

# Retreat of Thwaites Glacier Triggered by its Neighbours

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## Key Points:

- Limited retreat of present-day Thwaites Glacier in response to submarine melting of its floating ice shelf
- Dynamical interactions with its neighbours can drive very rapid and substantial retreat in Thwaites
- Extreme ice shelf forcing scenarios or reduced basal stress near the grounding line can also drive widespread grounding line retreat

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## Abstract

The Amundsen Sea Embayment in West Antarctica is experiencing the most rapid mass loss and grounding line retreat in Antarctica. Its glaciers are vulnerable to retreat through marine ice sheet instability. There is uncertainty over the timing and magnitude of retreat and in particular the response of Thwaites Glacier to thinning of its ice shelf and to ocean forced retreat of its neighbouring glaciers. We find that the response of Thwaites to melting of its ice shelf is limited. However, retreat of its neighbours can drive substantial retreat in Thwaites. We examine the impact of ice shelf buttressing on the stability of the grounding line. Further experiments show that extreme ice shelf forcings are required to trigger retreat in Thwaites in isolation. We also demonstrate that long-term stability is sensitive to the treatment of basal stress near the grounding line.

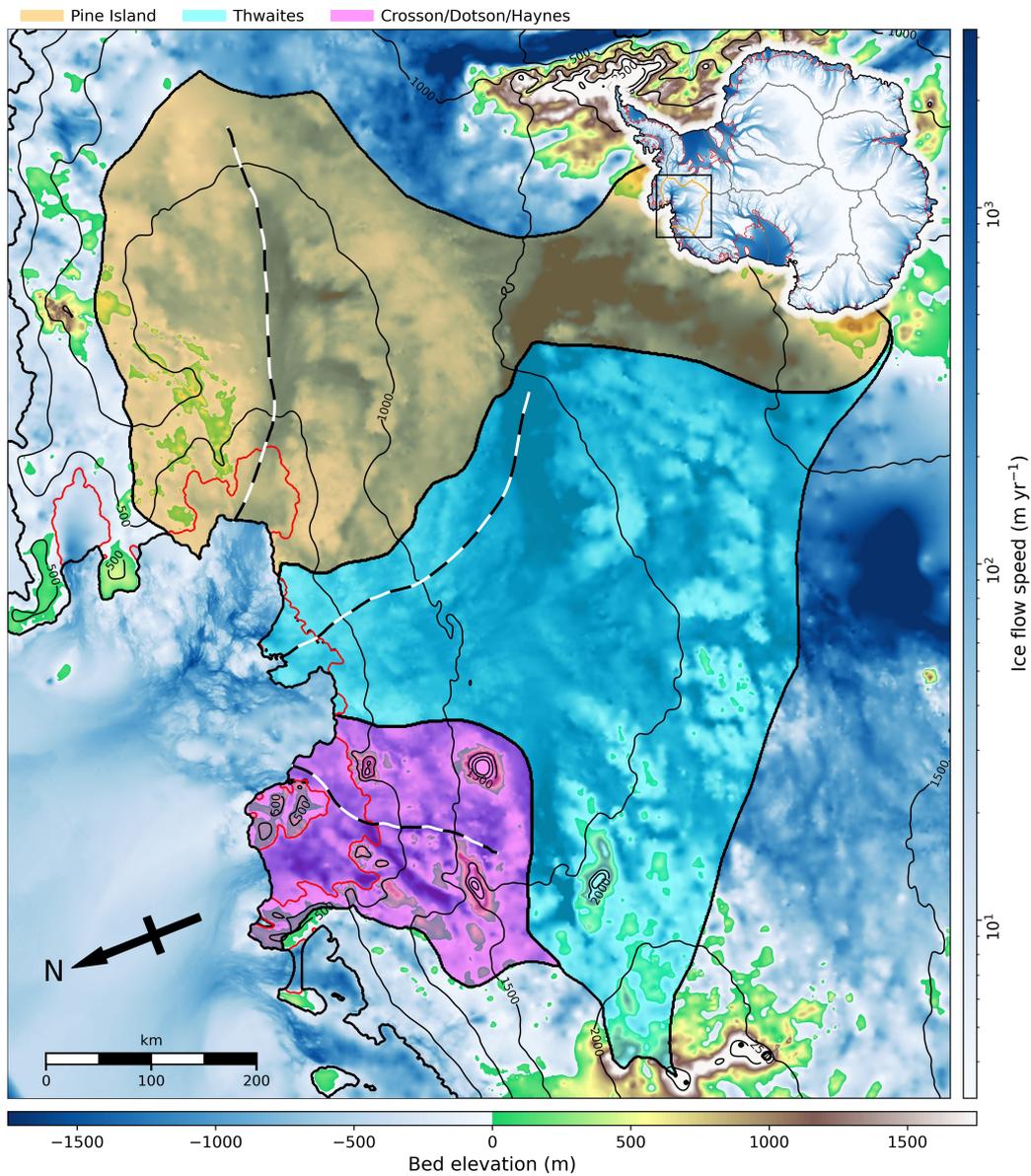
## Plain Language Summary

Glaciers of the Amundsen Sea Embayment in West Antarctica, including Thwaites Glacier, are discharging ice to the oceans and contributing to rising sea levels faster than anywhere else in Antarctica. Thwaites' ice shelf, a floating extension of the glacier, is likely to disintegrate over coming decades. There is disagreement over the impact this will have on the flow of upstream ice, with some recent studies suggesting that the ice shelf is already so weakened that its loss will not have any major consequence. In line with those studies, we find that over millennial timescales Thwaites is not strongly affected by ocean-driven melting of its ice shelf, except in extreme ocean circulation scenarios. However we find that interactions with neighbouring glaciers can trigger widespread retreat across the Amundsen Sea Embayment through previously unexplored feedback processes. We also find that Thwaites' long-term stability is dependent on the physics of the ice-bed interface. Our results demonstrate that individual Antarctic glaciers cannot be modelled as isolated systems, and highlight the need for an improved understanding of basal conditions and processes.

## 1 Introduction

The largest uncertainty in projections of global sea level rise (SLR) over the coming centuries is due to the contribution of the Antarctic Ice Sheet (Church et al., 2013). The fastest present-day mass loss is occurring in the Amundsen Sea Embayment (ASE) in West Antarctica (Shepherd et al., 2018). Thinning rates of several meters per year are observed for the ice shelves and grounding regions of the ASE (B. E. Smith et al., 2020) driven by strong ocean warming and sub-shelf melting (e.g. Naughten et al., 2022; Holland et al., 2023). The ASE is at risk of rapid grounding line retreat by marine ice sheet instability (MISI; Weertman, 1974; Schoof, 2007), which could potentially lead to collapse of the marine-based sectors of the West Antarctic Ice Sheet (WAIS) (Hughes, 1981; Feldmann & Levermann, 2015a). MISI can occur when the grounding line is positioned on a retrograde bed slope below sea level. Buttressing arising from lateral drag in confined ice shelves or pinning on ice rises beneath unconfined tongues can confer stability to grounded ice on a retrograde bed slope (e.g. Dupont & Alley, 2005; Goldberg et al., 2009; Favier & Pattyn, 2015). Ocean-forced thinning of ice shelves therefore has the potential to trigger grounding line retreat (R. B. Alley et al., 2015).

