13.

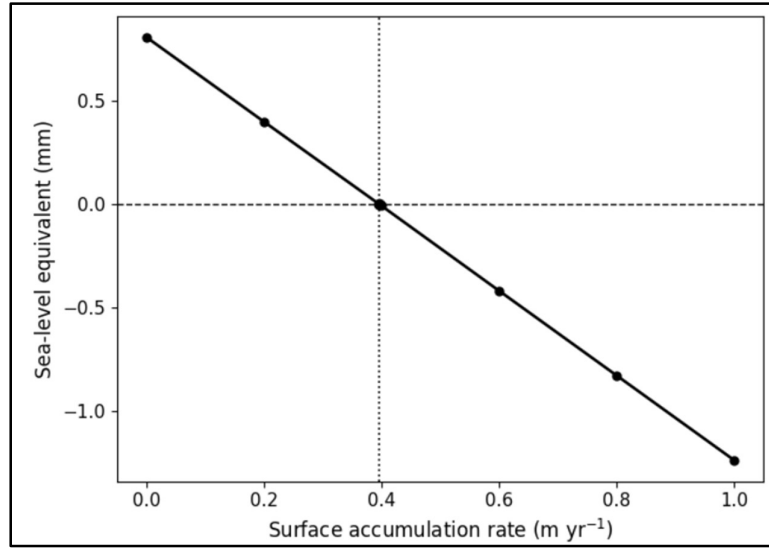


Figure 13: Graph showing accumulation rate vs sea level equivalent

3.2.4. Projection of Volume above Floatation under Various Climatic Scenarios

The volume above floatation was used to measure the influence of grounded ice sheets on SLR. SLs responded to climate change on timescales from decades to millennia. Projections were calculated using climate models. This study included 2 climatic scenarios: the RCP 2.6 along with RCP 8.5 scenario. The projection of PIG for 100 (2000 to 2100) years on the RCP 2.6 as well as RCP 8.5 scenario is given in Figures 14 and 15, respectively.

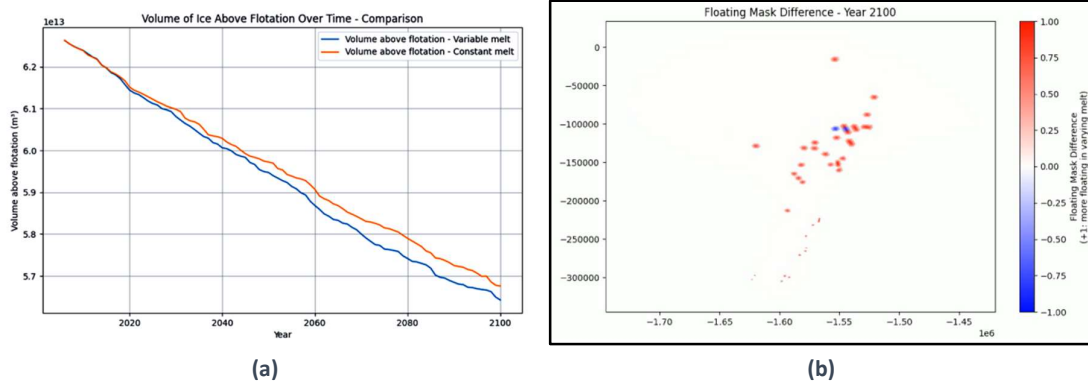


Figure 14: RCP 2.6 Scenario (a) volume of ice above floatation and (b) floating mask difference

