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Citation for published version:
Benn, DI & Sugden, D 2021, 'West Antarctic ice sheet and CO2 greenhouse effect: a threat of disaster', *Scottish Geographical Journal*, vol. 136, no. 1-4, pp. 13-23. https://doi.org/10.1080/14702541.2020.1853870

Digital Object Identifier (DOI):
10.1080/14702541.2020.1853870

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Publisher's PDF, also known as Version of record

Published In:
Scottish Geographical Journal

Scottish Geographical Journal

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/rsgj20

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To cite this article: Douglas I. Benn & David E. Sugden (2020) West Antarctic ice sheet and CO_2 greenhouse effect: a threat of disaster, Scottish Geographical Journal, 136:1-4, 13-23, DOI: 10.1080/14702541.2020.1853870

To link to this article: https://doi.org/10.1080/14702541.2020.1853870

SCOTTISH GEOGRAPHICAL JOURNAL
2020, VOL. 136, NOS. 1–4, 13–23
https://doi.org/10.1080/14702541.2020.1853870

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West Antarctic ice sheet and CO_2 greenhouse effect: a threat of disaster

Douglas I. Benn[a] and David E. Sugden[b]

[a]School of Geography and Sustainable Development, University of St Andrews, St Andrews, UK; [b]School of Geo Sciences, University of Edinburgh, Edinburgh, UK

ABSTRACT
Over 40 years ago, the glaciologist John Mercer warned that parts of the West Antarctic Ice Sheet were at risk of collapse due to the CO2 greenhouse effect. Mercer recognised the unique vulnerability of ice sheets resting on beds far below sea level (marine-based ice sheets), where an initial warming signal can initiate irreversible retreat. In this paper, we review recent work on evidence for ice sheet collapse in warmer periods of the recent geological past, the current behaviour of the ice sheet, and computer models used to predict future ice-sheet response to global warming. Much of this work points in the same direction: warming climates can indeed trigger collapse of marine-based portions of the West Antarctic Ice Sheet, and retreat in response to recent warming has brought parts of the ice sheet to the threshold of instability. Further retreat appears to be inevitable, but the rate of collapse depends critically on future emissions.

KEYWORDS
Ice sheet instability; Antarctica; climate change

Introduction

The title of this paper is identical to that used by John Mercer in Nature over 40 years ago, in which he predicted that anthropogenic climate change could threaten the stability of the West Antarctic Ice Sheet (Mercer, 1978). The introduction to Mercer's paper has an impressively modern touch and highlights the existence of a marine basin beneath the West Antarctic Ice Sheet. He argues that the stability of the ice sheet covering the basin depends on the presence of shallow topographic thresholds and ice shelves around its periphery. With continued rise in CO_2 this stability is threatened, bringing a danger of ice-sheet collapse and eventual global sea-level rise of several metres. Mercer warned that we should keep an eye on ice shelves in the Antarctic Peninsula as an early warning sign. Since then, several ice shelves in the Peninsula have been lost, such as the Larsen B Ice Shelf in 2002 (Cook & Vaughan, 2010; Scambos et al., 2000) and rapid changes have occurred around the margins of the Amundsen Sea (Christie et al., 2016; MacGregor et al., 2012).

CONTACT Douglas I. Benn dib2@st-andrews.ac.uk School of Geography and Sustainable Development, University of St Andrews, KY16 9AL, UK

The word ‘collapse’ is often used in the context of ice sheets and glaciers, but is seldom defined. Here, we use it to mean an irreversible process of mass loss initiated when some trigger causes the system to cross a threshold into instability. Most land-based glaciers do not exhibit this kind of behaviour. Although warming may cause rapid melting of land-based glaciers, their responses to climatic signals are typically linear and reversible. That is, if the climate signal changes, melting will slow down and the glacier may stabilise or even grow again. Marine-based glaciers, on the other hand, can undergo irreversible retreat in response to warming of the atmosphere and oceans, and ice loss may continue until all is gone even if the initial signal is removed. Another important point about the idea of ‘collapse’ is that it may happen over short or long timescales. In the case of a floating ice shelf such as Larsen B, collapse may occur over a few days once the critical stability threshold is crossed (MacAyeal et al., 2003). On the other hand, collapse of a large marine-based ice sheet may play out over hundreds or a thousand years. The key issue is not the rate of ice loss, but the fact that the system has no stable state after the initial ‘push’.

So, how much of the Antarctic Ice Sheet is at risk of collapse, and how fast could ice be lost to the ocean? There are three main approaches to answering these questions. First, study of the long-term history of an ice sheet reveals what has happened in the past. It is particularly useful to examine what happened during climates warmer than present, for example in the Pliocene 5.3–2.6 million years Ma ago and the last interglacial period some 120 thousand years ka ago. Second, we can study the current behaviour of the ice sheet alongside observations of the oceans and atmosphere, to identify areas of rapid change and understand the key processes at work. Third, computer modelling techniques allow us to perform experiments with ‘virtual glaciers’, and to study system response to changing conditions. Computer models can help us understand what has happened in the past, analyse the controls on ice-sheet behaviour in the present, and address the all-important question of how rapidly the ice sheet may change in response to alternative greenhouse gas futures.

