



Multistability and hysteresis of the Greenland Ice Sheet in a fully-coupled Earth System-Ice Sheet Model

Malena Andernach^{1,2}, Marie-Luise Kapsch^{1,3}, and Uwe Mikolajewicz¹

¹Climate Variability, Max Planck Institute for Meteorology, Bundesstraße 53, 20146 Hamburg, Germany

²now at Friedrich-Alexander University, Erlangen-Nuremberg, Germany

³now at Deutscher Wetterdienst, Offenbach, Germany

Correspondence: Malena Andernach (malena.andernach@mpimet.mpg.de)

Abstract. The Greenland Ice Sheet (GrIS) is a critical tipping element in our Earth system, whose complete melt would raise global-mean sea levels by over 7 m. Yet, the temperature thresholds for its disappearance and subsequent recovery remain uncertain. Here, we simulate the state of the GrIS under increasing and decreasing temperatures in transient and equilibrium simulations using, for the first time, a comprehensive Earth System Model coupled to an Ice Sheet Model (ISM) that explicitly considers ice sheet-climate feedbacks and interactions. Our simulations indicate that the present-day GrIS destabilizes and disintegrates under a global warming of $2.55 \pm 0.15^\circ\text{C}$ above pre-industrial (PI) temperatures, corresponding to the model's equilibrium response of a sustained atmospheric CO_2 concentration (pCO_2) of 403.5 ± 3.5 ppm, once its volume declines to 87% of its PI state. Feedbacks and interactions of the GrIS with the atmosphere and ocean cause hysteresis and prevent full regrowth unless temperatures fall $1.3 \pm 0.1^\circ\text{C}$ below PI temperatures (equivalent to 227 ± 2.5 ppm pCO_2), which is substantially lower than previous estimates. These feedbacks also stabilize the GrIS at multiple intermediate states during regrowth, which remain stable even if subjected to warming. We also apply statistical early warning signals to our transient retreat and regrowth branch simulations to test whether the critical transitions can be predicted. These indicators detect GrIS destabilization, but not regrowth. Our results suggest that we have already crossed the critical pCO_2 threshold in our current climate: maintaining or increasing our present-day pCO_2 level in the long-term, triggers a practically irreversible loss of the GrIS. In our simulations, regrowth requires pCO_2 reductions far below PI levels sustained over a significantly longer period than the duration of the ice sheet retreat. This implies that full GrIS recovery is unlikely under realistic long-term carbon removal and stabilization pathways.

1 Introduction

At present, the Greenland Ice Sheet (GrIS) has become a major contributor to global sea-level rise due to the increase in surface meltwater run-off and the retreat of marine-terminating outlet glaciers van den Broeke et al. (2016); Bamber et al. (2018); on Climate Change (IPCC). Beyond a critical temperature threshold, the present GrIS could destabilize and undergo



rapid, self-sustained retreat, owing to positive feedbacks with the climate system (Robinson et al., 2012; Bochow et al., 2023; Höning et al., 2023; Gutiérrez-González et al., 2026). An example is the melt-elevation feedback, whereby the initial melt is amplified through the lowering of the surface elevation, exposing the ice sheet to warmer surface temperatures (Fyke et al., 2018). Such positive feedbacks could lead to a complete ice sheet loss and a persistent ice-free state, which would raise global-mean sea level by more than 7 m (Aschwanden et al., 2019; Van Breedam et al., 2020; Bochow et al., 2023). This would have far-reaching environmental, social and economic implications, such as a displacement of millions of people due to inundation (Hauer et al., 2020). Precursors of an impending critical transition have already been found for the western GrIS (Boers and Rypdal, 2021). This underscores the need for a profound understanding of long-term GrIS stability and the climate conditions leading to state transitions.

The temperature threshold for which the present-day GrIS potentially reaches a critical transition (bifurcation point) and becomes unstable has been estimated to fall within a warming range of 0.8 and 3.2 °C above pre-industrial (PI) levels (Robinson et al., 2012; Höning et al., 2023; Gutiérrez-González et al., 2026). Hence, given the 2015–2024 average of ~1.2 °C above PI levels (Forster et al., 2025), temperatures are already close to or even past the threshold for a destabilization of the GrIS, should the warming be maintained over the long-term. A loss of the GrIS could be irreversible, even if temperatures are subsequently reversed to PI levels, due to the existence of multiple steady states of the GrIS under PI greenhouse gas concentrations (Ridley et al., 2010; Gregory et al., 2020; Andernach et al., 2026). To return to a state comparable to the present-day GrIS configuration, climatic conditions colder than PI or than present-day temperatures might be required, indicative of hysteresis in the ice sheet behavior (Robinson et al., 2012; Solgaard and Langen, 2012; Höning et al., 2023; Gutiérrez-González et al., 2026). Previous studies suggested temperatures slightly below or above PI or present-day that are conducive for regrowth (Letréguilly et al., 1991; Robinson et al., 2012; Solgaard and Langen, 2012; Höning et al., 2023; Gutiérrez-González et al., 2026). However, these results are derived from models that do not capture the full complexity of ice sheet-climate interactions, although varying GrIS volumes induce substantial changes in atmospheric circulation patterns (Dethloff et al., 2004; Petersen et al., 2004; Junge et al., 2005; Langen et al., 2012; Andernach et al., 2025) and ocean dynamics (Davini et al., 2015; Andernach et al., 2025), which in turn impact the ice sheet’s mass balance (Andernach et al., 2026). For example, previously used Earth System Models of Intermediate Complexity (EMICs) feature strongly simplified atmospheric dynamics and coarse spatial resolution that limit the representation of key processes such as atmospheric circulation changes, moisture transport and cloud feedbacks (Claussen et al., 2002; Willeit et al., 2022). Thus, previous estimates of the temperature thresholds may not accurately reflect the GrIS’s stability. Further, it is uncertain whether the ice sheet experiences a single or multiple bifurcation points in its retreat and in its regrowth, as previous studies have yielded contrasting behavior (Letréguilly et al., 1991; Robinson et al., 2012; Höning et al., 2023; Gutiérrez-González et al., 2026). A stepwise response of the ice sheet to changing temperatures is supported by simulated multistability of the GrIS under PI and present-day temperature conditions (Ridley et al., 2010; Gregory et al., 2020; Andernach et al., 2026). For example, Andernach et al. (2026) identified four steady states of the GrIS under PI atmospheric CO₂ concentrations (hereafter referred to as pCO₂) using an Earth System Model (ESM) coupled to an Ice Sheet Model (ISM) and a solid Earth model.



When under gradually changing conditions, a dynamical system approaches a bifurcation point from one stable state to another, it recovers more slowly from small perturbations and shows an increased amplitude of fluctuations (Lenton, 2011; Lenton et al., 2012; Rietkerk et al., 2025). This 'critical slowing down' can be detected in time series through statistical parameters, so-called early warning signals, and allows us to predict critical transitions (Lenton et al., 2008; Scheffer et al., 2009). The most commonly used parameters in climatic and environmental data are the variance and the autocorrelation at lag-1 (AC1), which is the system's 'memory' (Held and Kleinen, 2004; Dakos et al., 2008; Lenton, 2011; Dakos et al., 2012; Boers and Rypdal, 2021; Smith and Boers, 2023; Rietkerk et al., 2025). As early warning signals can detect subtle signs of critical slowing down, they could provide early insight into upcoming state transitions, informing timely and effective mitigation strategies.

Here, we investigate the multiple steady states of the GrIS and the bifurcation points that lead to transitions between these states as a function of temperature for the first time with a comprehensive ESM, including dynamic ice sheets and solid Earth under transient climate forcing (see Section 2.1). Our model system features a physically consistent representation of the complex, nonlinear interactions between ice sheets and the other components of the climate system. Assessing the stability range of the multiple steady states of the GrIS allows us to examine its potential bifurcation points and hysteresis behavior in its regrowth. Given the possibility of the GrIS approaching a bifurcation point under continuous warming, and the devastating consequences of its disintegration, we also test whether potential bifurcation points in our transient simulations are preceded by a statistical early warning.

The study is organized as follows: Sect. 2 describes the model system, the simulation set-up and the parameter choice for the applied early warning signals. In Sect. 3, we present the stability landscape of the GrIS as a function of $p\text{CO}_2$ and the resulting global-mean temperature. We also answer the question whether it is possible to predict the bifurcations in our simulations. Sect. 4 discusses the results with respect to previous studies and puts them into a broader context. A conclusion is given in Sect. 4.

2 Methods

2.1 Model setup

We employ the fully-coupled atmosphere–ocean–vegetation–ice sheet–solid earth model MPI-ESM/mPISM/VILMA that has been described in detail in Mikolajewicz et al. (2025) and has previously been used in Andernach et al. (2026) to study the multiple steady states of the GrIS under PI climate conditions. The ESM is the coarse resolution MPI-ESM version 1.2 (Mikolajewicz et al., 2018; Mauritsen et al., 2019). It comprises the ECHAM6.3 spectral atmospheric general circulation model (Stevens et al., 2013) at a T31 horizontal resolution (approximately 3.75°) and 31 vertical levels together with the land surface vegetation model JSBACH3.2 (Raddatz et al., 2007). The ocean is represented by the MPIOM1.6 primitive equation ocean general circulation model with a nominal resolution of 3° (Marsland et al., 2003; Mikolajewicz et al., 2007; Jungclaus et al., 2013). The retreating ice sheets require the application of an expanded ocean grid to capture ocean dynamics in newly exposed



ocean grid cells. Therefore, we extend the ocean model grid GR30 across the present-day land-sea boundaries of Greenland and Antarctica compared to Mikolajewicz et al. (2025).

MPI-ESM is fully coupled to the modified Parallel Ice Sheet Model (mPISM) (Ziemen et al., 2019), which is based on PISM version 0.7.3 and has a horizontal mesh resolution of 10 km in the northern and southern hemisphere. Both, the GrIS and the Antarctic Ice Sheet (AIS) evolve interactively. Basal melt beneath floating ice shelves is estimated from extrapolating ESM salinity and temperature averages from 203 to 523 m depth to the ice shelves, following the three-equation method by Holland and Jenkins (1999). Iceberg calving is parametrized with Eigencalving (Levermann et al., 2012), where calving follows ice-shelf spreading rates, and a thickness-based criterion that calves ice fronts thinner than 100 m at a maximum calving rate of one grid cell per time step. We use a physically-based energy balance model (EBM) at the atmosphere-ice interface to compute the surface mass balance (SMB) of the ice sheet from hourly atmospheric data (Kapsch et al., 2021). The atmospheric fields are linearly interpolated to elevation classes. Near-surface air temperature, dew-point temperature, humidity, downward longwave radiation, precipitation and near-surface air density fields are adjusted to account for differences in elevation between the atmospheric forcing fields and the elevation class. Temperatures are corrected using a constant lapse rate of -4.6 K km^{-1} across the ice sheet. Surface melt rates are calculated by the EBM from the energy balance at the atmosphere-snow interface, accounting for radiative and turbulent heat fluxes, as well as heat fluxes associated with rainfall and subsurface heat conduction. The EBM employs an albedo parameterization (Oerlemans and Knap, 1998), which accounts for snow aging, snow depth, and cloud cover. The resulting three-dimensional fields of surface melt, accumulation, and surface mass balance (SMB) are subsequently interpolated vertically and horizontally to the actual ice-sheet topography. For details on the EBM see Kapsch et al. (2021). Adjustments in the bed topography in response to ice sheet changes are computed with the 1D configuration of the global viscoelastic lithosphere and mantle model VILMA, assuming that the Earth's viscosity structure varies only vertically (Martinec et al., 2018; Schannwell et al., 2026). To be able to simulate the long time scales inherent to ice sheet dynamics (Cuffey and Paterson, 2010), we use an asynchronous coupling between mPISM/VILMA and MPI-ESM. For every 10 years of simulated climate in MPI-ESM, mPISM and VILMA run for 100 years. The ice sheet and solid Earth output is then used as input for the ESM. The asynchronous coupling method has no significant impact on the results, as we focus on the quasi-equilibrium and the equilibrium of the GrIS.

The main advance to previous studies on the hysteresis of the GrIS is not only the use of a comprehensive ESM, but also the inclusion of modules that interactively change the ocean bathymetry, topography, land-sea mask (Meccia and Mikolajewicz, 2018) and river routing directions (Riddick et al., 2018). Further, an Eulerian iceberg module is included (Erokhina and Mikolajewicz, 2024).

2.2 Experimental design

To study the stability range of the multiple steady states of the GrIS under a changing global-mean temperature, we trace the ice sheet volume in dependence of prescribed $p\text{CO}_2$. Some previous studies used constant CO_2 or temperature forcing at discrete intervals (e.g., Letréguilly et al., 1991; Höning et al., 2023). In our approach, we run transient simulations with gradually increasing and decreasing $p\text{CO}_2$ over time to capture the exact location and number of bifurcation points and the true degree



of non-linearity in the system. All other greenhouse gases (CH_4 of 711.09 ppb and N_2O of 270.28 ppb; Köhler et al. 2017), insolation and orbital parameters are prescribed at PI levels (Berger and Loutre, 1991). Note that these factors could also impact the stability diagram of the GrIS. To ensure a quasi-equilibrium of the GrIS and the simulated climate, the changing speed of the pCO_2 is chosen slower than the typical response timescale of an ice sheet and the simulated climate. Our ramping speed is a doubling or halving of our initial CO_2 concentration of 282.59 ppm exponentially over 80,000 ISM years (8000 ESM years). With increasing proximity to a critical transition, we lower the speed to 160,000, 320,000 or 400,000 ISM years to ensure that pCO_2 evolves more slowly than the comparatively rapid changes in the GrIS volume.

