CLIMATE_SPACE: TIPPING ELEMENTS ACTIVITY

CryoTipping

Science Requirements Document

TABLE OF CONTENTS

LIST OF FIGURES

VERSION HISTORY TABLE

Version	Author	Affected Section	Change	Status
1.0	All	All	Document Creation	
2.0	All		Document Revised	

ACRONYMS AND ABBREVIATIONS

Abbreviation	Meaning
CCI+	Climate Change Initiative Plus
CMUG	Climate Modelling User Group
DLR	Deutsches Zentrum für Luft und Raumfahrt (German Aerospace Center)
ENVEO	Environmental Earth Observation Information Technology GmbH
EO	Earth Observation
ESA	European Space Agency
GLL	Grounding Line Location
IPCC	Intergovernmental Panel on Climate Change
IV	Ice Velocity
MICI	Marine Ice Cliff Instability
MISI	Marice Ice Sheet Instability
NU	Northumbria University
PISM	Parallel Ice Sheet Model
SEC	Surface Elevation Change
SEMI	Surface Elevation Melt Instability
SSP	Shared Socio-Economic Pathway
VILMA	VIscoelastic Lithosphere and MAntle
WP	Work Package

1. INTRODUCTION

1.1 Purpose and Scope

This document reviews the current knowledge gaps on Antarctica's tipping points and examples of previous studies where satellite-derived climate data records have been used to investigate tipping points, assessing the need for conducting new scientific studies as part of CryoTipping Climate_Space: Tipping Elements Activity.

1.1 Overview of document

This science requirements document consists of the following sections:

Section 2. Review of current knowledge on Antarctica's tipping points

Section 3. Knowledge gaps

Section 4. Definition of project activities

Section 5. References

2. REVIEW OF CURRENT KNOWLEDGE ON ANTARCTICA'S TIPPING POINTS

2.1 Antarctica's tipping points and future sea level rise

The latest IPCC report predicts future sea level rise between 26 and 160 cm by 2100 depending on the shared socio-economic pathway scenario (SSP) and between 37 and 482 cm by 2150 (Fox-Kemper et al., 2021). Beyond 2100, the high-end sea level projections are largely driven by ice sheet instabilities, with a rapid retreat of the West Antarctic Ice Sheet leading to more sea level rise. The cryosphere has changed rapidly during the satellite era owing to the combined effects of rising air temperatures and forcing from the ocean, resulting in growing concerns about the proximity of crossing tipping points. In particular, the Antarctic Ice Sheet is prone to three major instability mechanisms: the marine ice sheet instability (MISI), the marine ice cliff instability (MICI), and the surface elevation melt instability (SEMI). These instability mechanisms drive considerable uncertainties in projections of future sea-level rise (Figure 1), and therefore need to be carefully investigated.
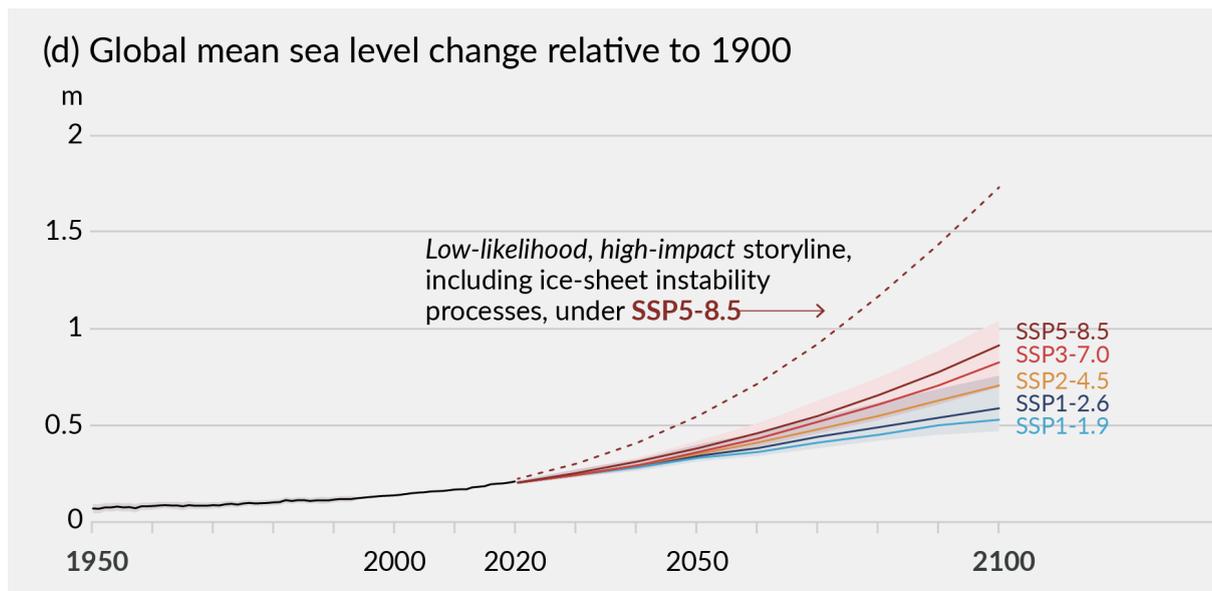
Figure 1 - Global mean sea level change in metres, relative to 1900. Reproduced from the IPCC AR6 Figure SPM.8d.

