Reviewing the elements of marine ice cliff instability

Zhe Zhang
School of Biosciences, University of Nottingham, University Park, Nottingham, NG7 2RD, UK
styzz3@nottingham.ac.uk

Abstract. Antarctica’s ice sheets are the largest potential sea-level rise contributors, but projections of future sea-level rise yield wide ranges of estimates under different emission scenarios. An important factor in the variability of estimates is marine ice cliff instability (MICI). Inclusion of MICI yields the highest potential sea-level rise cases but also the largest uncertainty due to poor understanding of the factors that control it and the mechanisms of how it happens. Although evidence for MICI has been implied by paleo-ice sheet studies and observations of keel plough mark on sea-floor, recent statistical and modelling studies have suggested a lower magnitude of MICI effect on sea-level rise due to thinning of ice sheets and buttressing forces exerted on potentially failing cliffs. This paper reviews the factors that control MICI with the goal of identifying priorities for modern ice sheet studies to better bound the estimates.

Keywords: Sea-level Rise; Antarctic Ice Sheet; Antarctica’s Ice Loss; Marine Ice Cliff Instability

1. Introduction - Ice Loss and Contribution to Sea-level Rise
As shown in Fig. 1a, much of West Antarctica’s ice sheet is grounded hundreds to thousands meters beneath sea level, and even major areas of East Antarctica’s ice sheet is grounded below sea level [1]. Previous study (Bedmap2) estimate of Antarctic ice sheet area, including ice shelves, is nearly 14000 million km², and ice volume of close to 27 million km³, which has the potential to rise the global mean sea level (GMSL) by 58 meters [2]. Several recent studies measuring Antarctica’s ice loss by tide gauge observations, calculations of mass balance, and satellite altimetry have reported acceleration of that over the past decades; the Antarctic ice sheets have lost around 3000 Gt from 1992 to 2017 and the rate is accelerating along with its contribution to sea-level rise (Fig. 1b); specifically, West Antarctica ice loss has increased from 53 Gt to 159 Gt per year during the period [3–5].

Accelerating sea-level rise (SLR) has become a major concern and an area of a high study priority because of its great threat to coastal regions [6]. The Assessment Report 5 and a Special Report from IPCC [7–8] suggest that global mean sea-level rise had accelerated from 3.2 mm/yr (1993 - 2015) to 3.6 mm/yr (2006 - 2015), measured with the help of precise satellite altimetry. The prediction of GMSL rise remains highly uncertain, ranging from 0.3 m at lowest emission scenario to 2.5 m in the worst case, by the end of 21st century [9]. The Antarctic ice sheets contain the major ice masses on Earth and Antarctica is thus the largest potential SLR contributor. But the projected response of Antarctica’s ice sheets to climate change from the range of current modelling provides a relatively inconclusive contribution to the future GMSL projection, especially after 2050, under foreseen climate change conditions. In the
highest Representative Carbon Pathway scenario (RCP8.5) Antarctica’s ice sheets may contribute close to a meter of GMSL by 2100. This high estimate is based on processes of MICI [10]; however, more recent modelling suggests a less extreme role for MICI [8, 11, 12]. The importance of predicting the rate and degree of GMSL rise makes it vital to understand how Antarctic ice sheet dynamics respond to climate change. In this paper the current state of understanding Antarctic ice margin collapsing and the factors that control Marine Ice Cliff Instability is reviewed.

Fig.1 (a) Estimate of Antarctic bedrock elevations from BedMachine by Morlighem et al. [1]. Importantly many places in Antarctica, especially West Antarctica have ice grounded below sea level. Fig.1 (b), Time series from the IMBIE team [5], illustrating Antarctica’s ice mass change along with its Sea-level contribution from 1992 to 2017.
2. Antarctica's Ice Retreat
Where the ice sheets are grounded hundred to thousand meters deep below sea level, the bottom of the ice is directly in contact with upwelling warm seawater under the ice shelf. Tendency to melt increases as the ocean temperature increases, leading to accelerated ice loss due to the basal melting. Furthermore, the refrozen water beneath the front of ice shelf together with freezing of precipitation above make the ice shelf more likely to fracture and calve icebergs. The grounding line of the ice sheet may move backwards because of the erosion of warming seawater along with the thinning of ice shelf [13; 14].