Simulations are initialized from two different ice sheet reference states (gray circles in Fig. 1). For the retreat branch, we start from an equilibrium simulation with a steady-state PI GrIS and PI AIS. The simulation is obtained from an equilibrated asynchronous fully-coupled spin-up simulation and has previously been used in Andernach et al. (2026). Our initial GrIS volume is in good agreement with that obtained from the IceBridge BedMachine of the NASA National Snow and Ice Data Center (NSIDC) Distributed Active Archive Center (Morlighem et al., 2022), differing by only 1.7% (see Appendix Figs. A1 & A2 for a spatial comparison of the GrIS and AIS thickness). We then gradually increase pCO_2 until a complete disappearance of the GrIS. The regrowth branch is initialized with the smallest PI GrIS steady state that has been found in Andernach et al. (2026). This steady state was obtained by initially removing the GrIS and letting the underlying bedrock adjust isostatically and the GrIS equilibrate. Under PI pCO_2 conditions, the GrIS reaches a new stable equilibrium with a volume of approximately 19% of its PI volume (XS' in Figure 1). Initialized with this smaller GrIS, we then gradually decrease CO_2 concentrations from 282.59 ppm until the GrIS has regrown to its initial PI state. This allows us to examine a potential hysteresis in its regrowth. To close the stability loop, we continue this simulation with a fully regrown GrIS under gradually increasing pCO_2 until 282.59 ppm. Similarly, we use the final disintegrated state of the retreat branch simulation and gradually decrease pCO_2 until reaching the initial state of the regrowth branch.

We additionally perform equilibrium simulations under constant CO_2 concentrations to constrain the bifurcation points in the transient hysteresis curve. This is done by branching off simulations from the transient ones and keeping the respective CO_2 concentration constant, similar to Garbe et al. (2020) and Gutiérrez-González et al. (2026). These simulations are integrated until the GrIS reaches a new equilibrium, but for a minimum of 15,000 ISM years.

To pinpoint the critical ice volume threshold at which destabilization of the PI GrIS commences, we branch off a series of sensitivity experiments at varying ice sheet volumes, derived from a warming-driven GrIS retreat equilibrium simulation. Each experiment is run for at least 10,000 ISM years or until the system reaches a new equilibrium under a pCO_2 level right below the destabilization threshold.

2.3 Early warning signals

To assess the potential for prediction of a nearing tipping of the GrIS, we apply statistical early warning signals for the main bifurcations in our stability diagram. We compute the variance and AC1 from the melt rate, calculated as the time derivative of the ice volume in a time step of 100 ISM years. The time series is cut off before the critical transition to avoid the introduction of a bias in the estimate of the critical slowing down (Dakos et al., 2008). The mean of the time series may include non-



stationarities, which could add a bias to the signal of an impending transition (Dakos et al., 2012). Therefore, the time series are detrended first by subtracting a Gaussian kernel smoothing function from the data. Gaussian filtering has been frequently used to filter out long trends in previous studies (Dakos et al., 2008; Lenton, 2011; Lenton et al., 2012; Boers and Rypdal, 2021). We choose a bandwidth of about 10% of the data, to remove the long-term trends without overfitting the data and removing the low frequencies needed to compute the slowing down. As the detrending method and the bandwidth can have an impact on the result (Lenton et al., 2012), we also test detrending with a rolling mean and different bandwidths (see Appendix Fig. D1). For the remaining analysis the residuals are used, for which we estimate the AC1 and variance. A combination of two early warning signals is used to lower the risk of a false alarm (Lenton, 2011). Both indicators are computed using a sliding window size of about 40%. Hence, our sliding window size is comparable to previous climate studies who used between 40% and 50% of their time series length (Dakos et al., 2008, 2012; Lenton et al., 2012; Boers, 2021; Boers and Rypdal, 2021). Appendix Figure D1 shows that our results are robust for different sliding window sizes.

To test the statistical significance of the slowing down, we calculate the non-parametric Kendall rank correlation coefficient (τ) with a significance level of 5% on the estimates of the variance and AC1 (as in Lenton (2011); Lenton et al. (2012); Smith and Boers (2023); Rietkerk et al. (2025)). Kendall's τ is a measure of the magnitude of an indicator's trend. Positive values indicate an increasing trend and negative values a decreasing trend. Thus, a statistically significant positive trend suggests a critical slowing down and an early warning of an approaching bifurcation point.

3 Results and discussion

3.1 Self-enhancing feedbacks destabilize the GrIS under rising temperatures

As the CO₂ concentration in our simulation increases, the GrIS remains quasi-stable initially but reaches a bifurcation point for destabilization at 403.5 ± 3.5 ppm pCO₂, equivalent to an equilibrium warming of 2.55 ± 0.15 °C (Fig. 1). Note that the equilibrium simulation indicates a slightly lower temperature threshold than the transient one. This can be explained with the longer response time of the ice sheet than of the change in the transient forcing. At this stage of the transient simulation, the external forcing has pushed the system beyond its stable equilibrium, leaving the GrIS in an unstable state. To keep the GrIS in a quasi-equilibrium state throughout the transient simulation and more closely align with the results from the equilibrium simulations, slower pCO₂ changes would have been required. For the retreat branch, the doubling of pCO₂ is performed over about 124,500 ISM years, which equals a mean increase of about 2.3 ppm per 1000 ISM years. This is about a thousand times slower than our current growth rate of pCO₂. An even slower ramping rate was not feasible with our ESM-ISM due to its high computational cost and resource demands. Thus, the critical pCO₂ or temperature at which the GrIS disintegrates is lower than it appears in the transient simulations. This applies to several phases in our hysteresis curve.

At forcing values below the bifurcation point, the present-day large state of the GrIS appears quasi-stable with a maximum mass loss of 10% of its total PI volume. This mass loss is equivalent to a global-mean sea-level rise of 0.75 m (compare L1 and L2 in Fig. 1b and Fig. 2). Quasi-stability arises from the central GrIS's high surface elevation and the high albedo of the overlying snow that create a locally cold climate and inhibit surface melt (Appendix Fig. B1). Hence, surface accumulation



190 exceeds surface ablation, causing a positive SMB in the high-elevation interior of the GrIS and making the vast majority of the ice sheet area less vulnerable to the warming (Fig. 3). Mass loss is confined only to the low-lying coastal areas of the GrIS, where near-surface air temperatures are sufficiently high to drive surface melt exceeding accumulation, resulting in a negative SMB (Fig. 3). The mass gained through surface accumulation in the interior flows downslope towards the low-elevation margins, where it is lost through calving and surface melt, keeping the ice sheet in a dynamic equilibrium.

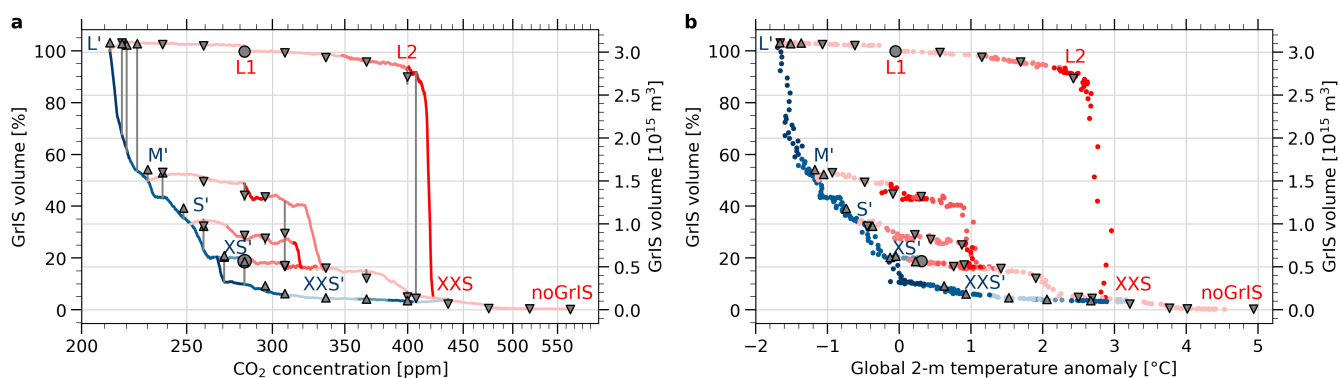


Figure 1. Stability diagram of the GrIS. Shown are the transient response of the GrIS volume to (a) changing pCO_2 levels and (b) global-mean 2-m temperature anomalies. The different shades of red (= increasing forcing) and blue (= decreasing forcing) correspond to different ramping speeds of the applied external forcing, with brighter colors indicating faster changing speeds and darker colors showing slower changing speeds during rapid transitions (see Section 2.2). The gray circles mark the two initial equilibrium ice volumes at PI pCO_2 . The gray vertical lines in (a) show the trajectory of each equilibrium simulation and the triangles their end points. Downward facing triangles indicate retreat and upward facing triangles regrowth of the GrIS. Equilibrium states as discrete values constrain the range of each critical transition under constant CO_2 concentrations. The range of a critical threshold is defined using the equilibrium simulations prior to and following a critical transition. Note, that the temperature threshold is slightly higher in the transient than in the equilibrium simulations, as the response time of the ice sheet is longer than the change in the transient forcing.

195 To examine the processes and feedbacks that lead to the decay of the GrIS at a sustained warming level of $2.55 \pm 0.15^{\circ}\text{C}$, we analyze the equilibrium simulation at 407 ppm. In this simulation, the GrIS disappears within about 25,000 ISM years, exhibiting a non-linear melt response. During the first 14,000 years, surface melt occurs in the coastal areas and mass loss proceeds gradually over time. The north-west of Greenland is particularly sensitive to the warming, which is consistent with previous modeling studies (Pattyn et al., 2018). In this region, low snow fall rates cannot compensate for enhanced melt, and
 200 low surface elevation leads to a rapid increase in the ablation area, even for a small temperature rise. Destabilization and an associated acceleration in the melt rate occurs when the ice connection between the central part and north-western tip of the GrIS becomes too thin to sustain stability, causing the detachment of the central GrIS from the north-western sector. This detachment happens at a critical ice volume of 87% (Fig. 4). With the loss of the pinning point, retreat continues in the central part of the GrIS, followed by the southern part. The breakup coincides with a strong acceleration of the melt rate due to the
 205 melt-elevation feedback. On millennial time scales, self-reinforced melting through the melt-elevation feedback is slightly

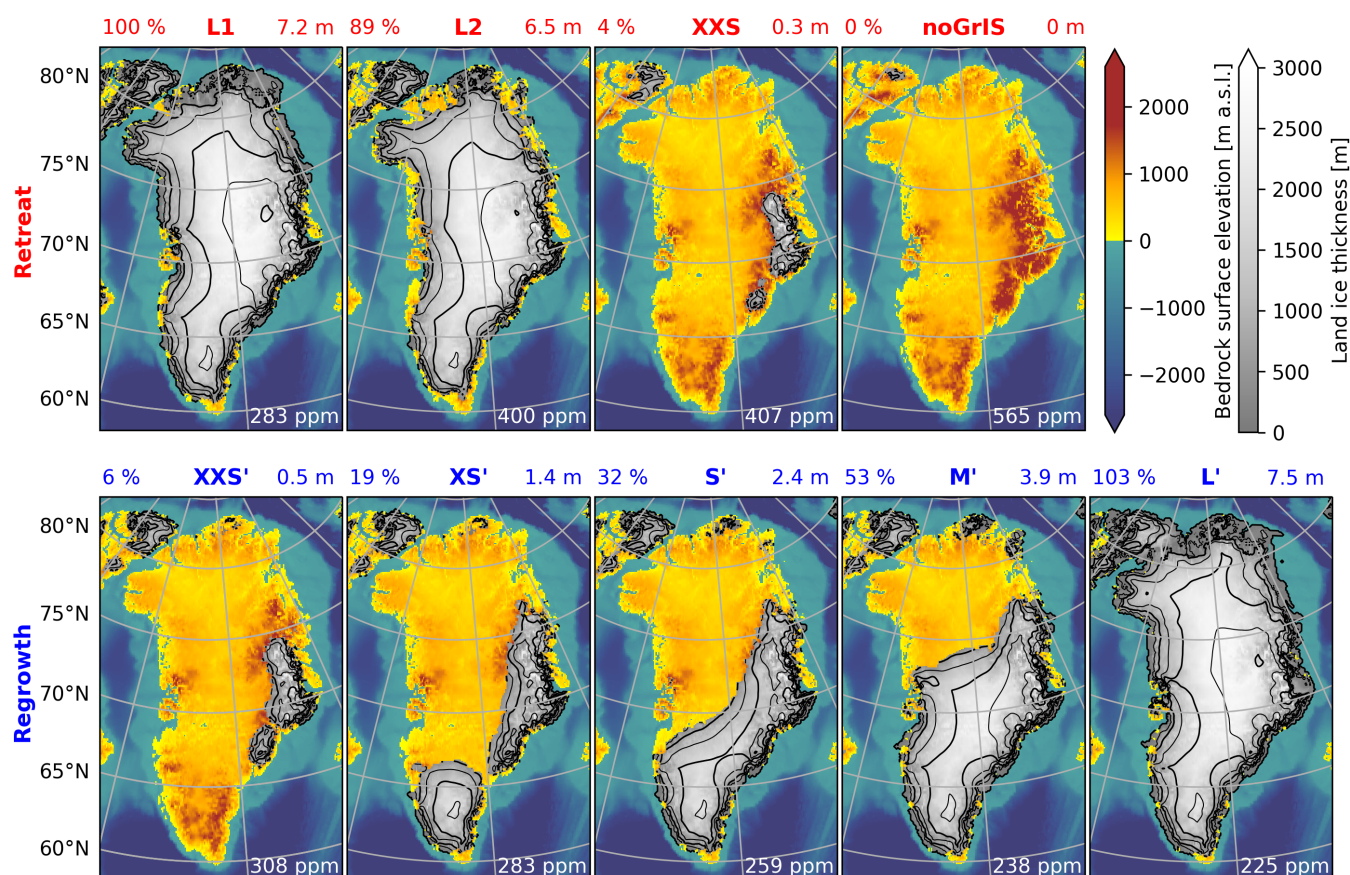


Figure 2. Steady states of the GrIS for different warming and cooling levels during the retreat and regrowth. The equilibrium ice sheet thickness is shown in meters and the underlying bedrock in meters above sea level (m a.s.l.) for the different states during the retreat (upper panels) and the regrowth (lower panels) of the GrIS as indicated in Fig. 1. Ice thickness contours are delineated every 500 m. Also provided is the ice volume for each state relative to PI (L1), expressed as percentage (upper left), the sea level equivalent in meters (upper right) and the corresponding pCO₂ level.