The configuration of the ASE ice streams, shelves and drainage basins is shown in Figure 1. The Crosson/Dotson (CD) basin contains the complex system of (from west to east) Kohler, Smith, Pope and Haynes glaciers discharging ice into the confined Dotson and Crosson ice shelves which branch around Bear Peninsula. The CD shelves and their tributary glaciers have seen thinning, acceleration and grounding line retreat in recent years (Lilien et al., 2018), with retreat rates of up to 11.7 km/year observed for Pope Glacier in 2017 (Milillo et al., 2022). This retreat is hypothesised to be driven by strong ice-ocean interactions in newly opened cavities.



**Figure 1.** Bed topography of the ASE domain. Thick black lines show the initial ice front extent and basin boundaries, red lines the initial grounding line, thin black contours ice surface elevation and dashed black and white lines flowlines used in this study. Transparent shaded regions highlight individual glacier basins (Mouginot et al., 2017). The inset map shows Antarctic-wide flow speeds (Mouginot et al., 2019) with drainage boundaries from (Zwally et al., 2012). The black box shows the extent of the ASE domain within Antarctica.

Thwaites Glacier (TG) contains the sea level equivalent (SLE) of 0.6 m of ice and is one of the largest contributors to modern-day SLR (Holt et al., 2006). The grounding line retreated by 14 km from 1992 to 2011 (Rignot et al., 2014) and the mass loss rate increased by 22 Gt/year between 2006 and 2014 (Mouginot et al., 2014). The present-day grounding line is situated on a submarine ridge roughly 250 to 1000 m below sea level, with the bed rapidly deepening upstream. The TG ice shelf (TGIS) has undergone significant changes in recent decades (K. E. Alley et al., 2021). The TGIS is composed of the western ice tongue (TWIT) and the eastern ice shelf (TEIS) separated by a shear margin. TWIT detached from its pinning point around 2009 and rapidly disintegrated and accelerated (Miles et al., 2020). TEIS remains grounded on a pinning point near its ice front, confining TEIS and slowing ice flow relative to TWIT. TEIS initially accelerated following unpinning of TWIT but decelerated again as the shear margin weakened. The TEIS pinning point has progressively weakened due to thinning of TEIS since 2009 and may unpin entirely within a decade (Wild et al., 2022). Benn et al. (2022) suggested that backstress from the pinning point contributes to weakening and fracturing of TEIS as it thins.

Pine Island Glacier (PIG) is the single largest Antarctic contributor to SLR in recent decades (Rignot et al., 2019). It experienced significant 20th century retreat following ungrounding from a prominent seafloor ridge (J. A. Smith et al., 2017). Its present day grounding line is located in a constriction of the bed trough through which it discharges ice into its confined ice shelf (PIIS) (Reed et al., 2024). It has continued to thin and retreat in recent years (Mouginot et al., 2014; Rignot et al., 2019).