2.2 Antarctic ice sheet instability mechanisms

There are three principal instability mechanisms that can trigger irreversible tipping in the cryosphere, leading to the (partial) collapse of the Antarctic Ice Sheet: the marine ice sheet instability (MISI), the marine ice cliff instability (MICI), and the surface elevation melt instability (SEMI). Parts of the ice sheets where the bed is grounded below sea level and deepens inland are subject to MISI. In this configuration, a retreat of the grounding line leads to an increase in ice discharge as the ice thickness increases inland and, in turn, entails a

further retreat of the grounding line in a hysteretic behaviour (Schoof, 2007). This retreat continues until a region with a downward sloping bed or a new pinning point is reached. MICI is associated with a collapse of tall ice cliffs (~100 m) triggered by ice-shelf collapse inducing a rapid and sustained retreat of the ice sheet as further taller ice cliffs, also prone to failure, are exposed behind (DeConto and Pollard, 2016) (Figure 2). While it would lead to a non-linear response of the ice sheets and a more extreme sea level rise contribution, this proposed mechanism has not yet been observed and is subject to debate within the scientific community (Edwards et al., 2019). Finally, SEMI relates to the self-sustaining effect between increased melt and reduced surface elevation: as the ice sheet melts, their surface elevation decreases and is exposed to higher temperatures further increasing melt (Levermann and Winkelmann, 2016).
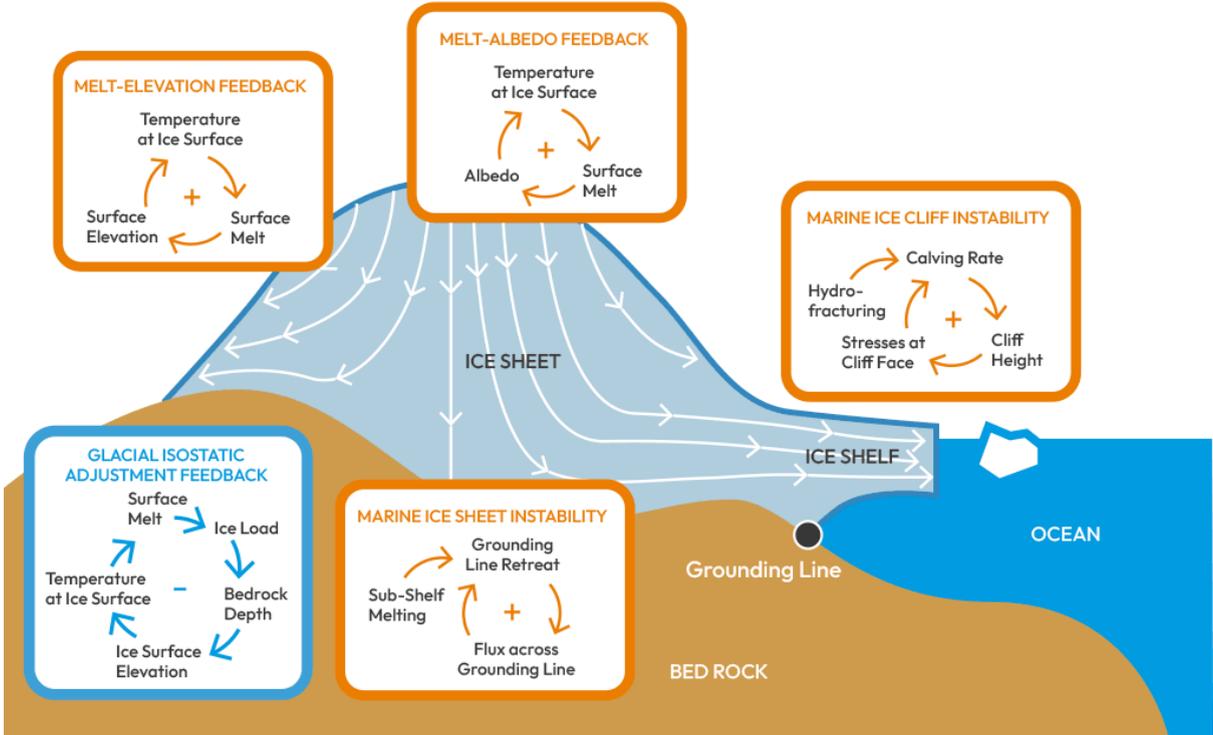
Figure 2 - Illustration of the principal instability mechanisms in the ice sheet-climate system. Reproduced from Armstrong McKay et al. (2023).