counteracted by isostatic uplift of the bedrock by several hundreds of meters, as the ice load on the bedrock is reduced due to the thinning of the GrIS (Zeitz et al., 2022). However, the effect of the glacial-isostatic adjustment feedback is too low to offset enhanced melting through the positive melt-elevation feedback, as shown in a previous study using the same model set-up (Andernach et al., 2026). Melting is further amplified by increased short-wave absorption, since the ice loss leads to the exposure of darker ice and bedrock and the growth of vegetation, referred to as melt-albedo feedback (Fyke et al., 2018; Zeitz et al., 2021). The positive melt-elevation and melt-albedo feedback amplify surface melting and sustain it even under a stable CO₂ concentration, eventually leading to the near-complete disappearance of the GrIS. Under these conditions, 82% of the remaining ice volume disappears within 9,500 ISM years in our equilibrium simulation. Glaciers are only preserved in the highlands of eastern Greenland, due to the locally cold conditions and high, orographically-induced precipitation rates (XXS



215 in Fig. 2). Snow accumulation in the east of Greenland is also favored by a north-east shift in the precipitation pattern, as the GrIS retreats, consistent with previous studies (Lunt et al., 2004; Petersen et al., 2004; Davini et al., 2015; Andernach et al., 2025, 2026). However, these remaining ice caps also disappear under even higher temperatures. Above a global warming of 4 °C (or 500 ppm pCO₂), Greenland is ice-free and covered by vegetation (noGrIS in Fig. 2).

The ice sheet's inherent inertia and associated long response times (Imbrie et al., 1993) would allow for a temporary tem-
 220 perature overshoot without immediately triggering self-enhanced mass loss. However, the maximum duration of such a delay depends on the magnitude of the overshoot (Bochow et al., 2023). Our simulations designed to investigate the critical volume threshold for GrIS destabilization indicate that preventing long-term destabilization requires cooling below the critical threshold before 13% of the PI ice volume is lost (Fig. 4). According to our simulations, this requires a reduction in pCO₂ below 403.5 ± 3.5 ppm. At current pCO₂ levels, halting emissions may suffice, as the Earth system would sequester much of
 225 the excess within decades to centuries (Joos et al., 2013). However, continued high emissions may necessitate active carbon dioxide removal, as ocean outgassing under negative emissions can offset atmospheric drawdown (Yao et al., 2025).

Our simulations capture the quasi-equilibrium response of the climate system and the GrIS, allowing us to assess long-term stability thresholds. This contrasts with the current climate, in which the global-mean temperature has not yet equilibrated to the radiative forcing from present-day CO₂ levels. As a result, although current pCO₂ exceeds 425 ppm (Lan et al., 2026),
 230 which is past our critical threshold for GrIS disintegration, our derived temperature threshold of 2.55 ± 0.15 °C has not yet been reached in reality. According to our simulations, if present-day or higher pCO₂ levels are sustained in the long-term, the critical temperature threshold for GrIS destabilization is expected to be reached.

3.2 Ice sheet-climate feedbacks stabilize the GrIS at intermediate states during regrowth

Unlike retreat, which can be triggered by crossing a single critical threshold, regrowth of the GrIS after its complete disinte-
 235 gration involves traversing multiple sequential bifurcation points. Full regrowth to a state similar to the PI GrIS configuration requires a global-mean temperature of 1.3 ± 0.1 °C below PI associated to 227 ± 2.5 ppm pCO₂ (Fig. 1). This reflects the multistability of the GrIS across a large temperature range and the associated hysteresis behavior in the regrowth branch.

The GrIS persists in a very small state, with two separate ice caps forming only over the eastern mountains of Greenland for a cooling almost down to PI temperatures. In this state, the GrIS contains 6% of its PI volume (XXS' in Fig. 1 and in Fig. 2). An
 240 expansion of the ice caps is prevented by surface temperatures above freezing in the low-lying surrounding areas, similar to the smallest state found previously by Andernach et al. (2026). Additionally, orographic blocking on the atmospheric circulation is considerably weaker with a smaller GrIS (Petersen et al., 2004; Andernach et al., 2025, 2026). Instead, this small GrIS favors southerly winds at 500 hPa that advect warmer air masses towards Greenland, consistent with previous studies using the same model set-up (Andernach et al., 2025, 2026). At the surface, easterly winds advect near-surface air from an anomalously-
 245 warmed adjacent Irminger Sea and prevent the accumulation of a perennial snow cover in the south of Greenland. Warm and dry air from Föhn winds in the lee of the eastern mountains and the smaller GrIS impede an ice sheet expansion towards the north-west (Langen et al., 2012). As storm tracks and air masses can penetrate further north-east due to the reduced mechanical

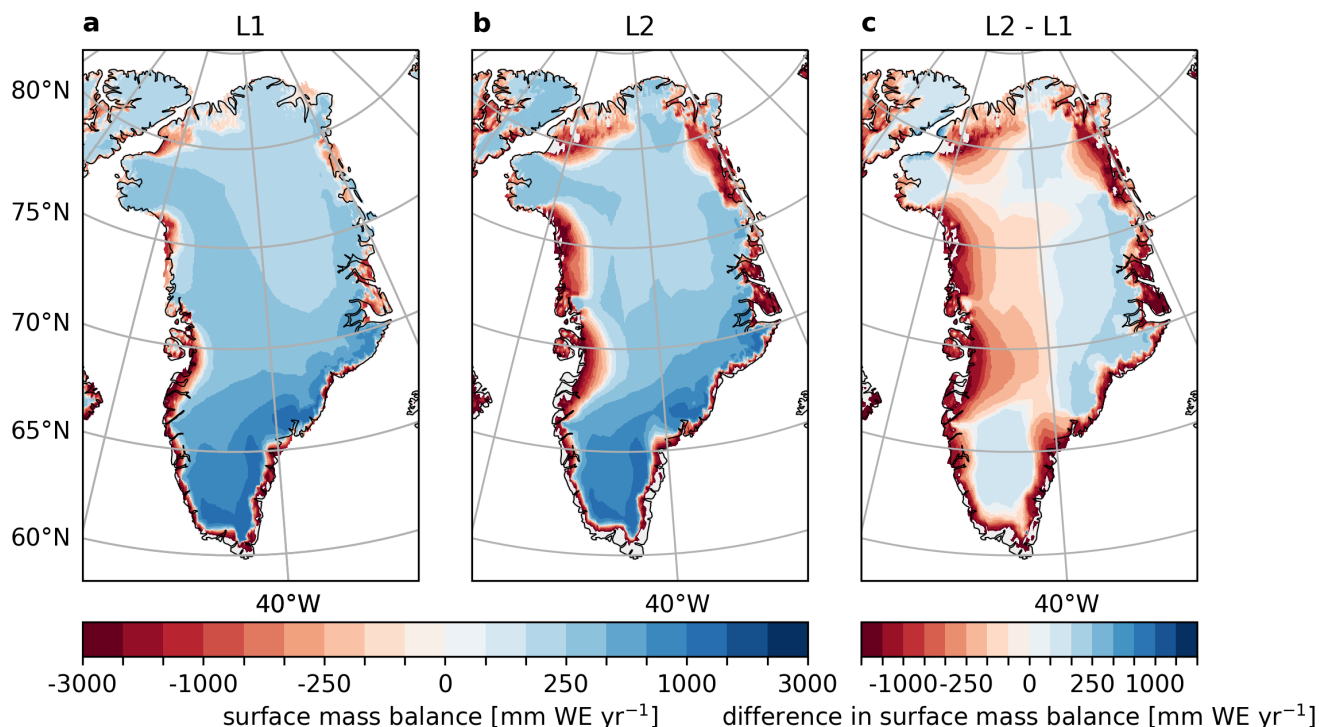


Figure 3. SMB of the GrIS under different equilibrium states corresponding to (a) PI conditions and (b) a $p\text{CO}_2$ level of 400 ppm. Panel (c) illustrates the difference in SMB between the two states. Note the logarithmic scale of the color bars.

blocking, precipitation is higher in the glaciated east, but lower in the ice-free west and south of Greenland (Lunt et al., 2004; Petersen et al., 2004; Davini et al., 2015; Andernach et al., 2026).

At and below a global temperature anomaly of $0.4 \pm 0.2^\circ\text{C}$, corresponding to 289 ± 6 ppm $p\text{CO}_2$, regrowth continues in the south of Greenland. The GrIS subsequently stabilizes at a state with 19% of its PI volume, characterized by two separate ice caps located in the eastern and southern mountains of Greenland (XS' in Fig. 2). With a further decreasing global-mean temperature, these ice caps dynamically expand and merge, and the GrIS passes through two additional intermediate states with 33% and 54% of the PI volume (S' and M' in Fig. 2). The three intermediate ice sheet states are stable due to the described interactions with the climate system. These interactions cause near-surface air temperatures beyond the ice margin that are too high to sustain ice. Consequently, ice dynamically transported from the interior of the smaller ice sheets into low-lying, ice-free regions of Greenland cannot persist, precluding any advancement of the ice sheet. At the same time, ice dynamical transport also maintains the equilibrium of the states. To overcome these limiting impacts and to enable a full recovery of the GrIS, global temperatures need to drop $1.3 \pm 0.1^\circ\text{C}$ below PI (L' in Fig. 2). Such climate conditions lie far beyond those projected under any realistic future climate scenario, rendering recovery practically unfeasible. Even if such cold conditions were achieved, our transient simulation in which $p\text{CO}_2$ was decreased at a rate of about 1.3 ppm per 1000 ISM years indicates that full regrowth

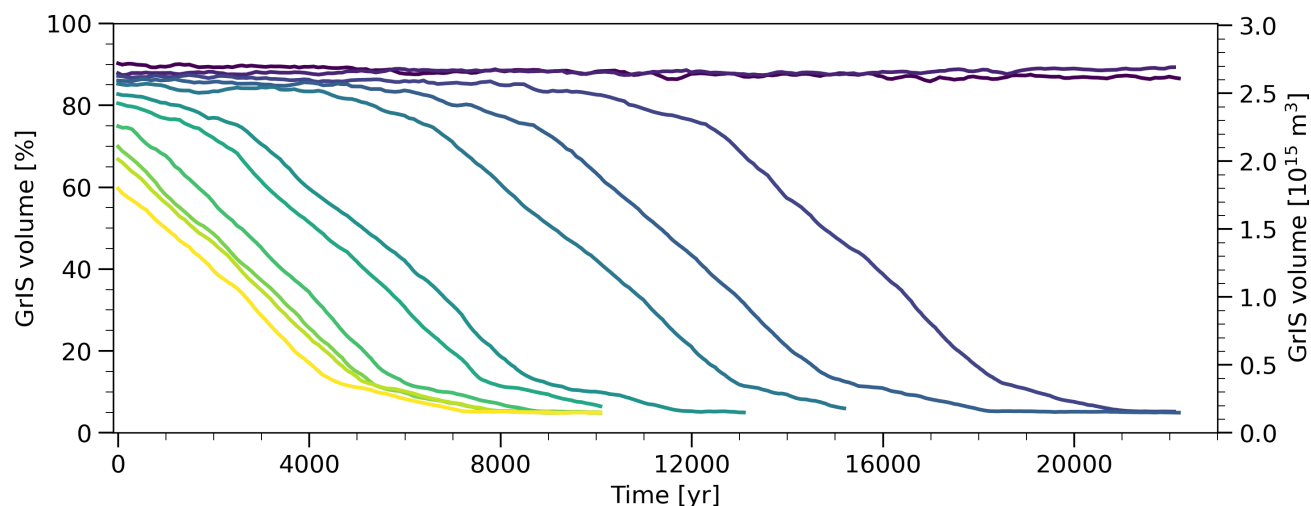


Figure 4. Critical volume threshold leading to the destabilization of the GrIS. Time series of different GrIS volumes branched off from the equilibrium simulation at 407 ppm and run until equilibrium under 400 ppm $p\text{CO}_2$. Only the simulations started at 90% and 87.5% remain stable, whereas the simulations started from ice volumes of 85% or lower destabilize and disintegrate within several millennia.

would take approximately 266,000 years, making the loss effectively irreversible on human timescales. Notably, regrowth could be faster under even colder conditions. Nevertheless, such sustained cold climate conditions are difficult to establish even under ambitious climate mitigation scenarios.

265 When each of the intermediate states is subjected to warming induced by increasing $p\text{CO}_2$, they remain stable for a certain forcing range due to the interplay between the physical structure of the intermediate GrIS states, the broader climate and ice dynamical processes. The intermediate states exhibit lower critical temperature thresholds for ice sheet retreat than the PI GrIS. This is due to the lower mean surface elevation of the smaller ice sheets, which exposes them to warmer near-surface air via the environmental lapse rate, thereby enhancing surface melt. It also reduces the fraction of precipitation that falls as snow.