Both modelling and observational studies have suggested that MISI-driven retreat may already be underway for PIG and TG (e.g. Favier et al., 2014; Rignot et al., 2014; Mouginot et al., 2014; Joughin et al., 2014). More recent modelling studies have suggested a more limited SLR contribution by 2100, with the timing and magnitude of retreat sensitive to uncertain model parameters and the applied forcing (Yu et al., 2018; Alevropoulos-Borrill et al., 2020). Nias et al. (2016) found that unpinning of TEIS had negligible effect on the flow of grounded ice, while Benn et al. (2022) and Gudmundsson et al. (2023) both suggested that TEIS has limited buttressing impact and that its loss would be unlikely to trigger significantly increased ice discharge from TG.

A number of studies have demonstrated that dynamical interactions between neighbouring basins can significantly effect projected mass loss rates (Feldmann & Levermann, 2015a, 2015b; Martin et al., 2019). However ice sheet models commonly model isolated basins to limit the computational cost (e.g. Favier et al., 2014; Joughin et al., 2014; Seroussi et al., 2017) or whole ice sheets at reduced resolution (e.g. Feldmann & Levermann, 2015a; Gollidge et al., 2015; DeConto et al., 2021). In this study we examine interbasin interactions within the ASE and their dynamical impact on the evolution of the individual basins over millennial timescales. We find that TG retreat can be driven by the evolution of its neighbours and we explore the mechanisms driving the interactions. We conduct an analysis of the buttressing strength for different configurations of the TG ice shelf and grounding line. Further experiments apply enhanced forcings to test the limits of TG's grounding line stability.

## 2 Methods

We used the BISICLES adaptive mesh refinement (AMR) ice flow model (Cornford et al., 2013). The AMR functionality enables mesh resolution of 500 m at the grounding line in concert with coarser resolution of 4 km for inland ice. A modern-day ASE initial condition comprising consistent fields of basal friction coefficient  $C$ , ice stiffening factor  $\phi$  and a relaxed surface geometry was derived through an iterative procedure which follows Bevan et al. (2023); van den Akker et al. (2023) and which is detailed in Supporting Text S1. BedMachine v3 (Morlighem et al., 2020; Morlighem, 2022) provided

118 bed topography and pre-initialisation ice geometry. Non-evolving surface accumulation  
 119 rates came from the 1980 to 2021 mean of the MAR regional climate model (Agosta et  
 120 al., 2019). The three dimensional temperature field was generated by a thermal spin-up  
 121 which is described in Supporting Text S2. Model inputs are shown in Figure S3.

122 We carried out two sets of experiments, detailed separately below. The first set of  
 123 experiments, described in Section 2.1, explore the dynamical interactions between drainage  
 124 basins in the ASE. The second set, described in Section 2.2, apply a range of enhanced  
 125 forcings to TG in isolation.

## 126 2.1 Interbasin Interactions

127 These experiments explored the response of the ASE to the focused regional ap-  
 128 plication of basal melt, and the interactions between drainage basins. Sub-ice shelf melt  
 129 was applied for 1000 years to the isolated PIG, TG and CD basins, the combinations of  
 130 PIG+TG and CD+TG, and finally to all three basins combined. We applied the depth-  
 131 dependent melt rate parameterisation described in Supporting Text S3 which reached  
 132 a maximum of 250 m/year at a depth of 1000 m.

133 Basal stress for grounded ice was determined by a Regularised Coulomb friction  
 134 law,

$$135 \quad \boldsymbol{\tau}_{b,r} = -C |\mathbf{u}_b|^{m-1} \left( \frac{|\mathbf{u}_b|}{u_0} + 1 \right)^{-m} \cdot \mathbf{u}_b, \quad (1)$$

136 where  $C$  is the spatially varying friction coefficient,  $\mathbf{u}_b$  the basal sliding velocity,  $m =$   
 137  $1/3$  the friction law exponent and  $u_0 = 50$  m/year the fast sliding speed. This expres-  
 138 sion is equivalent to that introduced by Joughin et al. (2019). A variable calving rate  
 139 was applied at the ice front anti-parallel to the direction of ice flow,

$$140 \quad \mathbf{u}_c = -r_c \cdot \mathbf{u}_T, \quad (2)$$

141 where  $\mathbf{u}_T$  is the terminus velocity and  $r_c$  the constant calving multiplier. We set  $r_c =$   
 142  $1$  to prohibit ice front advance, while retreat can still result from thinning.

143 Results and discussion of these experiments are presented in Section 3.1, along with  
 144 an analysis of the buttressing strength for different configurations of the TG ice shelf and  
 145 grounding line. Animated plots of all experiments in this section are provided with the  
 146 supplementary material.

## 147 2.2 Thwaites Enhanced Forcings

148 In these experiments a range of enhanced forcings were applied to TG in order to  
 149 probe the limits of stability of its grounding line. Experiments were continued from the  
 150 final state after 1000 years of the TG melt experiment described in Section 2.1.