2.3   Evidence of Antarctic tipping points in modelling studies

Modelling studies have been instrumental in identifying critical thresholds in Antarctica and advance our knowledge of processes that could lead to the destabilisation of the ice sheet. Garbe et al. (2020) have identified three critical thresholds in Antarctica that could be triggered at different warming levels. At 2°C of warming above pre-industrial levels, West Antarctica is committed to long-term partial collapse triggered by MISI. At 6-9°C, 70% of

Antarcica's ice volume would be lost due to SEMI. Above 10°C warming, Antarctica would become ice-free. Simulations run over the last 800,000 years have shown that tipping points have been triggered in West Antarctica leading to its collapse in warmer interglacial periods (Chandler et al., 2025). These paleo-simulations indicate that a very small ocean warming (0.25 °C) would be sufficient to tip the West Antarctic Ice Sheet, suggesting that it is already very close to tipping. Hill et al. (2024) have also identified ocean warming as a trigger for the irreversible retreat of the Antarctic Ice Sheet, where a shift of the Filchner and Ronne ice shelves' cavities from cold to warm states would lead to the destabilisation and irreversible retreat of the grounding line in some locations in the region (Figure 3). There are only sparse in-situ observations of ocean properties (temperature, salinity, pressure, and ocean currents) around Antarctica due to the challenging logistics and presence of icebergs and sea ice affecting ship-based deployment and collection of moored instruments. To represent ocean forcing in ice sheet numerical simulations, rather than using direct observations, standalone ice sheet models use parametrisations of sub-ice shelf melting (Burgard et al., 2022) and coupled ice-ocean models allow the interactions of an ice sheet model and ocean circulation model so that the ice geometry and ocean state are both changing over time (e.g. De Rydt & Gudmundsson, 2016; Jordan et al., 2017). Simulations run over the next centuries have demonstrated that Thwaites and Pine Island Glaciers will experience continued, accelerated retreat (Joughin et al., 2014; Favier et al., 2014). Model studies indicate that this retreat is not MISI-driven yet, but might become so under current climate conditions (Hill, et al., 2023; Reese et al., 2023).
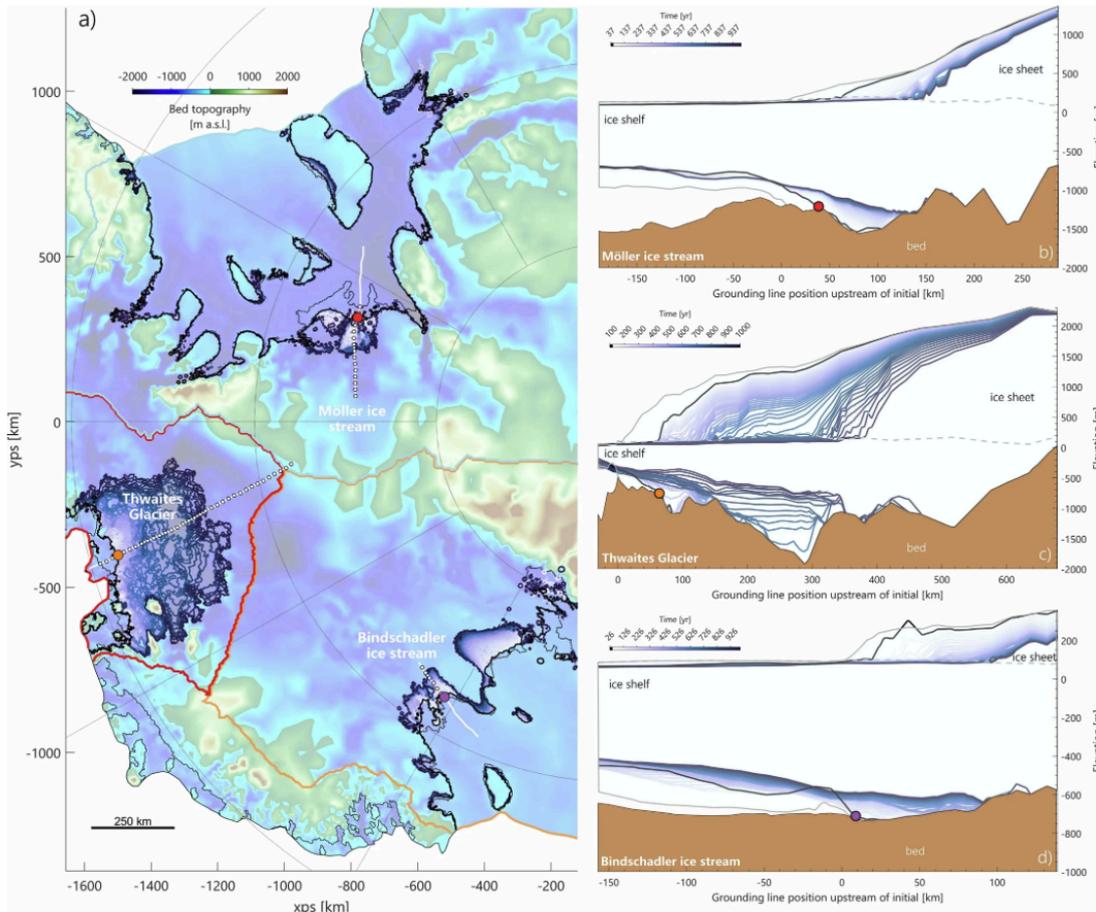
Figure 3 - Reversibility experiments showing grounding line migration at Möller ice stream, Thwaites glacier and Bindschadler ice stream. Reproduced from Hill et al. (2024).