270 Thus, the intermediate states are more vulnerable to warming than the large GrIS. Figure 1 depicts three hysteresis curves of the three intermediate GrIS states (XS', S' and M') that are nested within the main hysteresis. While they all follow a slightly negative trend under increasing temperatures, the loops of M' and S' undergo more fluctuations than the one of XS'. M' and S are only weakly stable as the associated GrIS is larger and extends over parts of the low-lying central areas of Greenland (Fig. 2). This makes them more vulnerable to variations in the climate than the GrIS in XS', for which the ice caps are confined

275 to the highlands, providing a more stable climate (Fig. 2). As a consequence, the northwestern edge of the GrIS in the nested hysteresis loops of M' and S' exhibits strong variability. Also Andernach et al. (2026) found that the medium state can be destabilized by natural climate variability under PI $p\text{CO}_2$. The authors of that study showed that this steady state is susceptible to small changes in the Atlantic Meridional Overturning Circulation (AMOC). These AMOC variations can trigger a transition



of the medium state into a smaller state. Hence, the state of the GrIS depends not only on the global-mean temperature, but
 280 also on the present ice sheet configuration and the climate that it induces.

3.3 Uncertainties in the location of the bifurcation points

The critical temperature threshold for disintegration of the PI GrIS in our transient and equilibrium simulations falls within
 the upper range of previously suggested values (Robinson et al., 2012; Höning et al., 2023; Gutiérrez-González et al., 2026).
 Our results support the view of the existence of a single bifurcation point beyond which the GrIS disintegrates, consistent with
 285 findings from Robinson et al. (2012) and Gutiérrez-González et al. (2026). This is in contrast to other studies that proposed
 multiple sequential bifurcation points (Letréguilly et al., 1991; Höning et al., 2023), which is likely related to differences in the
 model setup.

Our simulated threshold for full regrowth is significantly lower than in any previous study, which had suggested a recovery
 near or even above PI or present-day temperatures (Letréguilly et al., 1991; Robinson et al., 2012; Solgaard and Langen,
 290 2012; Höning et al., 2023; Gutiérrez-González et al., 2026), but supports findings of multistability under PI or present-day
 temperatures (Ridley et al., 2010; Gregory et al., 2020; Andernach et al., 2026). The intermediate states passed during regrowth
 are similar to the steady states found under PI pCO₂ (Andernach et al., 2026), but are more numerous and occur at much higher
 GrIS volumes than in earlier studies (Robinson et al., 2012; Solgaard and Langen, 2012; Höning et al., 2023). Based on
 previous studies using the same model set-up (Andernach et al., 2025, 2026), we attribute this behavior to the representation
 295 of a large range of ice sheet-climate feedbacks in our model. For instance, the regrowth of an ice cap in the south of Greenland
 is impeded by the advection of near-surface air from a warmer adjacent ocean surface, as demonstrated by Andernach et al.
 (2026). Furthermore, changes in the ice-sheet geometry induce changes in the atmospheric circulation, which in turn alter
 the SMB through changes in temperature and precipitation (Andernach et al., 2025, 2026). Thereby, our results show that
 specifically the regrowth of the GrIS is more complex than previously assumed and explains why ice sheet-only simulations
 300 or simulations with less complex models did not find such a pronounced stepwise regrowth and found higher temperature
 thresholds (Letréguilly et al., 1991; Robinson et al., 2012; Solgaard and Langen, 2012; Höning et al., 2023; Gutiérrez-González
 et al., 2026).

The bifurcation points obtained in our simulations might differ from those obtained with other models, as they are sensitive
 to the choice of model parameters and grid resolution. For example, a coarse grid resolution limits the model's realism of
 305 small-scale climate features, including orographic precipitation and temperature variation over steep topography near the ice
 sheet margins and in mountainous regions (van Kampenhout et al., 2019; Tao et al., 2020). This can impact the SMB, which
 critically determines where the GrIS grows and melts, hence, where it remains stable and becomes unstable. Schannwell et al.
 (2026) showed that the inter-model spread in future ice mass loss projections of the GrIS can largely be explained by differences
 in the SMB, and in particular differences in the net surface melt. This suggests that differences in the spatial distribution of
 310 SMB among models may contribute to the contrasting responses of the GrIS to rising temperatures. The most pronounced
 differences in the spatial distribution of the SMB appear when comparing our results with those of Höning et al. (2023), who
 used CLIMBER-X coupled to SICOPOLIS. In our simulations, the highest SMB values occur in southern and southeastern



Greenland, consistent with results from higher-resolution regional models (Fettweis et al., 2020). In contrast, Höning et al. (2023) simulate peak SMB values primarily along the eastern coast. These differences in the spatial distribution of SMB likely explain the contrasting GrIS retreat dynamics between the two studies, namely the greater resistance of the ice sheet in the south of Greenland in our simulations as well as the existence of a single bifurcation point in our simulations versus multiple bifurcation points in Höning et al. (2023).

The pCO_2 thresholds for GrIS retreat and regrowth also depend on the equilibrium climate sensitivity (ECS) of the model. The MPI-ESM/mPISM/VILMA version used in this study has an ECS of $4.1^\circ C$ (Schannwell et al., 2026). Unlike standard ECS simulations, our transient experiment features a gradual pCO_2 rise over millennia, leading to an amplified ice sheet mass loss and an Earth system sensitivity (ESS) of $4.6^\circ C$. This elevated ESS reflects the cumulative impact of slow feedbacks, which are not fully included in the ECS that is derived through shorter simulations. Our ECS places our model within the mid-range of the Coupled Model Intercomparison Project (CMIP) 6 ensemble but toward the upper end of the CMIP5 ensemble range (Meehl et al., 2020). With a lower ECS, the pCO_2 thresholds in our simulations would be higher.

3.4 Hysteresis of the Antarctic Ice Sheet

While our focus has been on the GrIS, our bi-hemispheric model set-up also simulates changes in the AIS. We find that the temperature increase causes a destabilization of parts of the AIS, which is triggered at a lower global temperature anomaly than for the GrIS (Appendix Fig. C1 and Appendix Fig. C2). The specific threshold remains to be investigated in a follow-up study, as not all of our equilibrium simulations are long enough for the AIS to reach a steady state. At a global warming anomaly of $2.4^\circ C$ ($400\text{ ppm } pCO_2$), when the bifurcation point of the GrIS is imminent, the volume of the AIS is already reduced by about 19%, equivalent to about 6.9 m SLE (L2 in Fig. 5). The mass loss is concentrated in the West Antarctic Ice Sheet (WAIS). The WAIS is particularly vulnerable as it is based mostly on bedrock below sea level, which makes it sensitive to basal melt from intruding warm ocean waters Naughten et al. (2023); Joughin and Alley (2011); Thoma et al. (2008); Depoorter et al. (2013); Hillenbrand et al. (2017). Enhanced thinning of the floating ice shelves reduces their buttressing effect and promotes grounding line retreat Joughin and Alley (2011); Pegler (2018); Joughin et al. (2021). The retrograde slope of the WAIS bedrock can further accelerate grounding line retreat through Marine Ice Sheet Instability Schlemm et al. (2022). Additionally, the WAIS is more susceptible to atmospheric warming due to its lower surface elevation and lower ice sheet thickness compared to the East Antarctic Ice Sheet (EAIS, L1 in Fig. 5). In its degraded state, the Filchner-Ronne and Ross Ice Shelf have disintegrated and large parts of the Antarctic Peninsula have disappeared, opening up new ocean passages (L2 in Fig. 5). In East Antarctica, the Fimbul Ice Shelf and the ice shelves along the Dronning Maud Land have been strongly reduced in size. At a global warming between 2 and $5^\circ C$ above PI levels, the melt rate slows down and the WAIS stabilizes at a strongly reduced state with only about 10% of its PI volume (compare L2, XXS and noGrIS in Fig. 5 and Appendix Fig. C1). In contrast, the EAIS experiences a significantly higher threshold for complete disappearance and continues to lose mass (Appendix Fig. C2).

Regrowth of the AIS under decreasing temperatures is delayed due to ice sheet-climate feedbacks. A stepwise regrowth starts at temperatures similar to PI levels (XXS' to L' in Fig. 5). However, the AIS recovers more slowly and under lower temperatures



than the GrIS. Thus, the final volume of the AIS at 210 ppm is lower by about 6% compared to its initial PI volume (compare L' and L1 in Fig. 5). Particularly, the Ross, Filchner-Ronne and Amery Ice Shelves, along with their catchment areas, have not fully recovered. Global temperatures lower than 1.7 °C below PI levels are necessary to allow for a full recovery of the AIS.

350 This is in strong contrast to previous studies using a standalone ISM or an EMIC, which had suggested that the AIS could fully regrow at or at slightly colder than PI climate conditions (Garbe et al., 2020; Leloup et al., 2025). Hence, our findings imply that even if the original GrIS volume is regained at a global temperature of 1.3 ± 0.1 °C below PI levels, a contribution to sea-level rise of over 3 m will persist, as the threshold for a complete regrowth of the AIS lies at even lower temperatures.

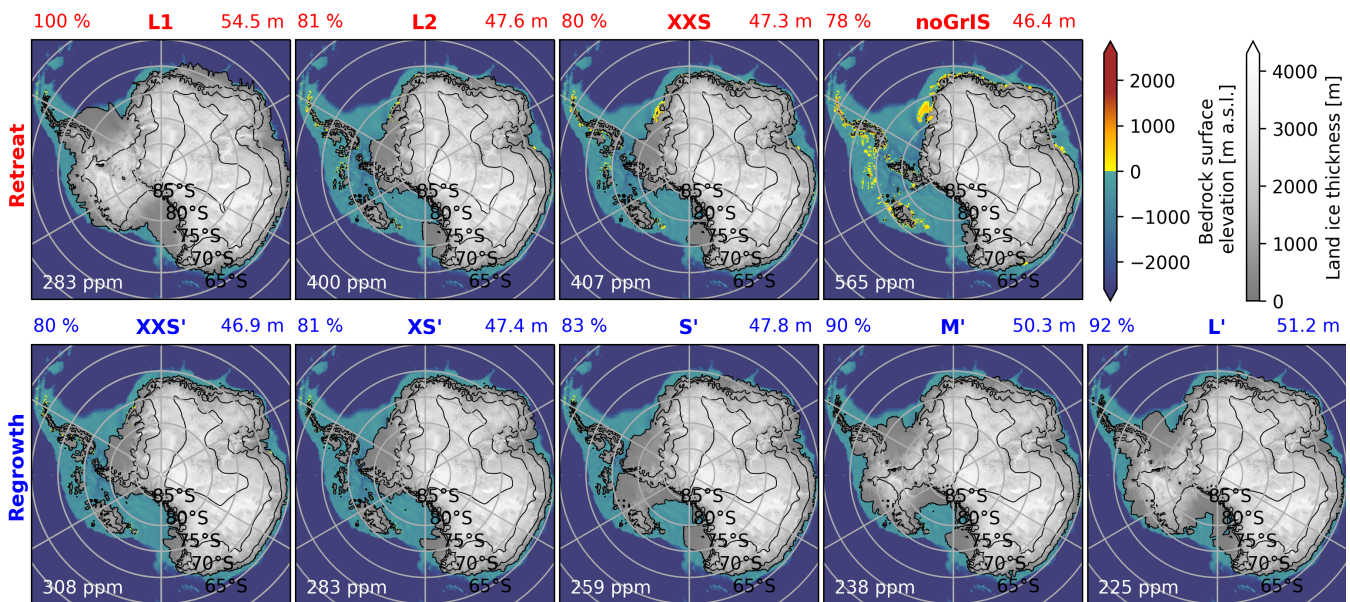


Figure 5. Similar to Fig. 2 but for the AIS. Note that not all of the AIS states have reached an equilibrium by the end of the simulation.

3.5 Critical transitions are only partly predictable

355 Given the severe impacts of a disintegrating GrIS, it would be essential to strategies of climate change mitigation to predict the self-sustained retreat. Therefore, we compute two early warning signals (variance and AC1) for the main transition in the retreat and the regrowth branch of the GrIS (see Section 2.3). Already multiple millennia before the abrupt onset of GrIS retreat, the system gradually loses resilience, as indicated by a statistically significant increase in variance and AC1 (Fig. 6a). However, these early warning signals do not provide information about the system's proximity to the bifurcation point. This limits their

360 utility for mitigation strategies and policy planning. Further note that reliable early warning signals of the bifurcation during the GrIS retreat are only detectable using a sliding window of several thousand years. This limits the method's applicability to observational data, which are typically too short to support such long windows. The bifurcation in the regrowth branch of the hysteresis curve is not preceded by a characteristic early warning signal (Fig. 6b). This 'missed alarm' in the regrowth is likely

caused by high internal variability, which can lead to an unannounced crossing of a bifurcation (Lenton, 2011; Lenton et al., 2012).