151 Sub-ice shelf melt was applied for a further 1000 years to the TG basin. Four sets  
 152 of enhanced forcings were applied: (1) The depth-dependent melt rate described in Sup-  
 153 porting Text S3 with a range of maximum values up to 2000 m/year at 1000 m depth.  
 154 (2) Melting was applied uniformly across the ice shelf independent of depth, with a range  
 155 of melt rates up to 1250 m/year. (3) Enhanced calving via a range of additional calv-  
 156 ing multipliers applied to floating ice in the TG basin with a draft of less than 100 m.  
 157 (4) Application of an alternative Coulomb-limited friction law introduced by Tsai et al.  
 158 (2015),

$$159 \quad \boldsymbol{\tau}_{b,T} = -\frac{\mathbf{u}_b}{|\mathbf{u}_b|} \cdot \min [|\boldsymbol{\tau}_{b,r}|, \alpha N], \quad (3)$$

160 where  $\alpha = 0.5$  is a dimensionless coefficient and  $N$  is the basal effective pressure.  $\boldsymbol{\tau}_{b,r}$   
 161 was calculated from Equation 1. This expression, referred to as the Tsai law from hereon  
 162 in, prohibits the basal stress from exceeding the effective pressure.

163 For all enhanced forcing experiments, model parameters from Section 2.1 were ap-  
 164 plied unless otherwise specified. Results and discussion of the response of TG to these  
 165 enhanced forcings are presented in Section 3.2.