2.4 Evidence of rapid changes in West Antarctica over the satellite era

A recent review by Lenton et al. (2024) has highlighted the potential of satellite data for monitoring cryosphere tipping points. While the ice sheets' response time is too slow to show signs of early warning signals indicating tipping over the four-decade long satellite record, satellite observations can provide valuable information on changes in the mean state of the ice sheets and can also help with process-based monitoring. Satellite observations have revealed that glaciers in West Antarctica have experienced rapid grounding line retreat (Konrad et al., 2018), speedup (Mouginot et al., 2014), and a wave of thinning propagating inland (Shepherd et al., 2019) over the past two decades, possibly indicating the development of MISI (Rignot et al., 2014). Almost a quarter of surveyed grounding lines in West Antarctica have been observed to retreat at a rate faster than the typical pace of grounding line retreat since the Last Glacial Maximum (Figure 4). On the other hand, MICI has not been observed yet and triggers of MICI are still poorly understood.
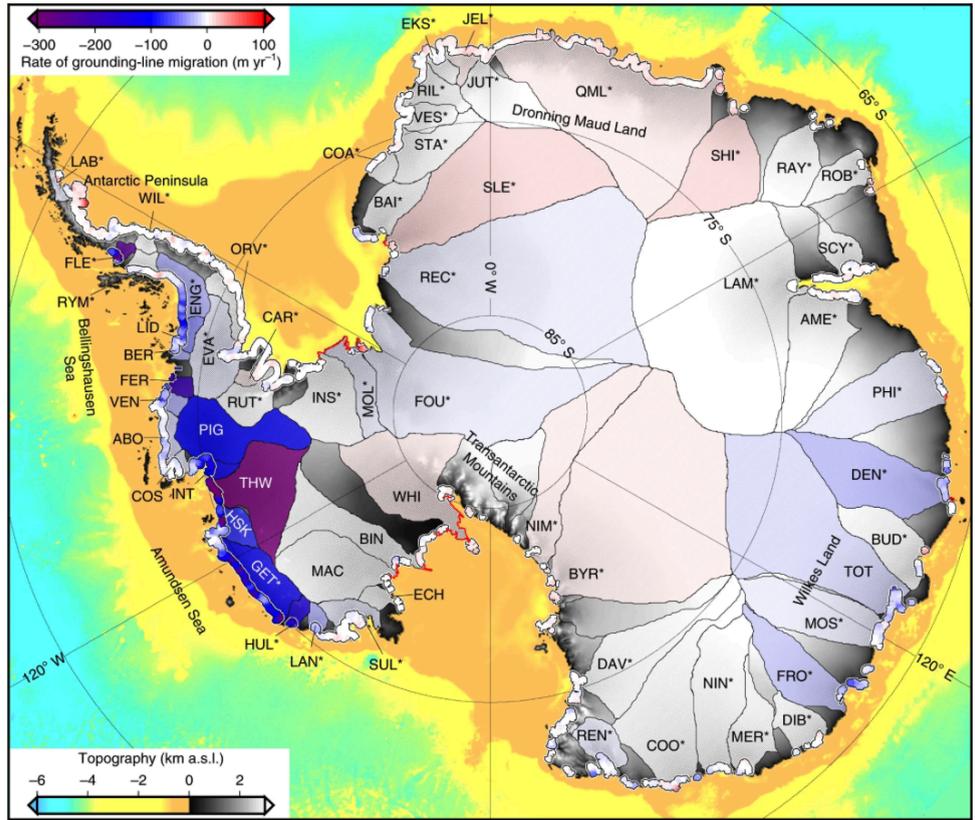
Figure 4 - Rates of grounding line migration between 2010 and 2016 derived from CryoSat-2 radar altimetry and bed topography. Reproduced from Konrad et al. (2018).