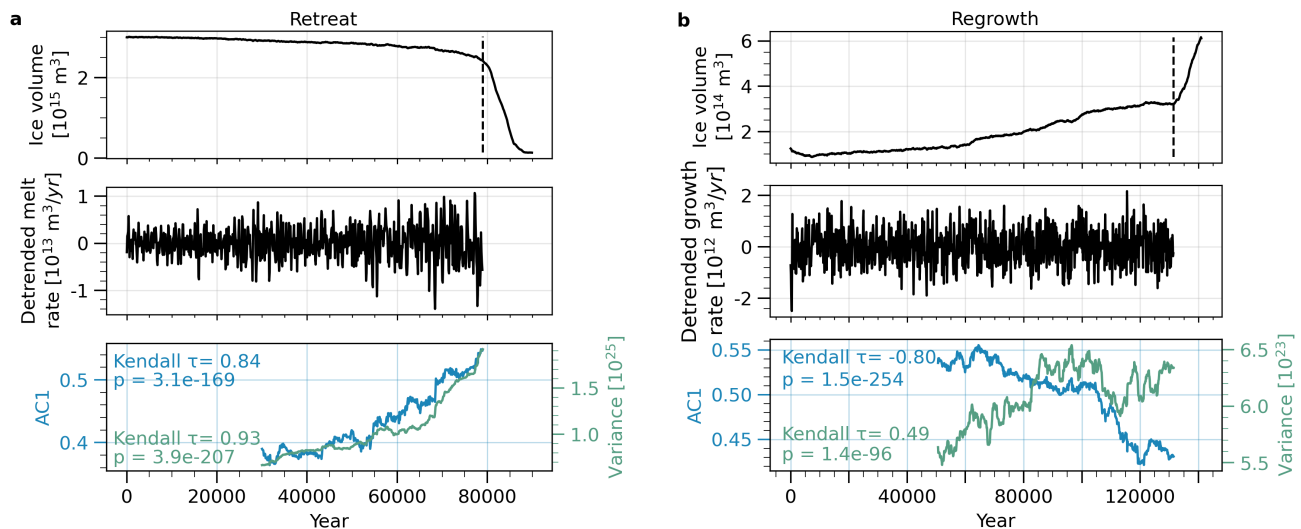


Figure 6. Early warning signals computed for the main critical transitions. Early warning precedes the critical transition in the (a) retreat, but not in the (b) regrowth of the transient hysteresis curve of the GrIS. The upper panels show the change in ice volume over time. The vertical dotted line delimits the section of the time series that has been used to compute the early warning signals. The middle panels show the detrended melt and growth rate that have been used as input for the computation of the early warning signals. The lower panels show AC1 and the variance computed as early warning indicators. The lower panels also include the result of the Kendall rank correlation coefficient (τ), which indicates whether the trends in the variance and AC1 are statistically significant at $\alpha = 5\%$. The trends of the correlations are robust against different filtering bandwidths and sliding window sizes (Appendix Fig. D1).

4 Summary and conclusions

Using a comprehensive bi-directionally coupled ESM-ISM, we study the stability landscape and the bifurcation points of the GrIS under changing temperatures. Our model shows that the present-day GrIS is quasi-stable for global warming anomalies below 2.55 ± 0.15 °C. A continuous crossing of this critical temperature threshold risks triggering a self-sustained GrIS retreat, causing a sea level rise of more than 7 m. Ice sheet-climate feedbacks, such as the melt-elevation feedback, would sustain and strongly amplify the retreat, once initiated, even under a stable atmospheric pCO₂ forcing. At the bifurcation point, GrIS retreat would unfold over multiple millennia, with substantial acceleration under even higher temperatures (Aschwanden et al., 2019; Van Breedam et al., 2020; Kapsch et al.; Schannwell et al., 2026). Under a high-emission pathway, the GrIS could disappear by the year 2800, as shown in a previous study (Aschwanden et al., 2019). Thus, to maintain the GrIS in a state similar to present-day, global warming needs to be limited to below the critical threshold in the long-term. However, even at global warming anomalies below the bifurcation point, our results suggest a significant risk of a multiple-meter sea level rise. It is associated



with a partial loss of the AIS. At 2 °C, almost 7 m SLE are lost from the AIS, which is an amount roughly comparable to the total mass of the present-day GrIS. Recovery of these parts of the AIS require sustained cooling to temperatures even lower than those needed for GrIS regrowth, according to our simulations. To more precisely constrain the critical thresholds of the AIS, future studies need to employ fully-coupled ESM-ISM, using a wider range of pCO₂ values and slower changing rates.

In our model, a disintegration of the GrIS would be irreversible under PI pCO₂, as ice sheet-climate feedbacks render a simple return to PI conditions insufficient for restoring the full GrIS. The ice sheet would remain in a partially degraded state, unable to expand beyond a volume of 19%. Instead, temperatures as low as 1.3 ± 0.1 °C below PI are required to enable full regrowth over multiple hundreds of thousand of years, according to our simulations. This necessitates a sustained pCO₂ reduction to at least 227.5 ± 2.5 ppm, which corresponds to nearly glacial climate conditions and requires tremendous efforts in carbon capturing. Notably, regrowth could be faster under even colder conditions. Nevertheless, such sustained cold climate conditions are difficult to establish. Hence, once lost, the GrIS may not recover on timescales relevant to human civilization, underscoring the long-term consequences of current and future warming. Our simulated critical temperature threshold for recovery is significantly colder than in any previous modeling study and challenges the prevailing view that recovery could occur near or even above PI or present-day temperatures. Further, it is the first time that a strongly stepwise regrowth associated with ice sheet-climate feedbacks has been demonstrated. This highlights the need for comprehensive ESM-ISM including ice sheet-climate feedbacks to assess the stability of the GrIS and to also capture inter-model differences.

Nonetheless, one must consider that our simulated stability diagram of the GrIS is sensitive to the chosen model, parameter choices, and the coupling between model components. A recent inter-model comparison showed that, under identical forcing, different coupled climate-ice sheet models produce divergent future GrIS trajectories, suggesting that the location and number of bifurcation points may vary across fully-coupled ESM-ISMs. This highlights the need for coordinated model inter-comparison studies to reduce uncertainty in GrIS (in)stability. Further, in reality, orbital parameters evolve over time. If the regrowth of the GrIS coincides with a period of reduced summer insolation at high latitudes of the Northern Hemisphere, such as during glacial inception, the pCO₂ threshold required to establish a perennial snow cover could be closer to PI values (Calov et al., 2005; Talento et al., 2024). Compounding this, we find that the use of statistical early warning indicators is constrained and such indicators are not reliable means for predicting bifurcation points in the GrIS's stability landscape, as they require long time series and may miss bifurcations, according to our results. To assess whether current climate conditions represent a critical window for intervention or cause a more gradual reversible decline, we need reliable metrics of proximity to the tipping point.

For the first time in a fully-coupled ESM-ISM, we identify the bifurcation points and critical volume threshold of the GrIS. Our results demonstrate the added value of such comprehensive models, showing that ice sheet-climate feedbacks substantially alter the critical thresholds of the GrIS. Given the idealized set-up of our simulations, an important next step would be to investigate the behavior of the GrIS on human timescales in overshoot scenarios using a comprehensive ESM with dynamic ice sheets. Including two-way interactions between the ice sheet and the global climate system would provide a better understanding of such overshoots, enabling a more realistic assessment of their peak magnitude and duration.



This study represents a major step forward in the research of GrIS (in)stability, being the first to use a model system that integrates a comprehensive suite of ice sheet-climate feedbacks. By capturing key physical processes and non-linear interactions, it provides a physically-consistent perspective on GrIS stability under warming. This advancement not only enhances predictive accuracy for future sea level rise and climate change projections but also deepens our process understanding of ice
415 sheet dynamics under changing climate conditions.

Code and data availability. Max Planck Institute Earth System Model model code is available upon request from the Max Planck Institute for Meteorology under software license agreement version 2. The PISM base code of version 0.7.3 that was used for all simulations is available
420 at Zenodo under <https://doi.org/10.5281/zenodo.754141238>. The repository details installation instructions and contains information on how to run the model.



Appendix A: Comparison of the initial states of the ice sheets to observations

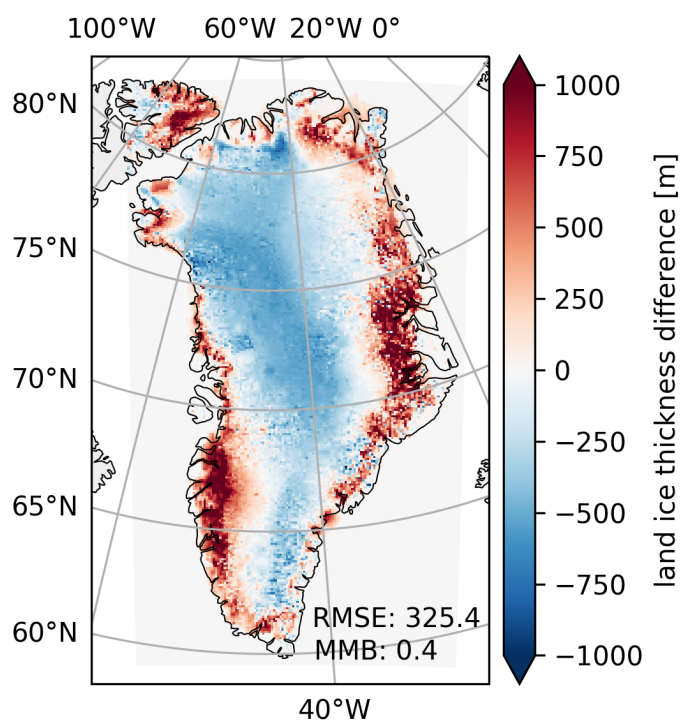


Figure A1. Difference between the simulated initial GrIS thickness and the observed GrIS thickness obtained from the IceBridge BedMachine of the NASA NSIDC Distributed Active Archive Center (Morlighem et al., 2022). Also shown are the root mean square error (RMSE) and the mean model bias (MMB).

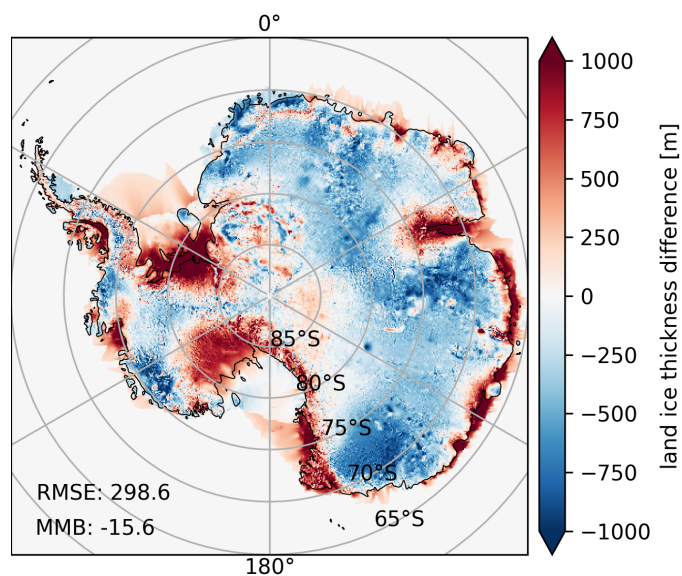


Figure A2. Difference between the simulated initial AIS thickness and the observed AIS thickness obtained from the MEaSURES BedMachine of the NASA NSIDC Distributed Active Archive Center (Morlighem, 2025). Also shown are the root mean square error (RMSE) and the mean model bias (MMB).



425 Appendix B: Surface accumulation and ablation over Greenland close to the threshold for destabilization

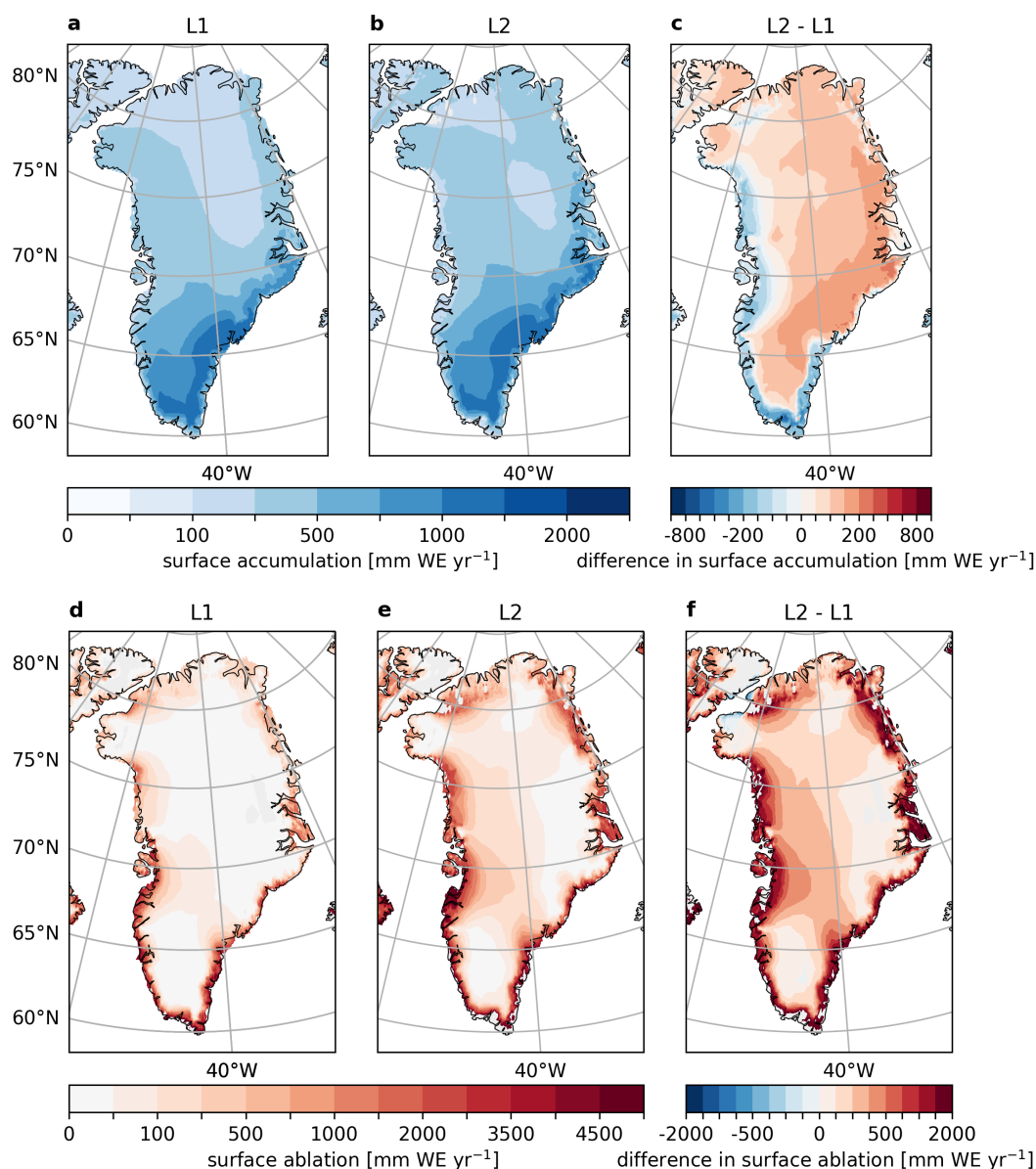


Figure B1. (a-c) Surface accumulation and (d-f) surface ablation over Greenland. The left column presents values at PI pCO₂ conditions, the middle column shows values at 400 ppm pCO₂ and the right column displays the difference between the two. Note the logarithmic scale of the color bars.