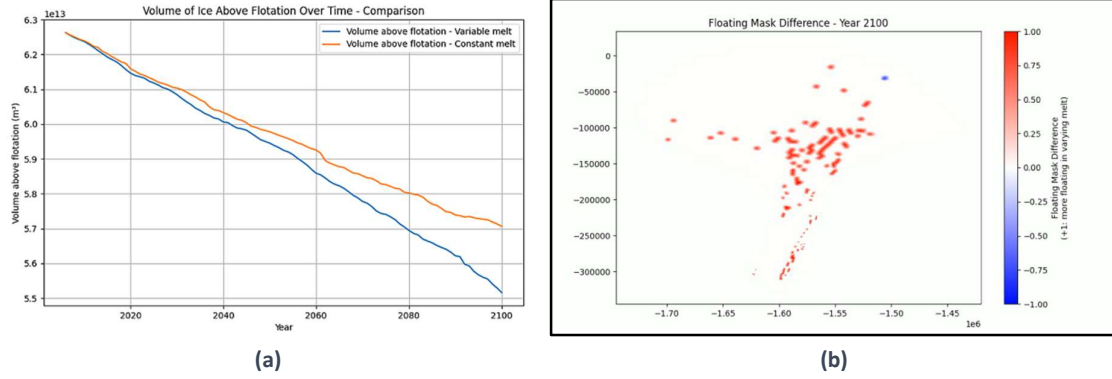


Figure 15: RCP 8.5 Scenario (a) volume of ice above floatation and (b) floating mask difference

Figures 14(a) and 15(a) show the comparison between variable melt and constant melt. Both scenarios show a significant surge in ice above floatation volume over 100 years. However, when compared with RCP 2.6, RCP 8.5 had a high constant melt and a low variable melt.

3.3. Oceanic Thermal Forcing and Its Influence on Ice-Shelf Melting

Ocean-driven melting of Antarctic ice shelves is governed by the thermal obliging of ocean waters entering the ice-shelf cavity, which depends on the surrounding ocean's temperature as well as salinity characteristics. Here, surface ocean temperature along with salinity fields are available only over the outer oceanic region adjacent to PIG and are therefore interpreted as boundary conditions characterizing the large-scale ocean forcing acting on the glacier system, rather than as representations of sub-ice-shelf conditions.

The surface ocean salinity and surface ocean temperature fields in the outer region of PIG are shown in Figure 16. These fields provide a first-order description of the oceanic environment supplying heat and salt to the ice-shelf margin. Surface salinity reflects relatively saline ocean waters characteristic of the Amundsen Sea continental shelf presence, while surface ocean temperatures indicate conditions sufficiently warm to contribute to basal melting once advected beneath the ice shelf. Given the available ocean data's limited spatial extent, no inference is made regarding the spatial variability of temperature or salinity within the ice-shelf cavity or beneath grounded ice.

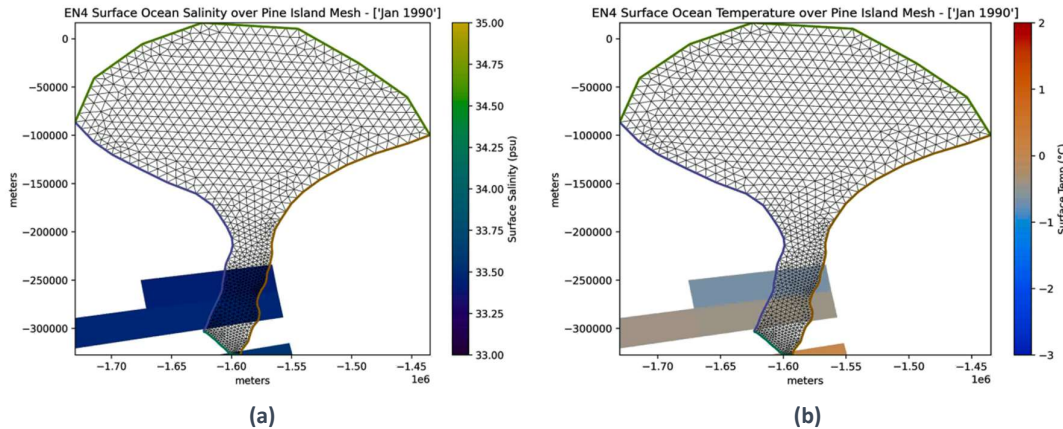


Figure 16: (a) surface ocean salinity and (b) surface oceanic temperature

The influence of ocean temperature and salinity on ice-shelf melting is mediated through their control on the resident freezing point of seawater and the resulting thermal forcing. Figure 17(a) shows the temporal evolution of the mean freezing point associated with the oceanic forcing of PIG between 1990 and 2020.