2.5 Dedicated investigations of Pine Island Glacier's tipping points

Two recent studies have looked at tipping points at Pine Island Glacier over the recent past and over the next centuries, using an ice flow model initialised with Earth Observation datasets. First, Reed et al. (2024) showed that Pine Island Glacier experienced irreversible mass loss and retreat, starting in the 1940s, likely caused by an increase in basal melting that triggered an irreversible retreat of the glacier until it reached a new bed high point in the early 1990s. To assess whether the modelled retreat of Pine Island glacier is irreversible, a reversibility analysis was performed using steady-state simulations to test for the existence of an hysteresis behaviour in the retreat of the glacier (Figure 5).
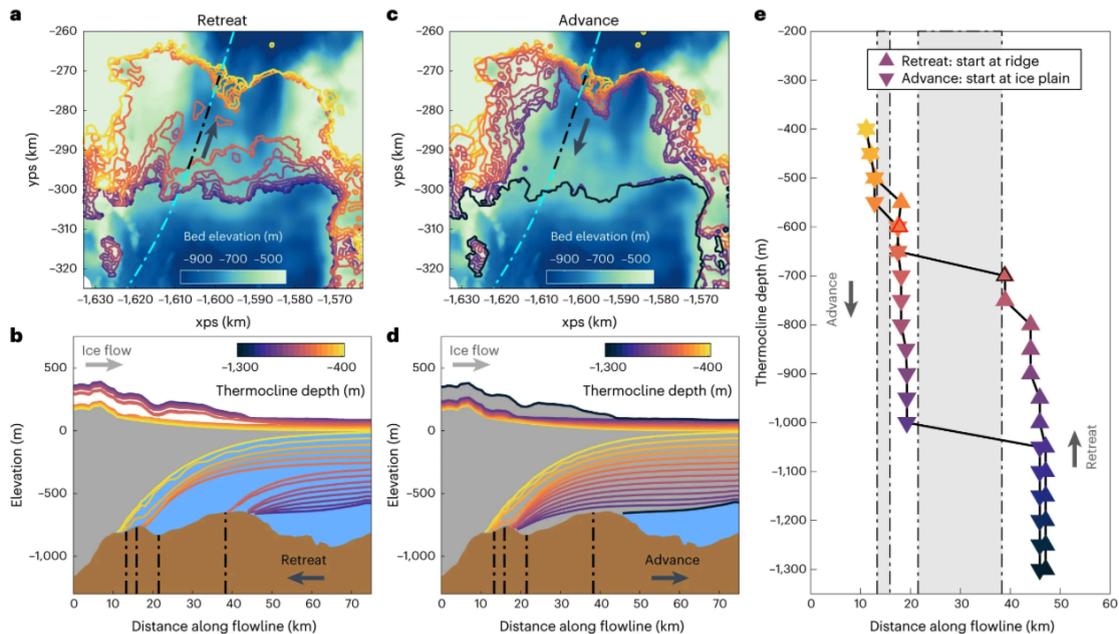
Figure 5 - Reversibility experiments performed at Pine Island Glacier, illustrating the different steady-state simulations performed with different thermocline depths. A small change in the thermocline depth results in a large change in the grounding line. Reproduced from Reed et al. (2024).

Next, Rosier et al. (2021) identified several tipping points at Pine Island Glacier being crossed over the next centuries in response to increased ocean thermal forcing. The methods developed in this study relies on identifying the critical slowing (Wissel, 1984) behaviour of the system as they approach a tipping point. This manifests itself as an increase in the time it takes for a system (in this case a glacier or the entire ice sheet) to recover from perturbations as a tipping point is approached. If a method can be found to extract the perturbation response time of the system of interest from a sufficiently long temporal record, critical slowing could be identified and used as an early warning indicator of an impending tipping point. Depending on the quality of the time series, this approach can not only serve as a warning that a tipping point is being approached, but can also predict how much further the system must be perturbed in order to cross the tipping point (Figure 6).

Figure 6 - Illustration of critical slowing down as an early warning signal. The blue and red panels represent the system states in the middle panel. If the system is far from a tipping point (blue case, the grounding line flux recovers quickly from perturbations in the control parameter. Conversely, close to a tipping point (red case), critical slowing manifests and the system state responds more slowly to perturbations in the control parameter. Reproduced from Rosier et al. (2021).