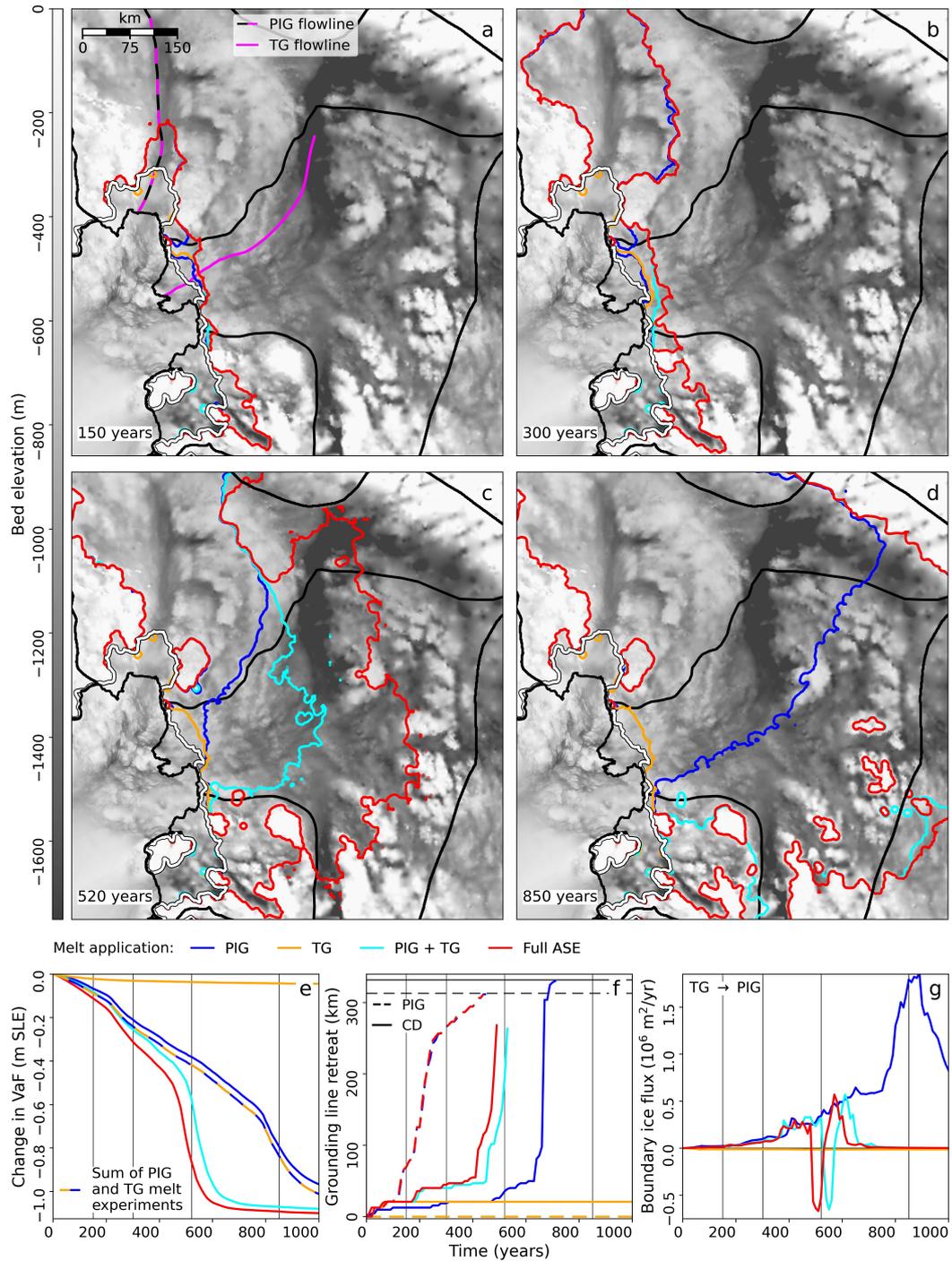
### 166 3 Results and Discussion

#### 167 3.1 Interbasin Interactions

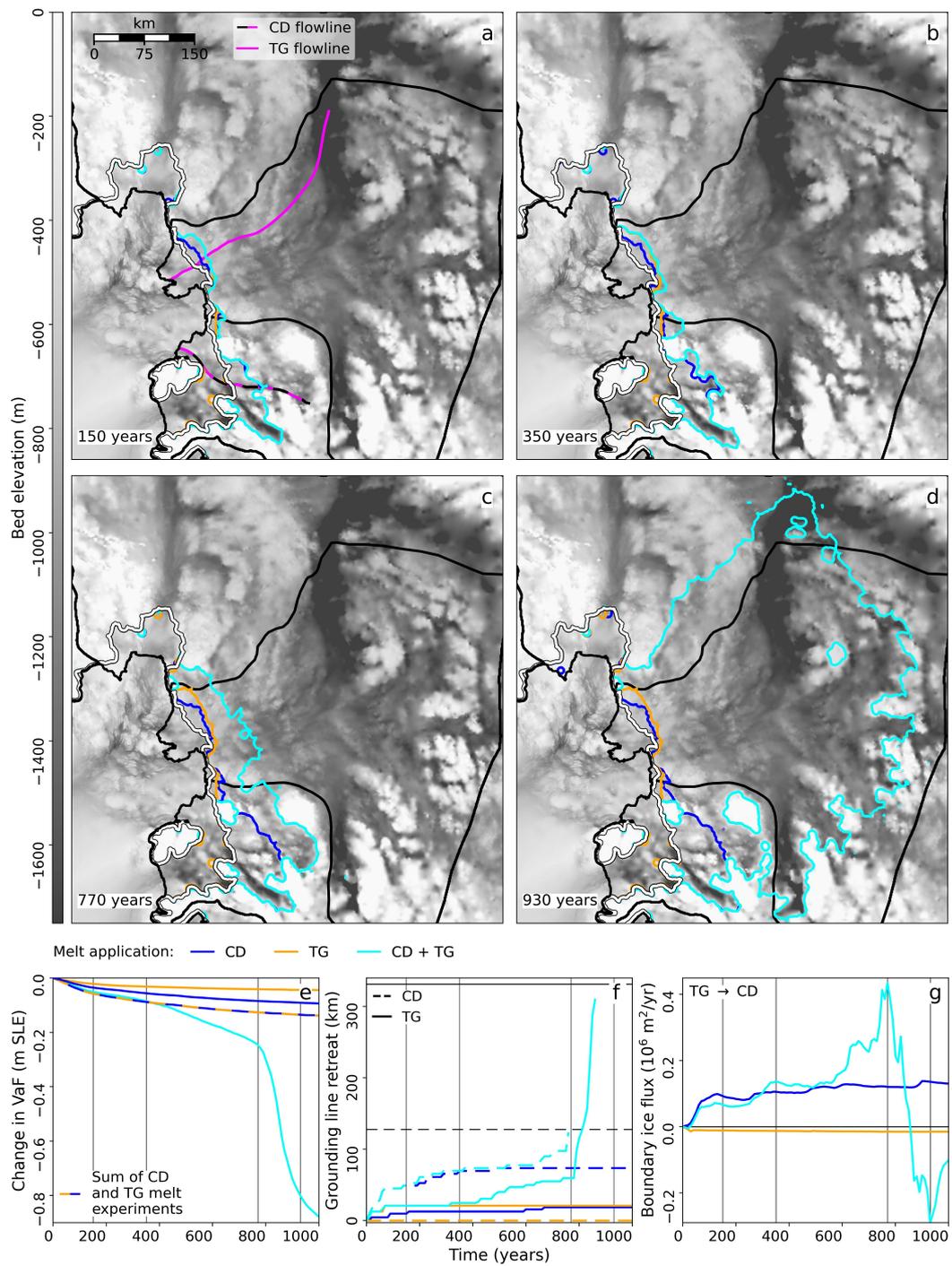
168 Figure 2 shows a contrast in the response of PIG and TG to melting of their ice  
 169 shelves. Melting of PIIS lead to almost complete deglaciation of the marine-based parts  
 170 of PIG within 1000 years, and complete or ongoing deglaciation of TG. PIG retreated  
 171 in every experiment in which it was subjected to the melt forcing (dashed lines, Panel  
 172 f). It retreated earlier than TG and at an almost identical rate between experiments,  
 173 indicating that its retreat is unaffected by its neighbour. By contrast, TG did not re-  
 174 treat significantly when TGIS was melted in isolation (orange lines), with its ground-  
 175 ing line restablising a few tens of kilometers upstream of its initial position. Instead re-  
 176 treat of PIG was necessary to trigger more substantial retreat in TG. The retreat and  
 177 thinning of PIG drove significant drawdown of ice from TG, seen as a large ice flux across  
 178 the basin boundary (blue line, Panel g). This enhanced thinning of inland ice in TG drove  
 179 retreat of its grounding line, which accelerated once it had retreated over deeper bed.  
 180 Applying melt simultaneously to both basins (cyan lines) triggered earlier retreat in TG  
 181 due to thinning from the combination of sources. The resulting simultaneous retreat in  
 182 both basins lead to ice fluxes in alternating directions across the dividing boundary at  
 183 different times (Panel g). At 525 years ASE mass loss peaked at  $\sim 7$  mm/year SLE, an  
 184 order of magnitude faster than the current observed mass loss rate for the entire ice sheet  
 185 (B. E. Smith et al., 2020). Grounding line retreat rates in TG peaked at  $\sim 7$  km/year  
 186 which is within the observed range of retreat rates Milillo et al. (2022). Applying melt  
 187 in all ASE basins (red lines) produced very similar patterns of mass loss, with retreat  
 188 in TG triggered 50 years earlier.