The freezing point remains within a narrow range, varying between approximately -1.81°C and -1.86°C , indicating modest variability in the combined temperature–salinity state of the ocean forcing over this period. The corresponding mean thermal forcing is shown in Figure 17(b), which exhibits more pronounced temporal variability, decreasing from approximately 2°C in the early 1990s to around 1°C by 2010.

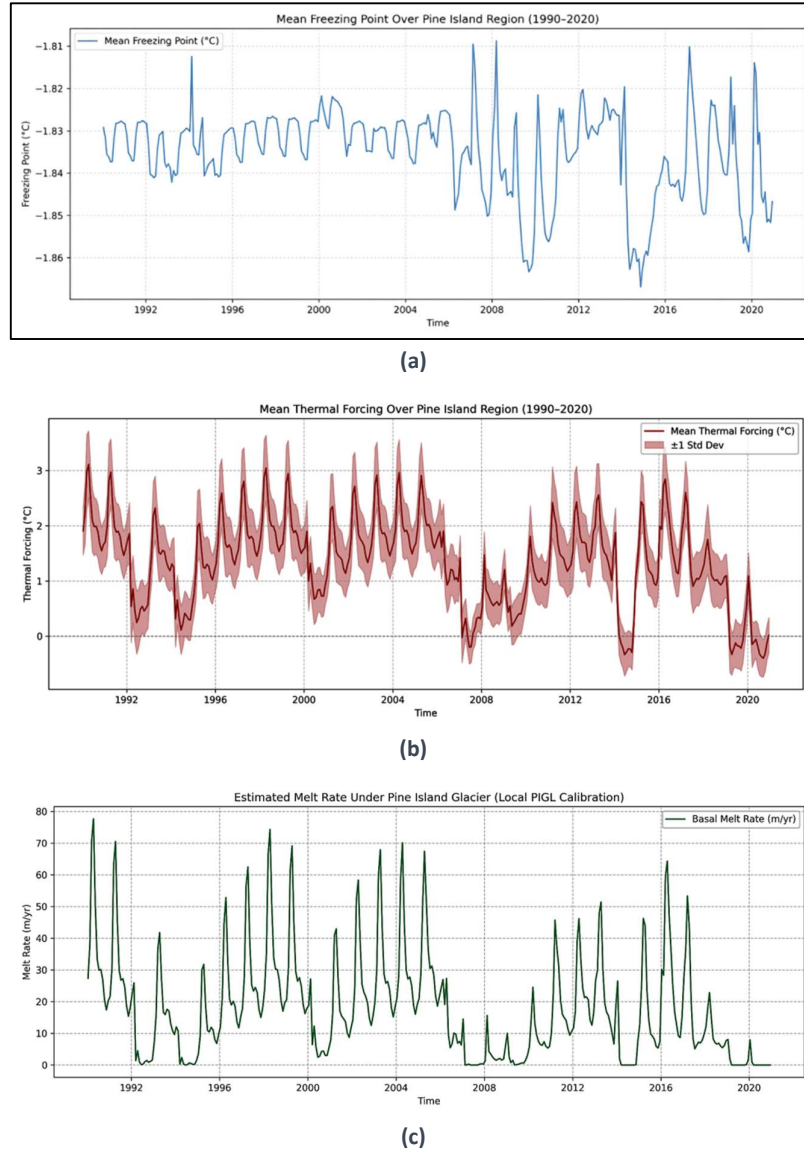


Figure 17: (a) Mean freezing point, (b) mean thermal forcing, and (c) melting rate