2.6 Dedicated investigations of Thwaites Glacier's tipping points

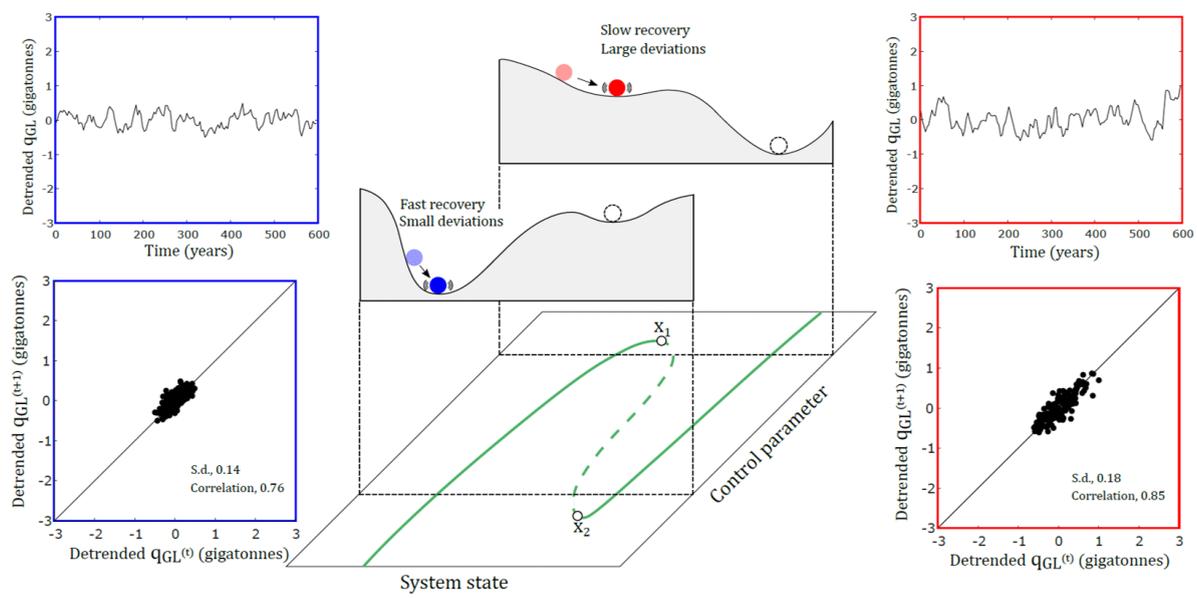Thwaites is a key glacier to investigate as it is thought to be unstable - it rests on a reverse-sloping bed and its collapse could destabilise its neighbouring glaciers, triggering a much faster and larger contribution to sea level rise. Joughin et al. (2014) conducted numerical simulations of the response of Thwaites Glacier to ocean melt, providing evidence that marine ice sheet destabilisation is already underway at Thwaites glacier. Numerical simulations of Thwaites' future behaviour have also shown that the glacier can enter periods of self-enhancing retreat, but that the Amundsen Sea Sector has not tipped yet (Reese et al., 2023) (Figure 7). In parallel, by identifying traces of the grounding line's former position on the seafloor, Graham et al. (2023) inferred that Thwaites Glacier previously experienced a very rapid pulse of ice retreat, probably dating between 50 and 200 years ago. This very rapid episode of retreat occurred at a pace twice faster than present observations of grounding line retreat. This also suggests that Thwaites could experience these rapid retreat pulses in the future and demonstrate that it is critical to monitor the glaciers' grounding line migration. While MISI is a concern for Thwaites Glacier, though the timing of its trigger is still poorly understood; a recent study has found that it might not be vulnerable to MICI over the 21st century. Morlighem et al. (2024) found that when a tall ice cliff is exposed, the subsequent increase in ice velocity and thinning reduce the calving rate, stabilising the cliff

and stopping the glacier from entering a phase of extreme rapid retreat as expected in a MICI setting. Finally, numerical models have also been used to quantify the buttressing provided by Thwaites ice shelf to its grounded upstream glacier, demonstrating that Thwaites ice shelf provides only limited buttressing to the glacier and its disintegration would not significantly impact Thwaites' future sea level contribution over the next 50 years (Gudmundsson et al., 2023).

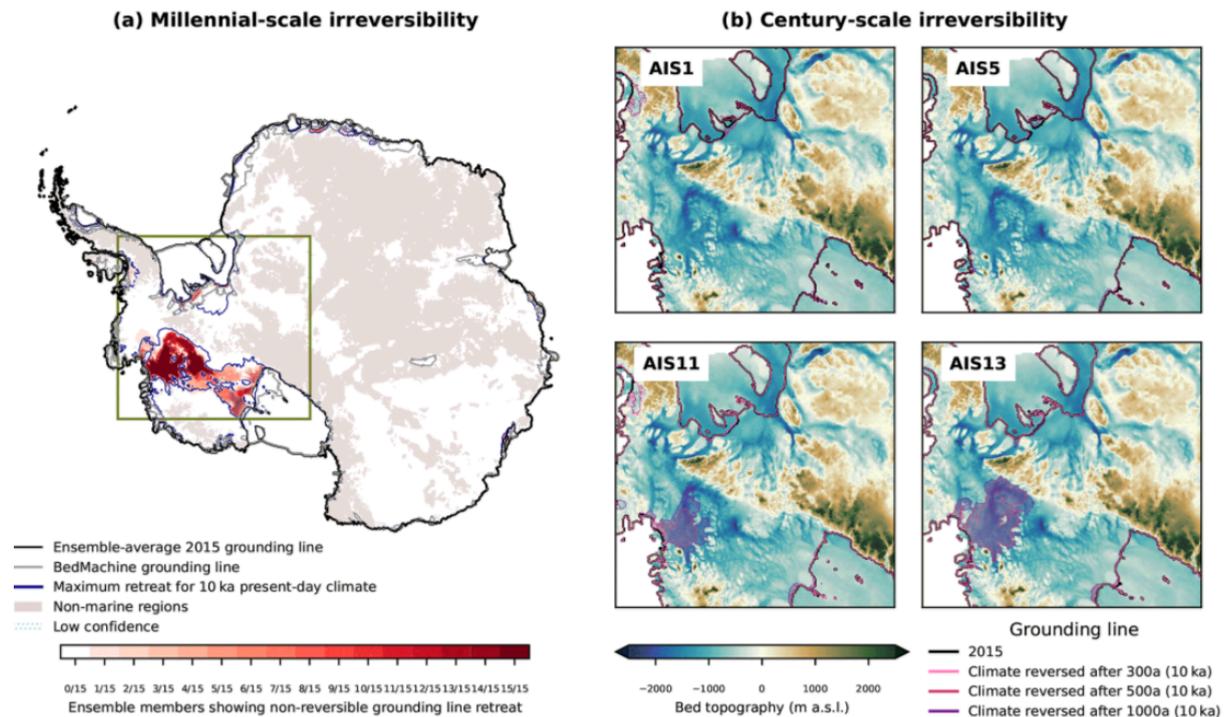Figure 7. Reversibility experiments of large-scale retreat of Antarctica. (a) Millennial-scale experiments showing in red regions that remain ungrounded after 20 000 years of (reverted) historical climate following 10 000 years of constant present-day climate. (b) Centennial-scale experiments showing the grounding line evolution after 300, 500, and 1000 years in the simulations. Reproduced from Reese et al. (2023).