189 Figure 3 shows the interactions between the CD and TG basins. With melt applied  
 190 in isolation CD saw limited retreat, with its grounding line eventually restablising in a  
 191 retreated position up to  $\sim 100$  km upstream. Thinning in CD drove drawdown from TG  
 192 across the dividing boundary (blue line, Panel g), but the associated thinning in TG wasn't  
 193 sufficient to trigger retreat there. With melt was also applied to TG, the boundary ice  
 194 flux into CD was initially smaller since TG was also thinning (cyan line, Panel g). The  
 195 reduced inflow from TG drove further retreat in CD (Panel b), in turn driving increased  
 196 inflow from TG after 325 years. The enhanced thinning of TG eventually lead to very  
 197 rapid retreat of the TG grounding line (Panel f) and widespread deglaciation in both basins  
 198 (Panels c, d).

199 Martin et al. (2019) demonstrated the importance of ice-dynamical interactions be-  
 200 tween basins at the regional scale. They found a modest increase in the rate of mass loss  
 201 after  $\sim 100$  years when ASE melting was combined with melting in either the Eastern  
 202 Ross Sector (including the Siple Coast ice streams) or the Western Ronne sector, as com-  
 203 pared with the summed mass loss when melt was applied separately. Similarly, Feldmann  
 204 and Levermann (2015a) showed that thinning and retreat in the ASE could cause mi-  
 205 gration of the upstream ice divide into the Ross and Filcher-Ronne drainage basins, ul-  
 206 timately triggering collapse in those basins after several thousand years. By contrast,  
 207 interbasin interactions in our experiments drove significantly increased discharge within  
 208 a few hundred years and could trigger collapse of the CD and TG basins within a thou-  
 209 sand years. The interacting basins in our experiments are side-by-side neighbours with  
 210 ice flowing parallel to dividing boundaries, thus flow reorganization can occur rapidly  
 211 after the onset of retreat. In the earlier studies interactions occurred across the upstream  
 212 ice divide, hence with a significant lag following the onset of ocean-driven thinning.



**Figure 2.** Maps and timeseries of the ASE evolution for PIG, TG, combined PIG+TG and full ASE melt experiments. (a) to (d) Grounding lines for all experiments (coloured lines) at selected snapshots. Also shown are the basin boundaries and initial ice front (black lines) and initial grounding lines (white lines with black edges). Panel (a) also shows PIG and TG flowlines. (e) Change in ASE Volume above Flotation (VaF), including the summed VaF change of the individual PIG and TG melt experiments. (f) Grounding line retreat in PIG (dashed lines) and TG (solid lines). Lines are truncated where the grounding line retreats beyond the end of the flowline. Black horizontal lines show the flowline extents in PIG and TG respectively. Note that blue, cyan and red dashed lines overlap. (g) Ice thickness flux per unit length across the PIG-TG basin boundary, defined such that positive flux refers to flow out of the TG basin. Vertical black lines in (e) to (g) refer to panels (a) to (d).



**Figure 3.** Maps and timeseries plots of the evolution of the ASE for CD, TG and combined CD+TG melt experiments. (a) to (g) as for Figure 2, except that the dashed blue and orange line in (e) shows the summed VaF loss from individual CD and TG melt experiments, dashed lines in (f) refer to the CD basin and fluxes in (g) are measured across the CD-TG basin boundary.