2.1. Marine Ice Sheet Instability
At the marine terminating margin of a glacier, several factors are key to its stability, including the position of the grounding line, the topography of the bedrock surface, and the nature of ocean circulation and water masses at the margin. Marine ice sheet instability is triggered where grounding bedrock is retrograde, that is sloping in the inland direction (Fig. 2). As the grounding line retreats the upstream thickness of the glacier tends to be greater but the margin of glacier tends to be thinner (Fig. 2b), therefore there is greater potential for faster ice flow. As the ice sheet retreats, the ice shelf tends to be thinner and to have more ice bergs calving. As a result the ice shelf that could have provided more buttressing force is disappearing more rapidly (Fig. 2c) and leads to a positive feedback [10]. Together with the increasing speed of ice flow, the ice loss acceleration of the ice sheet is taking place progressively but undoubtedly, and have been observed during the past few decades [e.g., 15].

2.2. Marine Ice Cliff Instability
The study of sub-glacial sedimentary records of the past warm climate periods over the last few million years have indicated sea-level rises that demand larger ice retreat or collapse than predicted by previous modelling studies [16]. For example, the isotopic record of terrigenous sediment provenance during the early Pliocene epoch indicates significant change of the Wilkes Land margin with the increased circum-polar marine temperature evidenced by diatoms and Ba/Al [17]. Catastrophic collapse of the relatively unstable West Antarctica Ice Sheet which has 5 meters of sea level equivalent has the potential to satisfy the sea level rise needed, where the mechanism of ice cliff failure that can trigger rapid ice loss and sea level rising is modeled as marine ice cliff instability.

Compared to relatively well studied marine ice sheet instability, marine ice cliff instability (MICI) can cause much greater rates of sea-level rise, however the degree to which MICI can change the overall stability of ice sheets is still controversial. In contrast to MISI, it is possible for MICI to happen either on a retrograde or a prograde grounding line. The outer part of the ice shelf (marine terminating glaciers)
may be retreating and calving under the processes of warm ocean melting or hydrofracturing, where accumulation of precipitation and surface ice melting may create crevasses then ice calving [18]. When the ice sheet margin retreats and terminates in a near vertical ice cliff that reaches about 100 meters above the sea-level and 800 meters basal height or higher, dramatic rupturing and collapsing may be triggered under its own weight or shear stresses at the fracturing crevasses; further studies have also suggested that the basal height of ice cliff can increase the risk of drastic ice cliff failure while faster ice flow as shown in fig.4 or a small buttressing force provided to the ice cliff can mitigate the threats of MICI significantly [19; 20; 21].

Unlike the marine ice sheet instability with sedimentary evidence and present day observations, MICI was only proposed recently for the inconsistent SLR from reconstructions of past inter-glacial periods with previous estimated sea-level contributions [10]. Although without direct evidence and observation being found, Wise et al. [22] have reported the evidence that large scale of drastic ice sheet retreat and collapse into Pine Island Bay, where the indicated marks signify similar ice sheet dynamic processes to what the MICI model concluded. This indication has strengthened the importance of studying the detail mechanisms of MICI and factors that affect its processes. Later studies as mentioned suggested that although higher ice cliff height may produce higher calving rate, factors of dynamic thinning and back stress exerted may press MICI oppositely, as discussed in the next section [21].