Appendix C: Stability landscape of the Antarctic Ice Sheet

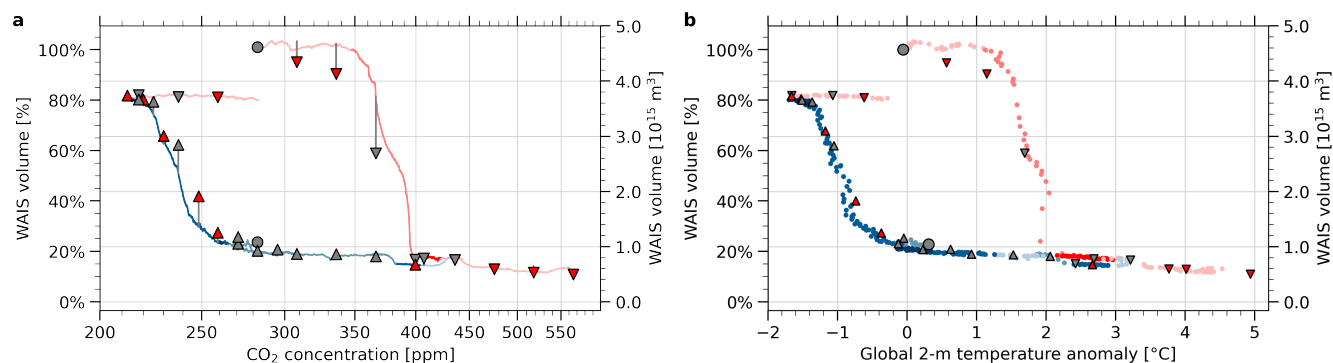


Figure C1. Similar to Figure 1 but for the WAIS response including the Antarctic Peninsula. Shown are the transient retreat and regrowth branch along with their additional equilibrium simulations. Red triangles indicate equilibrium simulations, in which the AIS has not reached a steady state until the simulation end.

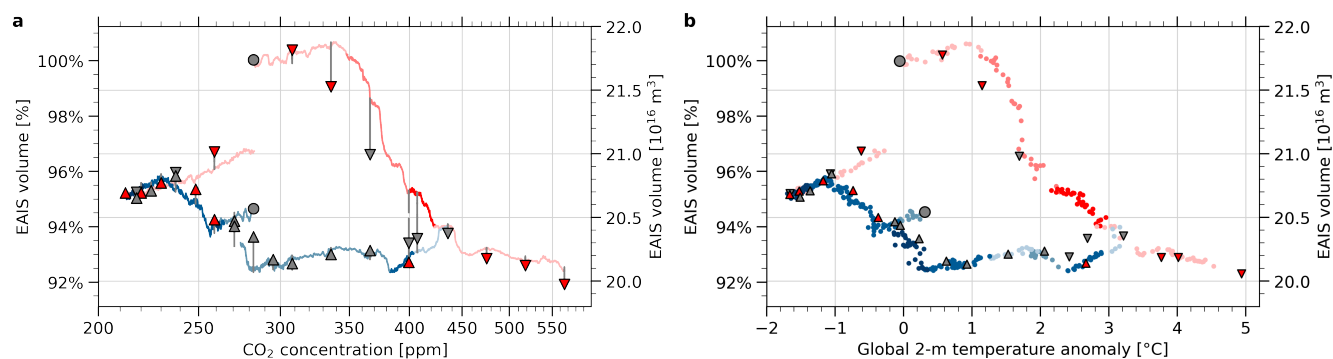


Figure C2. Similar to Figure C1 but for the EAIS response.



Appendix D: Significance of the early warning signals

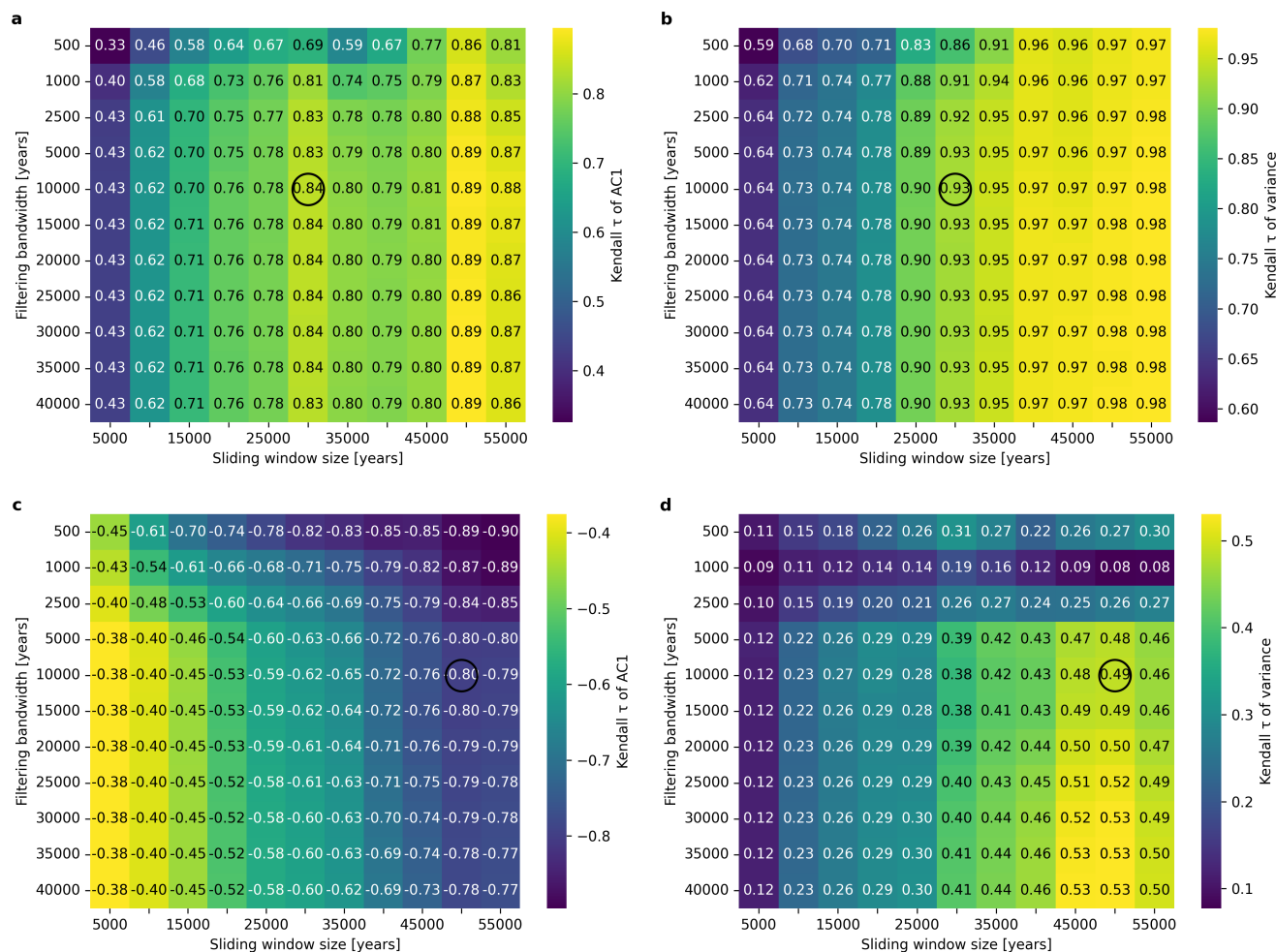


Figure D1. The trends of the correlations are robust against different filtering bandwidths and sliding window sizes. Shown is the Kendall rank correlation coefficient (τ) as a function of filtering bandwidth used in the Gaussian filtering for detrending the melt rate and of the sliding window size to compute (a & c) the AC1 and (b & d) variance. Bandwidths range from 500 to 40,000 ISM years and sliding window sizes from 5,000 to 55,000 ISM years. Hence, the sliding window sizes correspond to (a & b) 6% to 71% for the retreat branch and (c & d) 4% to 42% for the regrowth branch. Percentages differ due to the different lengths of the time series of the upper and regrowth branch. All Kendall's τ values are statistically significant at $\alpha = 5\%$. The chosen combination for Figure 6 is indicated by a black circle. Slightly higher correlations would have been archived with larger sliding windows.



Author contributions. All authors conceptualized the study and designed the experiments. MA carried out the simulations. MA performed the analysis and wrote the manuscript with input from all authors.

430 *Competing interests.* One of the (co-)authors serves as editor for the special issue to which this paper has been submitted. The authors have no other competing interests to declare.

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References

- Andernach, M., Kapsch, M. L., and Mikolajewicz, U.: Impact of Greenland Ice Sheet disintegration on atmosphere and ocean disentangled, *Earth Syst. Dynam.*, 16, 451–474, <https://doi.org/10.5194/esd-16-451-2025>, 2025.
- 440 Andernach, M., Kapsch, M.-L., and Mikolajewicz, U.: Stabilizing feedbacks allow for multiple states of the Greenland Ice Sheet in a fully coupled Earth System–Ice Sheet Model, *The Cryosphere*, 20, 1047–1069, <https://doi.org/10.5194/tc-20-1047-2026>, 2026.
- Aschwanden, A., Fahnestock, M. A., Truffer, M., Brinkerhoff, D. J., Hock, R., Khroulev, C., Mottram, R., and Khan, S. A.: Contribution of the Greenland Ice Sheet to sea level over the next millennium, *Science Advances*, 5, eaav9396, <https://doi.org/10.1126/sciadv.aav9396>, 2019.
- 445 Bamber, J., Westaway, R., Marzeion, B., and Wouters, B.: The land ice contribution to sea level during the satellite era, *Environmental Research Letters*, 13, 063 008, <https://doi.org/10.1088/1748-9326/aac2f0>, 2018.
- Berger, A. and Loutre, M. F.: Insolation values for the climate of the last 10 million years, *Quaternary Science Reviews*, 10, 297–317, [https://doi.org/10.1016/0277-3791\(91\)90033-Q](https://doi.org/10.1016/0277-3791(91)90033-Q), 1991.
- Bochow, N., Poltronieri, A., Robinson, A., Montoya, M., Rypdal, M., and Boers, N.: Overshooting the critical threshold for the Greenland
 450 ice sheet, *Nature*, 622, 528–536, <https://doi.org/10.1038/s41586-023-06503-9>, 2023.
- Boers, N.: Observation-based early-warning signals for a collapse of the Atlantic Meridional Overturning Circulation, *Nature Climate Change*, 11, 680–688, <https://doi.org/10.1038/s41558-021-01097-4>, 2021.
- Boers, N. and Rypdal, M.: Critical slowing down suggests that the western Greenland Ice Sheet is close to a tipping point, *Proceedings of the National Academy of Sciences*, 118, e2024192 118, <https://doi.org/10.1073/pnas.2024192118>, 2021.
- 455 Calov, R., Ganopolski, A., Claussen, M., Petoukhov, V., and Greve, R.: Transient simulation of the last glacial inception. Part I: glacial inception as a bifurcation in the climate system, *Climate Dynamics*, 24, 545–561, <https://doi.org/10.1007/s00382-005-0007-6>, 2005.
- Claussen, M., Mysak, L., Weaver, A., Crucifix, M., Fichet, T., Loutre, M. F., Weber, S., Alcamo, J., Alexeev, V., Berger, A., Calov, R., Ganopolski, A., Goosse, H., Lohmann, G., Lunkeit, F., Mokhov, I., Petoukhov, V., Stone, P., and Wang, Z.: Earth system models of intermediate complexity: closing the gap in the spectrum of climate system models, *Climate Dynamics*, 18, 579–586,
 460 <https://doi.org/10.1007/s00382-001-0200-1>, 2002.
- Cuffey, K. M. and Paterson, W. S. B.: *The physics of glaciers*, Butterworth-Heinemann/Elsevier, Burlington, MA, fourth edition edn., <https://doi.org/10.3189/002214311796405906>, 2010.
- Dakos, V., Scheffer, M., van Nes, E. H., Brovkin, V., Petoukhov, V., and Held, H.: Slowing down as an early warning signal for abrupt climate change, *Proceedings of the National Academy of Sciences*, 105, 14 308–14 312, <https://doi.org/10.1073/pnas.0802430105>, 2008.
- 465 Dakos, V., van Nes, E. H., D’Odorico, P., and Scheffer, M.: Robustness of variance and autocorrelation as indicators of critical slowing down, *Ecology*, 93, 264–271, <https://doi.org/10.1890/11-0889.1>, 2012.
- Davini, P., von Hardenberg, J., Filippi, L., and Provenzale, A.: Impact of Greenland orography on the Atlantic Meridional Overturning Circulation, *Geophysical Research Letters*, 42, 871–879, <https://doi.org/10.1002/2014GL062668>, 2015.
- Depoorter, M. A., Bamber, J. L., Griggs, J. A., Lenaerts, J. T. M., Ligtenberg, S. R. M., van den Broeke, M. R., and Moholdt, G.: Calving
 470 fluxes and basal melt rates of Antarctic ice shelves, *Nature*, 502, 89–92, <https://doi.org/10.1038/nature12567>, 2013.
- Dethloff, K., Dorn, W., Rinke, A., Fraedrich, K., Junge, M., Roeckner, E., Gayler, V., Cubasch, U., and Christensen, J. H.: The impact of Greenland’s deglaciation on the Arctic circulation, *Geophysical Research Letters*, 31, <https://doi.org/10.1029/2004GL020714>, 2004.