The temporal variability in thermal forcing is reflected in the modeled basal melt rates beneath the PIG ice shelf (Figure 17c). Mean melt rates decrease substantially over the 1990–2020 period, from approximately 78 m yr^{-1} in 1990 to around 8 m yr^{-1} by 2020. This decline occurs concurrently with the reduction in thermal forcing, indicating modeled melt rates' strong sensitivity to variations in external ocean heat supply. While the present analysis does not dynamically resolve ocean circulation in the ice-shelf cavity, the results demonstrate that variability in large-scale ocean temperature and salinity forcing exerts a first-order control on ice-shelf melt rates at PIG.

4. DISCUSSION

Here, the present study analyzed the coupled feedbacks between AISs as well as SL, particularly focusing on the PIG's evolution over a 100-year projection period. The basal and driving shear stress indicated that areas near the GL, tributary junctions, central flow line, and upstream floating regions exhibited higher stresses. Further, beneath fast-flowing streams, near ice shelves, and downstream, floating regions exhibited lower stresses. In a study, the authors (Joughin et al., 2024) found that basal shear stresses were found to be high in GL, central trunk, along with PIG's outlying tributaries (strong areas upstream). Driving stress was reduced near the GL (Joughin et al., 2019).

Surface ocean temperature and salinity exhibit spatial variability thru the PIG region, with relatively warmer and more saline conditions associated with enhanced ocean forcing. Variability in these ocean properties are depicted to play a key role in modulating basal melting at PIG. As per Webber et al. (2017), variations in ocean forcing can substantially influence melt rates, while also emphasizing the challenges of constraining melt processes using limited temperature and salinity observations. In long-term ice-sheet evolution context, Seroussi et al. (2024) found that under higher-emission scenarios, the Antarctic contribution to global mean SL remains below approximately 30 cm SLE by 2100 but surges to reach 4.4 m SLE by 2300. The present study found that in the RCP 8.5 scenario, the volume above floatation was 5.71m^3 and in the RCP 2.6, it was 5.68m^3 . The results from transect-based profiling and ice sheet thickness change over 100 years identified that there was a continued retreat and thinning of the glacier with the decrease in accumulation. An increase in accumulation led to a decrease in SL equivalent. Likewise, (Siahaan et al., 2022) stated that an upsurge in growth dominated the surface mass balance, and this had no direct contribution to SLR. Uncertainties' early estimates in projections of future SL change as of the AIS were derived as of sensitivity studies, which appraised a minor sample of a parameter space openly in individual ice sheet models (Hill et al., 2021). A sensitivity analysis of accumulation rate versus SLR equivalent indicated a nearly linear relationship, with a critical mass balance point around 0.4 m/yr. The current study's findings highlighted the PIG's mass balance sensitivity to changes in surface accumulation rates as well as its influence to SLR under diverse climate scenarios.

5. CONCLUSION

Here, the study explored the coupled feedback between AISs as well as SL, particularly focusing on the PIG evolution over a 100-year projection period. The analysis of basal and driving shear stresses revealed the areas of high stress near the GL, which acted as critical control points for ice discharge and stability. The thinning of ice was found near the GL and downstream areas, and thickening was found in upstream zones. The higher accumulation rate caused in a reduction in SL equivalent as well as an increase in ice volume and mass. At the accumulation rate of 0.4 m/yr, there was no net SLR. This study identified the sensitivity of ice sheet evolution to surface mass balance. However, the present study used a fixed accumulation rate and ignored temporal changes in ocean temperatures or sub-ice-shelf melt rates. Also, the study did not implement the dynamic coupling of GIA with evolving ice sheet geometry. Thus, the future study will use transient climate forcing to improve the projections. Also, it will include a 3D viscoelastic Earth model to provide a wider understanding of feedbacks affecting the GL's stability.

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