3. Controversial Ideas to MICI
A recent study by Bassis et al. [23] provided that the MICI may not be as threatening as suggested in earlier studies for example by DeConto and Pallard [10]. Bassis et al. [23] modeled ice flow as a power-law function in viscous material, with collapse happening as its yield strength is reached. Ice cliffs of three different thicknesses, where their initial heights above the sea-level are just over the threshold for collapsing, were modeled to examine ice cliff failure under a variety of geologic conditions. A relatively small buttressing force was also added (and removed) in the experiment to simulate the back-stress provided by calving icebergs or sea-ice. Their results showed that for the cases where (marine terminating) ice cliff collapse was possible, adding a buttressing force significantly reduced the likelihood of the massive ice collapsing. In some cases, the result was actually an advance of the ice sheet.
3.1. Effect of Dynamic Thinning to MICI

Following simulations examining the triggering of MICI and ice status due to varying speeds of ice flowing and grounding bed slopes were made to determine possible stable ice cliff without buttressing added. Based on the range of sensitivity tests conducted, Bassis et al. [23] concluded that there are two types of regimes for ice cliff collapsing: (1) ice sheet grounded on moderate bed slopes and (2) ice sheet grounded on bed slopes that are extremely retrograde. In their assessment, the thickness gradient is crucial to the judgement of two regimes. As schematically demonstrated in Fig. 4, when the grounding bedrock of the ice sheet tends to be more retrograde (facing towards the inland direction), the accumulation of ice sheet at more inland direction part (upstream part) is likely to be higher and the difference of height (thickness gradient) between the upstream and the ice cliff is larger, therefore there is a larger potential to drive faster ice flow. As the thickness of the inner ice sheet and speed of ice flow increases, this kind of dynamic thinning actually relieves the tensile pressure of the ice and eventually prevents chain-reaction of ice failure.

3.2. Mitigation of MICI by Buttressing

However when the bedrock of ice sheet is way too retrograde or the grounding of the ice cliff retreats to a bedrock of over-steep bed slope the thickness gradient of the ice sheet which is highly functional to the bed slope becomes too steep (where in the simulation of Bassis et al. [23] is -0.03 for an initial 800 meters tall ice cliff), the ice flow velocity cannot be fast enough to reduce the thickness of upstream ice sheet and eventually allows catastrophic ice sheet disintegration by MICI. In this second regime Bassis et al., [23] proposed that a small buttressing force provided by sea-ice or icebergs close to the pinning point or ice margin would tend to stabilize the collapsing ice sheet. The buttressing provided to the ice cliff can be the key to prevent catastrophic ice cliff collapses. However, there is still the question about what the sources of buttressing would be if there is no natural source of that, and a real world mechanism to add a back stress to the ice cliff will then be the major problem.

![Fig 4.](image-url)
3.3. Lack of Observation and Evidence for Prediction

The MICI remains controversial partly because it has not yet been directly observed in modern day ice sheets. It was originally proposed by Pollard et al. [18] as a hypothetical requirement to allow numerical simulation of past warm-climate periods reconstruction. However, a recent study by Edwards et al. [11] has instead suggested that invoking MICI is not essential to reproduce either mid-Pliocene or last interglacial period sea level rise. Will the MICI be happening due to climate change in the near future and how to reduce the uncertainty of ice sheet contribution in future sea level rise are important problems that remain to be resolved. Reconstructing and studying Antarctica’s ice sheet behavior in past interglacial periods as well as modelling modern, past, and future ice sheet dynamics are one of the most important strategies for refining our understanding of MICI. Despite multiple models of ice sheet reactions that have already made great progresses narrowing the errors of SLR projections significantly under different scenarios by various predicting methods, along with furthermore details of Antarctica topography measured and studied [1, 11, 21, 24, 25], direct observations and evidences of catastrophic ice collapse still remain critical. The future Sea-level rise may not be as threatening as previously thought, but precise projections of future sea level rise still need a lot of effort.

4. Summary and Conclusions

Marine Ice Cliff Instability has a great potential to affect the future sea-level rise by the worst scale. Although progresses have been made to understand the detailed mechanisms, and the conditions that constrain behaviour of MICI have been studied, the threat of MICI remains a significant concern. Many more observations and modeling efforts still need to be made to examine the factors that control the triggering and impacts of MICI. Additionally, further analysis of potential factors that could lead to natural mitigation of possible MICI triggering should also to be considered.

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