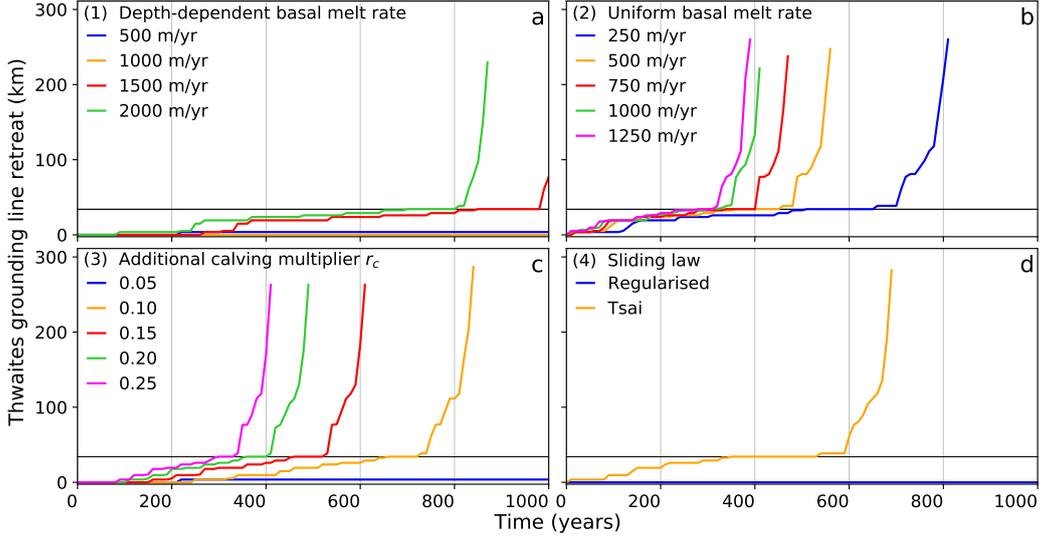
213 Gudmundsson et al. (2023) conducted an analysis of the strength of ice shelf but-  
 214 tressing in the ASE. They showed that TGIS provides limited buttressing compared with  
 215 the PIG and CD shelves, and that much of the buttressing provided by TGIS could be  
 216 explained by the small-scale embayments in the grounding line. We conduct a similar  
 217 analysis by computing the buttressing number  $\theta_n$ , the ratio of the resistive stress across  
 218 the grounding line to the resistive stress in the absence of an ice shelf. The formulation  
 219 of the buttressing number is described in Supporting Text S4. By definition  $\theta_n = 1$  where  
 220 there is zero buttressing. The ice shelf provides buttressing where  $\theta_n < 1$ , *anti-buttressing*  
 221 where  $\theta_n > 1$  and *super-buttressing* where  $\theta_n < 0$ . Figure S4 shows buttressing num-  
 222 bers calculated for TG grounding lines at the start and end of the isolated TG melt ex-  
 223 periment (orange lines, Figure 2). Both configurations follow elevated features of the un-  
 224 derlying bed. Local embayments were more heavily buttressed while convexities were of-  
 225 ten unbuttressed or even anti-buttressed. The histogram shows that the buttressing strength  
 226 in the final configuration decreased relative to the initial state, indicating that ground-  
 227 ing line stability was less dependent on the integrity of TGIS. Nonetheless, the final ground-  
 228 ing line still contains some localised strongly buttressed regions which might be vulner-  
 229 able to further degradation of TGIS. In three highlighted locations, the proximity of but-  
 230 tressed embayments in the final grounding line to overdeepened channels leading to the  
 231 basin interior provide potential pathways to rapid retreat and deglaciation.

232 We studied the impact of unpinning TEIS by reducing the basal friction coefficient  
 233 beneath the pinning point to zero in a diagnostic setting (Figure S5). This produced a  
 234 significant instantaneous speedup for floating ice, but the speedup for grounded ice was  
 235 limited to between 10 and 30% in a region within 25 km of the grounding line, focused  
 236 on an anti-buttressed grounded protrusion. There was a minor reduction in the buttress-  
 237 ing strength at the grounding line. A secondary pinning point located just downstream  
 238 of the grounding line was found to have negligible impact on buttressing or the flow of  
 239 TEIS. This demonstrates that while the pinning point constrains the flow of ice in TEIS,  
 240 its buttressing effect on grounded ice is limited due to the highly fractured nature of TEIS.  
 241 We find agreement with Benn et al. (2022) and Nias et al. (2016) who showed that un-  
 242 pinning of TEIS would have little impact on the discharge of grounded ice and is unlikely  
 243 to immediately trigger marine ice sheet instability, although both studies used the same  
 244 ice flow code as in this study. Wild et al. (2022) similarly found that ungrounding of TEIS  
 245 produced only a 10% speedup across the grounding line.

### 246 3.2 Thwaites Enhanced Forcings

247 In Section 3.1 we showed that TG is not strongly sensitive to melting of its own  
 248 ice shelf, with the grounding line restabilising a few tens of kilometers upstream. Ad-  
 249 ditional thinning of upstream grounded ice driven by interactions with neighbouring glaciers  
 250 was required to trigger more substantial retreat. The experiments in this section aim to  
 251 establish whether TG is always resistant to standalone forcing.

252 Figure 4 shows the TG grounding line retreat in response to the enhanced forcings  
 253 described in Section 2.2. These additional forcings were able to trigger substantial re-  
 254 treat in the TG basin, with more aggressive forcings producing earlier retreat. Retreat  
 255 followed a similar pattern in all cases, with gradual retreat in short sporadic episodes  
 256 until a final quasi-stable position was reached at 34 km. Further retreat from this po-  
 257 sition initiated rapid retreat as the bed deepens steeply upstream (Morlighem et al., 2020).  
 258 The rate of retreat slowed again across a region between  $\sim 75$  and  $\sim 125$  km upstream  
 259 before very rapid retreat was re-established, resulting in widespread deglaciation across  
 260 the TG basin. Retreat rates peaked between 5 and 10 km/year during the most rapid  
 261 phase of retreat (Figure S6). Figure S7 shows that the different types of forcing produced  
 262 similar patterns of retreat. Retreat tended to originate at the orange-highlighted em-  
 263 bayment in Figure S4 and followed overdeepened channels cutting through the elevated  
 264 bed region before reaching deeper bedrock further upstream. This demonstrates that de-



**Figure 4.** Grounding line retreat along the TG flowline for enhanced forcing experiments. Lines are truncated where the grounding line retreats beyond the end of the flowline, with the vertical scale covering the full flowline extent. Horizontal lines are drawn at 34 km.