- Erokhina, O. and Mikolajewicz, U.: A New Eulerian Iceberg Module for Climate Studies, *Journal of Advances in Modeling Earth Systems*, 16, e2023MS003 807, <https://doi.org/10.1029/2023MS003807>, 2024.
- 475 Fettweis, X., Hofer, S., Krebs-Kanzow, U., Amory, C., Aoki, T., Berends, C. J., Born, A., Box, J. E., Delhasse, A., Fujita, K., Gierz, P., Goelzer, H., Hanna, E., Hashimoto, A., Huybrechts, P., Kapsch, M. L., King, M. D., Kittel, C., Lang, C., Langen, P. L., Lenaerts, J. T. M., Liston, G. E., Lohmann, G., Mernild, S. H., Mikolajewicz, U., Modali, K., Mottram, R. H., Niwano, M., Noël, B., Ryan, J. C., Smith, A., Streffing, J., Tedesco, M., van de Berg, W. J., van den Broeke, M., van de Wal, R. S. W., van Kampenhout, L., Wilton, D., Wouters, B., Ziemen, F., and Zolles, T.: GrSMBMIP: intercomparison of the modelled 1980–2012 surface mass balance over the Greenland Ice Sheet,
- 480 *The Cryosphere*, 14, 3935–3958, <https://doi.org/10.5194/tc-14-3935-2020>, 2020.
- Forster, P. M., Smith, C., Walsh, T., Lamb, W. F., Lamboll, R., Cassou, C., Hauser, M., Hausfather, Z., Lee, J. Y., Palmer, M. D., von Schuckmann, K., Slangen, A. B. A., Szopa, S., Trewin, B., Yun, J., Gillett, N. P., Jenkins, S., Matthews, H. D., Raghavan, K., Ribes, A., Rogelj, J., Rosen, D., Zhang, X., Allen, M., Aleluia Reis, L., Andrew, R. M., Betts, R. A., Borger, A., Broersma, J. A., Burgess, S. N., Cheng, L., Friedlingstein, P., Domingues, C. M., Gambarini, M., Gasser, T., Gütschow, J., Ishii, M., Kadow, C., Kennedy, J., Killick, R. E.,
- 485 Krummel, P. B., Liné, A., Monselesan, D. P., Morice, C., Mühle, J., Naik, V., Peters, G. P., Pirani, A., Pongratz, J., Minx, J. C., Rigby, M., Rohde, R., Savita, A., Seneviratne, S. I., Thorne, P., Wells, C., Western, L. M., van der Werf, G. R., Wijffels, S. E., Masson-Delmotte, V., and Zhai, P.: Indicators of Global Climate Change 2024: annual update of key indicators of the state of the climate system and human influence, *Earth Syst. Sci. Data*, 17, 2641–2680, <https://doi.org/10.5194/essd-17-2641-2025>, 2025.
- Fyke, J., Sergienko, O., Löfverström, M., Price, S., and Lenaerts, J. T. M.: An Overview of Interactions and Feedbacks Between Ice Sheets
- 490 and the Earth System, *Reviews of Geophysics*, 56, 361–408, <https://doi.org/10.1029/2018RG000600>, 2018.
- Garbe, J., Albrecht, T., Levermann, A., Donges, J. F., and Winkelmann, R.: The hysteresis of the Antarctic Ice Sheet, *Nature*, 585, 538–544, <https://doi.org/10.1038/s41586-020-2727-5>, 2020.
- Gregory, J. M., George, S. E., and Smith, R. S.: Large and irreversible future decline of the Greenland ice sheet, *The Cryosphere*, 14, 4299–4322, <https://doi.org/10.5194/tc-14-4299-2020>, 2020.
- 495 Gutiérrez-González, L., Robinson, A., Alvarez-Solas, J., Tabone, I., Swierczek-Jereczek, J., Moreno-Parada, D., and Montoya, M.: Hysteresis of the Greenland ice sheet from the Last Glacial Maximum to the future, *The Cryosphere*, 20, 1139–1162, <https://doi.org/10.5194/tc-20-1139-2026>, 2026.
- Hauer, M. E., Fussell, E., Mueller, V., Burkett, M., Call, M., Abel, K., McLeman, R., and Wrathall, D.: Sea-level rise and human migration, *Nature Reviews Earth & Environment*, 1, 28–39, <https://doi.org/10.1038/s43017-019-0002-9>, 2020.
- 500 Held, H. and Kleinen, T.: Detection of climate system bifurcations by degenerate fingerprinting, *Geophysical Research Letters*, 31, <https://doi.org/10.1029/2004GL020972>, 2004.
- Hillenbrand, C.-D., Smith, J. A., Hodell, D. A., Greaves, M., Poole, C. R., Kender, S., Williams, M., Andersen, T. J., Jernas, P. E., Elderfield, H., Klages, J. P., Roberts, S. J., Gohl, K., Larter, R. D., and Kuhn, G.: West Antarctic Ice Sheet retreat driven by Holocene warm water incursions, *Nature*, 547, 43–48, <https://doi.org/10.1038/nature22995>, 2017.
- 505 Holland, D. M. and Jenkins, A.: Modeling Thermodynamic Ice–Ocean Interactions at the Base of an Ice Shelf, *Journal of Physical Oceanography*, 29, 1787–1800, [https://doi.org/10.1175/1520-0485\(1999\)029<1787:MTIOIA>2.0.CO;2](https://doi.org/10.1175/1520-0485(1999)029<1787:MTIOIA>2.0.CO;2), 1999.
- Höning, D., Willeit, M., Calov, R., Klemann, V., Bagge, M., and Ganopolski, A.: Multistability and Transient Response of the Greenland Ice Sheet to Anthropogenic CO₂ Emissions, *Geophysical Research Letters*, 50, e2022GL101 827, <https://doi.org/10.1029/2022GL101827>, 2023.



- 510 Imbrie, J., Berger, A., Boyle, E., Clemens, S., Duffy, A., Howard, W., Kukla, G., Kutzbach, J., Martinson, D., McIntyre, A., et al.: On the structure and origin of major glaciation cycles 2. The 100,000-year cycle, *Paleoceanography*, 8, 699–735, <https://doi.org/10.1029/93PA02751>, 1993.
- Joos, F., Roth, R., Fuglestad, J. S., Peters, G. P., Enting, I. G., von Bloh, W., Brovkin, V., Burke, E. J., Eby, M., Edwards, N. R., Friedrich, T., Frölicher, T. L., Halloran, P. R., Holden, P. B., Jones, C., Kleinen, T., Mackenzie, F. T., Matsumoto, K., Meinshausen, M., Plattner, G. K.,
- 515 Reisinger, A., Segschneider, J., Shaffer, G., Steinacher, M., Strassmann, K., Tanaka, K., Timmermann, A., and Weaver, A. J.: Carbon dioxide and climate impulse response functions for the computation of greenhouse gas metrics: a multi-model analysis, *Atmospheric Chemistry and Physics*, 13, 2793–2825, <https://doi.org/10.5194/acp-13-2793-2013>, 2013.
- Joughin, I. and Alley, R. B.: Stability of the West Antarctic ice sheet in a warming world, *Nature Geoscience*, 4, 506–513, <https://doi.org/10.1038/ngeo1194>, 2011.
- 520 Joughin, I., Shapero, D., Smith, B., Dutrieux, P., and Barham, M.: Ice-shelf retreat drives recent Pine Island Glacier speedup, *Science Advances*, 7, eabg3080, <https://doi.org/10.1126/sciadv.abg3080>, 2021.
- Jungclaus, J. H., Fischer, N., Haak, H., Lohmann, K., Marotzke, J., Matei, D., Mikolajewicz, U., Notz, D., and von Storch, J. S.: Characteristics of the ocean simulations in the Max Planck Institute Ocean Model (MPIOM) the ocean component of the MPI-Earth system model, *Journal of Advances in Modeling Earth Systems*, 5, 422–446, <https://doi.org/10.1002/jame.20023>, 2013.
- 525 Junge, M. M., Blender, R., Fraedrich, K., Gayler, V., Luksch, U., and Lunkeit, F.: A world without Greenland: impacts on the Northern Hemisphere winter circulation in low- and high-resolution models, *Climate Dynamics*, 24, 297–307, <https://doi.org/10.1007/s00382-004-0501-2>, 2005.
- Kapsch, M., Mikolajewicz, U., and Schannwell, C.: Feedback mechanisms between the climate and ice sheets drive long-term ice-sheet loss and sea-level rise, under review in *Nature Climate Change*.
- 530 Kapsch, M. L., Mikolajewicz, U., Ziemann, F. A., Rodehacke, C. B., and Schannwell, C.: Analysis of the surface mass balance for deglacial climate simulations, *The Cryosphere*, 15, 1131–1156, <https://doi.org/10.5194/tc-15-1131-2021>, 2021.
- Köhler, P., Nehrbass-Ahles, C., Schmitt, J., Stocker, T. F., and Fischer, H.: A 156 kyr smoothed history of the atmospheric greenhouse gases CO₂, CH₄, and N₂O and their radiative forcing, *Earth Syst. Sci. Data*, 9, 363–387, <https://doi.org/10.5194/essd-9-363-2017>, 2017.
- Lan, X., Tans, P., Thoning, K., et al.: Trends in globally-averaged CO₂ determined from NOAA Global Monitoring Laboratory measurements.
- 535 Version 2026-03, <https://doi.org/10.15138/9N0H-ZH07>, 2026.
- Langen, P. L., Solgaard, A. M., and Hvidberg, C. S.: Self-inhibiting growth of the Greenland Ice Sheet, *Geophysical Research Letters*, 39, <https://doi.org/10.1029/2012GL051810>, 2012.
- Leloup, G., Quiquet, A., Roche, D. M., Dumas, C., and Paillard, D.: Hysteresis of the Antarctic Ice Sheet With a Coupled Climate-Ice-Sheet Model, *Geophysical Research Letters*, 52, e2024GL111492, <https://doi.org/10.1029/2024GL111492>, 2025.
- 540 Lenton, T. M.: Early warning of climate tipping points, *Nature Climate Change*, 1, 201–209, <https://doi.org/10.1038/nclimate1143>, 2011.
- Lenton, T. M., Held, H., Kriegler, E., Hall, J. W., Lucht, W., Rahmstorf, S., and Schellnhuber, H. J.: Tipping elements in the Earth's climate system, *Proceedings of the National Academy of Sciences*, 105, 1786–1793, <https://doi.org/10.1073/pnas.0705414105>, 2008.
- Lenton, T. M., Livina, V. N., Dakos, V., van Nes, E. H., and Scheffer, M.: Early warning of climate tipping points from critical slowing down: comparing methods to improve robustness, *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering*
- 545 *Sciences*, 370, 1185–1204, <https://doi.org/10.1098/rsta.2011.0304>, 2012.
- Letréguilly, A., Huybrechts, P., and Reeh, N.: Steady-state characteristics of the Greenland ice sheet under different climates, *Journal of Glaciology*, 37, 149–157, <https://doi.org/10.3189/S0022143000042908>, 1991.