3. KNOWLEDGE GAPS

After reviewing the relevant literature (Section 2), we have found that, while there is definite evidence that Thwaites Glacier is vulnerable to MISI, the timescales of Thwaites entering a phase of irreversible retreat are poorly quantified and it is unclear whether this is already underway.

Exploiting Earth Observations datasets to assess the proximity of tipping points in West Antarctica

First, while satellite data have shown that West Antarctica has been changing very rapidly over the past four decades, this data record is too short to be used on its own to identify early warning signs of tipping in comparison to the slow response time of the ice sheets. However, satellite observations provide critical information at a high and spatio-temporal resolution that can be exploited with other datasets to determine whether present changes are indicative of the onset of a sustained and irreversible retreat. Contrasting grounding line migration rates from the past 20,000 years to those derived from remote sensing data over the satellite era has not been done yet and would contribute to assessing the proximity of tipping points in West Antarctica.

Understanding the timing of Thwaites future retreat

Second, there is concern that MISI could soon be initiated in some parts of the Amundsen Sea Sector; however, its timing and triggers are still poorly understood. A comprehensive study combining satellite observations of grounding line flux and surface elevation changes and numerical simulations over Thwaites Glacier would deliver an authoritative assessment of when and under what climatic conditions an irreversible retreat is triggered. Indeed, the initialisation of ice sheet models using satellite observations is a critical step and the timing of the irreversible retreat of the Amundsen Sea Sector Embayment has been found to be dependent on how the ice sheet model was initialised. While the vast majority of ice sheet numerical simulations make use of ice thickness and bed topography datasets from BedMachine (Morlighem et al., 2020) with a nominal date of 2015 in their initial configurations, various surface elevation change and ice velocities datasets have been used in the literature to initialise, validate, and calibrate ice sheet models. The choice of the observation dataset used (ice velocity, dynamic ice thickness change, or mass change) for calibrating ice sheet simulations has been shown to have a significant impact on Greenland simulations of future ice loss (Felikson et al., 2023), re-emphasing the need for robust observational datasets.

4. DEFINITION OF PROJECT ACTIVITIES

Earth Observations (Slater et al., 2021), theory (Weertman, 1974; Schoof, 2007), and numerical models (Gudmunsson et al., 2019) have been instrumental in bringing to light the rapid changes that have occurred in the cryosphere over the past three decades. Satellite measurements are an essential step to gaining a deeper understanding of both the recent past and present evolution of irreversible change in the polar ice sheets (Otosaka et al., 2023) and for detecting early warning signals of tipping points being crossed (Rosier et al., 2021). Importantly, it is now possible to measure changes in the ice sheet elevation, flow, and grounding line location - the vital signs of tipping - at fine spatial and temporal scales and over decades. In the context of MISI, measurements of grounding line location (Rignot et al., 2011) and ice velocities (Mouginot et al., 2017) are necessary to assess the stability of grounding line migration (Hill et al., 2023). While monitoring these parameters from space can undoubtedly provide useful information on the evolution of each system, it is necessary to complement these observations with targeted numerical model simulations to assess whether tipping has already occurred as well as the proximity and timing of tipping points under different climate warming scenarios.

In this project, we will use datasets produced as part of the ESA Antarctic CCI+ projects to i) contrast present-day grounding line migration rates to numerical simulations of Thwaites grounding line evolution over the past 20,000 years and ii) initialise an ice sheet model to identify and track early warning signals of Thwaites' irreversible retreat. Combining EO and numerical simulations to study past, present, and future changes of a key glacier of West Antarctica will contribute to developing new approaches for assessing the proximity and timing of cryosphere tipping points.