265 spite TGIS being largely passive, localised remnant ice shelf embayments can still pro-  
 266 duce significant buttressing and their continued degradation can destabilise vulnerable  
 267 portions of the grounding line. We stress that these enhanced melt rates are much higher  
 268 than could be expected under modern conditions and are intended to establish the lim-  
 269 its of stability.

270 A depth-dependent melt rate peaking at 1500 m/year at 1000 m depth (red line,  
 271 Panel a) was required to trigger substantial retreat, whereas only 250 m/year of uniform  
 272 melting (blue line, Figure 4b) triggered earlier retreat. The 1500 m/year depth-dependent  
 273 melt forcing produced 572 Gt/year of melt across TGIS at the start of the experiment  
 274 whereas the 250 m/year uniform melt forcing produced more melt at 684 Gt/year. The  
 275 enhanced calving experiments (Panel c) produced similarly timed retreat to the uniform  
 276 melt rates. The resulting calving rates which peak at 125 % of the shelf front velocity  
 277 are seemingly within a realistic range (e.g. DeConto et al., 2021). However it should be  
 278 noted that the calving rate forcing was designed to produce continual degradation of the  
 279 ice shelf, and therefore unlike for the melt forcings it was impossible for the ice shelf to  
 280 reach a balanced equilibrium with the calving rate.

281 Limiting the basal stress to the effective pressure with the application of the Tsai  
 282 Law (Panel d, Equation 3) lowered the basal stress within a few kilometers upstream of  
 283 the grounding line, triggering an instantaneous speedup of up to 500 m/year (Figure S8).  
 284 This drove additional dynamic thinning, episodic grounding line retreat and further ac-  
 285 celeration, eventually leading to rapid widespread retreat after 600 years. This sensitiv-  
 286 ity to the choice of sliding law reflects our uncertainty and lack of knowledge of basal  
 287 condition, sliding mechanisms and grounding processes (e.g. Parizek et al., 2013; Joughin  
 288 et al., 2019; Zoet & Iverson, 2020). Ice flow models commonly assume a discrete ground-  
 289 ing line representing an abrupt transition from grounded ice upstream to floating ice down-  
 290 stream. In reality there is a less clearly defined grounding zone with variable grounding  
 291 strength, driven by tidal motion (e.g. Ciraci et al., 2023). Walker et al. (2013) showed  
 292 that tidal flexure of ice shelves could cause low tide uplift at centimeter scales a few kilo-  
 293 meters upstream of the grounding line, with the possibility for seawater intrusions, while

294 Milillo et al. (2022) observed grounding zones up to 3 km in width for Pope, Smith and  
 295 Kohler glaciers. Parizek et al. (2013) inferred the possibility of seawater influence up to  
 296 10 km inland from the grounding line. They showed that incorporating a grounding zone  
 297 with decreased basal friction into a model of TG was able to trigger retreat. The reduc-  
 298 tion in basal stress generated by the Tsai law in our experiments occurred across sim-  
 299 ilar distances upstream of the grounding line, creating an effective grounding zone. Our  
 300 results therefore support their conclusions.

## 301 4 Conclusions

302 We have demonstrated that the dynamical interactions between neighbouring basins  
 303 are a crucial component of the evolution of the ASE, and therefore important in assess-  
 304 ing the stability of WAIS. TG was resistant to melting of TGIS in isolation, and required  
 305 additional thinning generated by simultaneous melting of its neighbours to trigger sub-  
 306 stantial retreat. By contrast retreat of PIG was easily triggered and dominated the dy-  
 307 namics of its neighbours. We explored the limits of stability of TG and found that fur-  
 308 ther degradation of TGIS through extreme melting or enhanced calving could tip the  
 309 glacier into retreat. Our results provide further evidence that the present-day TGIS pro-  
 310 vides limited stability to the grounded glacier (e.g. Benn et al., 2022; Gudmundsson et  
 311 al., 2023), but localised remnant ice shelf embayments can still produce sufficient but-  
 312 tressing to halt further retreat. An alternative sliding law mimicking a grounding zone  
 313 with reduced ice-bed contact also produced rapid retreat after several centuries. Our study  
 314 demonstrates that for projections beyond decadal timescales, individual glacier basins  
 315 of WAIS cannot be considered as isolated systems. We also highlight the importance of  
 316 improved model implementations of sliding processes and grounding zone conditions to  
 317 inform more accurate projections of ice sheet evolution over coming centuries.

## 318 Open Research Section

319 The BISICLES ice sheet model is open source and is available for download from  
 320 <https://github.com/ggslc/bisicles-uob>. The data on which this study is based are avail-  
 321 able in Mouginit et al. (2017), Agosta et al. (2019), Mouginit et al. (2019), Burton-Johnson  
 322 et al. (2020), B. E. Smith et al. (2020) and Morlighem (2022). We did not generate any  
 323 new observational data products.

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 330 the computational facilities of the Advanced Computing Research Centre, University of  
 331 Bristol (<http://www.bristol.ac.uk/acrc/>).

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