- Levermann, A., Albrecht, T., Winkelmann, R., Martin, M. A., Haseloff, M., and Joughin, I.: Kinematic first-order calving law implies potential for abrupt ice-shelf retreat, *The Cryosphere*, 6, 273–286, <https://doi.org/10.5194/tc-6-273-2012>, 2012.
- 550 Lunt, D. J., de Noblet-Ducoudré, N., and Charbit, S.: Effects of a melted greenland ice sheet on climate, vegetation, and the cryosphere, *Climate Dynamics*, 23, 679–694, <https://doi.org/10.1007/s00382-004-0463-4>, 2004.
- Marsland, S. J., Haak, H., Jungclaus, J. H., Latif, M., and Röske, F.: The Max-Planck-Institute global ocean/sea ice model with orthogonal curvilinear coordinates, *Ocean Modelling*, 5, 91–127, [https://doi.org/10.1016/S1463-5003\(02\)00015-X](https://doi.org/10.1016/S1463-5003(02)00015-X), 2003.
- Martinec, Z., Klemann, V., van der Wal, W., Riva, R. E. M., Spada, G., Sun, Y., Melini, D., Kachuck, S. B., Barletta, V., Simon, K., A,
555 G., and James, T. S.: A benchmark study of numerical implementations of the sea level equation in GIA modelling, *Geophysical Journal International*, 215, 389–414, <https://doi.org/10.1093/gji/ggy280>, 2018.
- Mauritsen, T., Bader, J., Becker, T., Behrens, J., Bittner, M., Brokopf, R., Brovkin, V., Claussen, M., Crueger, T., Esch, M., Fast, I., Fiedler, S., Fläschner, D., Gayler, V., Giorgetta, M., Goll, D. S., Haak, H., Hagemann, S., Hedemann, C., Hohenegger, C., Ilyina, T., Jahns, T., Jimenez-de-la Cuesta, D., Jungclaus, J., Kleinen, T., Kloster, S., Kracher, D., Kinne, S., Kleberg, D., Lasslop, G., Kornbluh, L.,
560 Marotzke, J., Matei, D., Meraner, K., Mikolajewicz, U., Modali, K., Möbis, B., Müller, W. A., Nabel, J. E. M. S., Nam, C. C. W., Notz, D., Nyawira, S.-S., Paulsen, H., Peters, K., Pincus, R., Pohlmann, H., Pongratz, J., Popp, M., Raddatz, T. J., Rast, S., Redler, R., Reick, C. H., Rohrschneider, T., Schemann, V., Schmidt, H., Schnur, R., Schulzweida, U., Six, K. D., Stein, L., Stemmler, I., Stevens, B., von Storch, J.-S., Tian, F., Voigt, A., Vrese, P., Wieners, K.-H., Wilkenskield, S., Winkler, A., and Roeckner, E.: Developments in the MPI-M Earth System Model version 1.2 (MPI-ESM1.2) and Its Response to Increasing CO₂, *Journal of Advances in Modeling Earth Systems*,
565 11, 998–1038, <https://doi.org/10.1029/2018MS001400>, 2019.
- Meccia, V. L. and Mikolajewicz, U.: Interactive ocean bathymetry and coastlines for simulating the last deglaciation with the Max Planck Institute Earth System Model (MPI-ESM-v1.2), *Geosci. Model Dev.*, 11, 4677–4692, <https://doi.org/10.5194/gmd-11-4677-2018>, 2018.
- Meehl, G. A., Senior, C. A., Eyring, V., Flato, G., Lamarque, J.-F., Stouffer, R. J., Taylor, K. E., and Schlund, M.: Context for interpreting equilibrium climate sensitivity and transient climate response from the CMIP6 Earth system models, *Science Advances*, 6, eaba1981,
570 <https://doi.org/10.1126/sciadv.aba1981>, 2020.
- Mikolajewicz, U., Vizcaíno, M., Jungclaus, J., and Schurgers, G.: Effect of ice sheet interactions in anthropogenic climate change simulations, *Geophysical Research Letters*, 34, <https://doi.org/10.1029/2007GL031173>, 2007.
- Mikolajewicz, U., Ziemann, F., Cioni, G., Claussen, M., Fraedrich, K., Heidkamp, M., Hohenegger, C., Jimenez de la Cuesta, D., Kapsch, M. L., Lemburg, A., Mauritsen, T., Meraner, K., Röber, N., Schmidt, H., Six, K. D., Stemmler, I., Tamarin-Brodsky, T., Winkler, A., Zhu,
575 X., and Stevens, B.: The climate of a retrograde rotating Earth, *Earth Syst. Dynam.*, 9, 1191–1215, <https://doi.org/10.5194/esd-9-1191-2018>, 2018.
- Mikolajewicz, U., Kapsch, M. L., Schannwell, C., Six, K. D., Ziemann, F. A., Bagge, M., Baudouin, J. P., Erokhina, O., Gayler, V., Klemann, V., Meccia, V. L., Mouchet, A., and Riddick, T.: Deglaciation and abrupt events in a coupled comprehensive atmosphere–ocean–ice-sheet–solid-earth model, *Clim. Past*, 21, 719–751, <https://doi.org/10.5194/cp-21-719-2025>, 2025.
- 580 Morlighem, M.: MEaSUREs BedMachine Antarctica, Version 4, <https://doi.org/10.5067/POJQI54A45HX>, 2025.
- Morlighem, M., Williams, C., Rignot, E., An, L., Arndt, J. E., Bamber, J., Catania, G., Chauché, N., Dowdeswell, J. A., Dorschel, B., Fenty, I., Hogan, K., Howat, I., Hubbard, A., Jakobsson, M., Jordan, T. M., Kjeldsen, K. K., Millan, R., Mayer, L., Mouginot, J., Noël, B., O’Cofaigh, C., Palmer, S. J., Rysgaard, S., Seroussi, H., Siegert, M. J., Slabon, P., Straneo, F., van den Broeke, M. R., Weinrebe, W., Wood, M., and Zinglensen, K.: IceBridge BedMachine Greenland, Version 5, <https://doi.org/10.5067/GMEVBWFLWA7X>, 2022.



- 585 Naughten, K. A., Holland, P. R., and De Rydt, J.: Unavoidable future increase in West Antarctic ice-shelf melting over the twenty-first century, *Nature Climate Change*, 13, 1222–1228, <https://doi.org/10.1038/s41558-023-01818-x>, 2023.
- Oerlemans, J. and Knap, W. H.: A 1 year record of global radiation and albedo in the ablation zone of Morteratschgletscher, Switzerland, *Journal of Glaciology*, 44, 231–238, <https://doi.org/10.3189/s0022143000002574>, 1998.
- on Climate Change (IPCC), I. P., ed.: *Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities*, pp. 321–446, Cambridge University Press, Cambridge, <https://doi.org/10.1017/9781009157964.006>, 2022.
- 590 Pattyn, F., Ritz, C., Hanna, E., Asay-Davis, X., DeConto, R., Durand, G., Favier, L., Fettweis, X., Goelzer, H., Golledge, N. R., Kuipers Munneke, P., Lenaerts, J. T. M., Nowicki, S., Payne, A. J., Robinson, A., Seroussi, H., Trusel, L. D., and van den Broeke, M.: The Greenland and Antarctic ice sheets under 1.5 °C global warming, *Nature Climate Change*, 8, 1053–1061, <https://doi.org/10.1038/s41558-018-0305-8>, 2018.
- 595 Pegler, S. S.: Marine ice sheet dynamics: the impacts of ice-shelf buttressing, *Journal of Fluid Mechanics*, 857, 605–647, <https://doi.org/10.1017/jfm.2018.741>, 2018.
- Petersen, G. N., Kristjánsson, J. E., and Ólafsson, H.: Numerical simulations of Greenland’s impact on the Northern Hemisphere winter circulation, *Tellus A: Dynamic Meteorology and Oceanography*, 56, 102–111, <https://doi.org/10.3402/tellusa.v56i2.14400>, 2004.
- Raddatz, T. J., Reick, C. H., Knorr, W., Kattge, J., Roeckner, E., Schnur, R., Schnitzler, K. G., Wetzel, P., and Jungclaus, J.: Will the tropical land biosphere dominate the climate–carbon cycle feedback during the twenty-first century?, *Climate Dynamics*, 29, 565–574, <https://doi.org/10.1007/s00382-007-0247-8>, 2007.
- 600 Riddick, T., Brovkin, V., Hagemann, S., and Mikolajewicz, U.: Dynamic hydrological discharge modelling for coupled climate model simulations of the last glacial cycle: the MPI-DynamicHD model version 3.0, *Geosci. Model Dev.*, 11, 4291–4316, <https://doi.org/10.5194/gmd-11-4291-2018>, 2018.
- 605 Ridley, J., Gregory, J. M., Huybrechts, P., and Lowe, J.: Thresholds for irreversible decline of the Greenland ice sheet, *Climate Dynamics*, 35, 1049–1057, <https://doi.org/10.1007/s00382-009-0646-0>, 2010.
- Rietkerk, M., Skiba, V., Weinans, E., Hébert, R., and Laepple, T.: Ambiguity of early warning signals for climate tipping points, *Nature Climate Change*, 15, 479–488, <https://doi.org/10.1038/s41558-025-02328-8>, 2025.
- Robinson, A., Calov, R., and Ganopolski, A.: Multistability and critical thresholds of the Greenland ice sheet, *Nature Climate Change*, 2, 429–432, <https://doi.org/10.1038/nclimate1449>, 2012.
- 610 Schannwell, C., Kapsch, M. L., Willeit, M., Ackermann, L., Knorr, G., Krebs-Kanzow, U., Lohmann, G., Six, K. D., Stepanek, C., and Mikolajewicz, U.: Unravelling the source for diverging long-term ice loss trajectories within the Greenland Ice sheet Coupled Model Intercomparison Project (GrICMIP), *EGUsphere*, 2026, 1–43, <https://doi.org/10.5194/egusphere-2026-3384>, 2026.
- Scheffer, M., Bascompte, J., Brock, W. A., Brovkin, V., Carpenter, S. R., Dakos, V., Held, H., van Nes, E. H., Rietkerk, M., and Sugihara, G.: Early-warning signals for critical transitions, *Nature*, 461, 53–59, <https://doi.org/10.1038/nature08227>, 2009.
- Schlemm, T., Feldmann, J., Winkelmann, R., and Levermann, A.: Stabilizing effect of mélange buttressing on the marine ice-cliff instability of the West Antarctic Ice Sheet, *The Cryosphere*, 16, 1979–1996, <https://doi.org/10.5194/tc-16-1979-2022>, 2022.
- Smith, T. and Boers, N.: Reliability of vegetation resilience estimates depends on biomass density, *Nature Ecology & Evolution*, 7, 1799–1808, <https://doi.org/10.1038/s41559-023-02194-7>, 2023.
- 620 Solgaard, A. M. and Langen, P. L.: Multistability of the Greenland ice sheet and the effects of an adaptive mass balance formulation, *Climate Dynamics*, 39, 1599–1612, <https://doi.org/10.1007/s00382-012-1305-4>, 2012.



- Stevens, B., Giorgetta, M., Esch, M., Mauritsen, T., Crueger, T., Rast, S., Salzmann, M., Schmidt, H., Bader, J., Block, K., Brokopf, R., Fast, I., Kinne, S., Kornbluh, L., Lohmann, U., Pincus, R., Reichler, T., and Roeckner, E.: Atmospheric component of the MPI-M Earth System Model: ECHAM6, *Journal of Advances in Modeling Earth Systems*, 5, 146–172, <https://doi.org/10.1002/jame.20015>, 2013.
- 625 Talento, S., Willeit, M., and Ganopolski, A.: New estimation of critical insolation–CO₂ relationship for triggering glacial inception, *Clim. Past*, 20, 1349–1364, <https://doi.org/10.5194/cp-20-1349-2024>, 2024.
- Tao, W., Huang, G., Lau, W. K. M., Dong, D., Wang, P., and Wen, G.: How can CMIP5 AGCMs’ resolution influence precipitation in mountain areas: the Hengduan Mountains?, *Climate Dynamics*, 54, 159–172, <https://doi.org/10.1007/s00382-019-04993-w>, 2020.
- Thoma, M., Jenkins, A., Holland, D., and Jacobs, S.: Modelling Circumpolar Deep Water intrusions on the Amundsen Sea continental shelf, Antarctica, *Geophysical Research Letters*, 35, <https://doi.org/10.1029/2008GL034939>, 2008.
- 630 Van Breedam, J., Goelzer, H., and Huybrechts, P.: Semi-equilibrated global sea-level change projections for the next 10 000 years, *Earth Syst. Dynam.*, 11, 953–976, <https://doi.org/10.5194/esd-11-953-2020>, 2020.
- van den Broeke, M. R., Enderlin, E. M., Howat, I. M., Kuipers Munneke, P., Noël, B. P. Y., van de Berg, W. J., van Meijgaard, E., and Wouters, B.: On the recent contribution of the Greenland ice sheet to sea level change, *The Cryosphere*, 10, 1933–1946, [https://doi.org/10.5194/tc-](https://doi.org/10.5194/tc-10-1933-2016)
- 635 10-1933-2016, 2016.
- van Kampenhout, L., Rhoades, A. M., Herrington, A. R., Zarzycki, C. M., Lenaerts, J. T. M., Sacks, W. J., and van den Broeke, M. R.: Regional grid refinement in an Earth system model: impacts on the simulated Greenland surface mass balance, *The Cryosphere*, 13, 1547–1564, <https://doi.org/10.5194/tc-13-1547-2019>, 2019.
- Willeit, M., Ganopolski, A., Robinson, A., and Edwards, N. R.: The Earth system model CLIMBER-X v1.0 –Part 1: Climate model description and validation, *Geosci. Model Dev.*, 15, 5905–5948, <https://doi.org/10.5194/gmd-15-5905-2022>, 2022.
- 640 Yao, W., Cao, L., and Jin, X.: Simulated Responses of the Ocean Carbon Cycle to Different Rates of Atmospheric CO₂ Removal, *Journal of Geophysical Research: Oceans*, 130, e2024JC022115, <https://doi.org/10.1029/2024JC022115>, 2025.
- Zeitz, M., Reese, R., Beckmann, J., Krebs-Kanzow, U., and Winkelmann, R.: Impact of the melt–albedo feedback on the future evolution of the Greenland Ice Sheet with PISM-dEBM-simple, *The Cryosphere*, 15, 5739–5764, <https://doi.org/10.5194/tc-15-5739-2021>, 2021.
- 645 Zeitz, M., Haacker, J. M., Donges, J. F., Albrecht, T., and Winkelmann, R.: Dynamic regimes of the Greenland Ice Sheet emerging from interacting melt–elevation and glacial isostatic adjustment feedbacks, *Earth Syst. Dynam.*, 13, 1077–1096, <https://doi.org/10.5194/esd-13-1077-2022>, 2022.
- Ziemen, F. A., Kapsch, M. L., Klockmann, M., and Mikolajewicz, U.: Heinrich events show two-stage climate response in transient glacial simulations, *Clim. Past*, 15, 153–168, <https://doi.org/10.5194/cp-15-153-2019>, 2019.