4.1 Contrasting past and present-day grounding line migration rates

The grounding line is defined as the boundary between floating ice in hydrostatic equilibrium with the ocean and grounded glacial ice (Cogley et al., 2011). In reality, the grounding line is a transitory feature with a location that fluctuates on short, sub-daily timescales due to the effect of ocean tides, resulting in a 'grounding zone' - a region of transition between the fully grounded ice and freely floating ice that can extend over several kilometres. However, the grounding zone also fluctuates on multi-annual timescales. Satellite observations have revealed that almost a quarter of West Antarctica grounding line retreated between 2010 and 2016 (Konrad et al., 2018). Grounding line migration is a key indicator of change in mass balance and internal instability in marine terminating ice masses. At Thwaites Glacier, coupled ice-ocean simulations have shown that bed topography is the primary control on grounding line retreat with the rate of retreat driven by ocean thermal forcing (Seroussi et al., 2017). As part of the proposed project, we will produce estimates of grounding line migration rates from Parallel Ice Sheet Model (PISM, Albrecht et al., 2020a, b) numerical ice flow simulations over the past 20,000 years and InSAR satellite observations from the 1990s to present day. We will compare these datasets to contrast present-day and past grounding line migration rates at Thwaites glacier.

Science requirements:

- **Present-day estimates from satellite observations:** . Here, we will use the grounding line location dataset produced as part of the ESA Antarctic Ice Sheet CCI+ project mainly from ERS-1/2 tandem data (1992, 1996 and 2011), and partly from Sentinel-1 A/B data acquired in the period 2018- 2021 over West Antarctica. Additional published DInSAR grounding lines derived from the COSMO SkyMed constellation in 2016/2017 (Milillo et al, 2019) and from the ICEYE SAR in 2023 (Rignot et al, 2024) will complete the time series of the grounding lines to recent dates. We will further refine this dataset to calculate present-day grounding line migration rates of Thwaites Glacier and ensure that it can be used in combination with grounding line migration rates estimates from the Holocene and future projections.

- **Paleo estimates from PISM numerical ice flow simulations:** To estimate the grounding line migration rates of Thwaites Glacier over the past 20,000 years, we will use numerical ice flow simulations that were done with PISM. PISM has recently been coupled to a three-dimensional viscoelastic solid Earth model (VILMA) (Albrecht et al., 2024) to take into account feedback mechanisms between the solid Earth, sea level, and ice dynamics. This is particularly important when modelling changes over long timescales as the glacial isostatic adjustment that follows a reduction in ice sheet extent or thickness can have a stabilising effect on grounding lines (Gomez et al., 2010; Konrad et al., 2015). Here we will analyse model simulations run with PISM-VILMA over the past 20,000 years to estimate past grounding line migration rates.

- **Uncertainty characterisation:** We will review and assess uncertainties in observational datasets over Thwaites glacier to quantify uncertainties associated with present-day grounding line migration estimates. To evaluate our simulated grounding line migration estimates, we will assess whether our paleo-simulations converge to present-day topography and will evaluate the mismatch against present-day bed topography from BedMachine.

4.2 4.2 Detecting tipping points in numerical simulations of Thwaites future evolution

A general feature of the type of tipping points present in Antarctica is that they exhibit a behaviour known as critical slowing (Wissel, 1984). This manifests itself as an increase in the time it takes for a system (in this case a glacier or the entire ice sheet) to recover from perturbations as a tipping point is approached. If a method can be found to extract the perturbation response time of the system of interest from a sufficiently long temporal record, critical slowing could be identified and used as an early warning indicator of an impending tipping point. Depending on the quality of the time series, this approach can not only serve as a warning that a tipping point is being approached but can also predict how much further the system must be perturbed in order to cross the tipping point. Early warning indicators have previously been used successfully in a modelling study of Pine Island Glacier, to identify several tipping points that are crossed in response to increasing ocean thermal forcing (Rosier et al., 2021). Here, we will develop a new method to assess the stability of

Thwaites glacier and apply it to future simulations. We will mimic the currently observed drivers of change in the region and slowly perturb the glacier through changes in ocean thermal forcing, tracking early warning indicators to identify if one or multiple tipping points are crossed over the course of the model simulation.

Science requirements:

- **Model initialisation:** we will use the latest Earth Observation datasets, taking into account their associated uncertainty to initialise the Úa ice sheet model
- **Stability analysis:** we will explore what methods are best suited to assess the stability of Thwaites Glacier. Reversibility experiments (Reed et al., 2024) and critical-slowing down analysis have both been used to explore tipping points at Pine Island Glacier. Here we would implement and use eigenvalue analysis, solving simultaneously for both velocity and ice thickness, to analyse the changes in the glacier behaviour as it approaches critical slowing down and identify tipping points.
- **Uncertainty characterisation:** Úa uses control methods to initialise the model to a present-day configuration using satellite observations of surface ice velocity and elevation change. A key component of this inverse methodology is reliable uncertainty estimates of the remotely sensed observations. Uncertain model parameters related to basal sliding and ice softness are inferred by minimising a cost function related to observations weighted by their spatially varying error fields and a regularisation term. Where observational errors are small, the inversion algorithm will ensure that model output agrees closely with those observations, and where errors or large or data gaps exist, the model relies more on prior estimates to obtain plausible parameter fields. The observational datasets used to initialise the model will come with uncertainties so that they can be propagated to the numerical simulations of Thwaites future evolution.

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