Antarctic ice sheet: general background

The Antarctic Ice Sheet is about 1.5 times the area of the USA and comprises two components: the East Antarctic Ice Sheet (EAIS) and the West Antarctic Ice Sheet (WAIS). The EAIS is by far the largest and is 4400–2600 km across, rising to elevations in excess of 4200 m and holding a mass of ice equivalent to 52 m of global sea level (Figure 1a). It covers a continental land mass similar in character to that of southern Africa (Jamieson et al., 2010). The WAIS, 3000 m high, is centred on an archipelago of three mountain massifs, separated by a basin up to 2500 m deep (Figure 1b). Ice flows into the Amundsen Sea and also into the Ross and Filchner-Ronne ice shelves, each individually the size of a European country such as France.

A widely accepted view is that Antarctic ice sheets first built up around 34 million years ago. Geomorphological evidence from the Transantarctic Mountains suggests that the EAIS has persisted for at least the last 14–15 Ma (Balter-Kennedy et al., 2020; Sugden & Denton, 1993). Some outlet glaciers in deep troughs around the peripheries may have thinned during warm periods (Morlighem et al., 2020), but increased snowfall near the coast could have compensated with an increase in ice mass, as happened in the

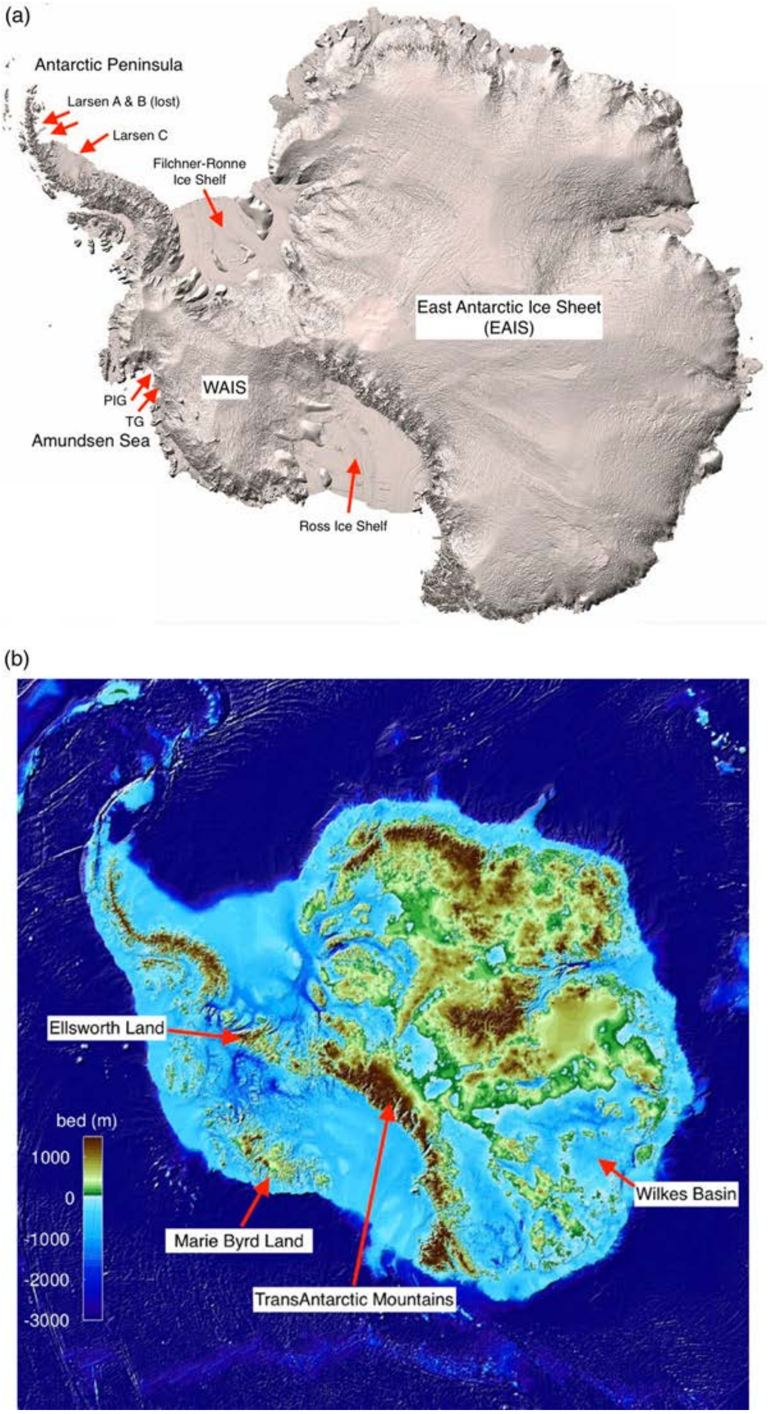

Figure 1. (a) The Antarctic Ice Sheet showing key locations mentioned in the text. PIG: Pine Island Glacier; TG: Thwaites Glacier. Background image: REMA elevation model (Howat et al., 2019). (b) The bed of the Antarctic Ice Sheet, showing key locations mentioned in the text. Note the large deep marine basin beneath West Antarctica, between Marie Byrd land and Ellsworth Land. From: Morlighem et al., 2020.

case of Taylor Glacier in the Transantarctic Mountains (Marchant et al., 1994). The WAIS is different in that its stability depends critically on processes at the peripheral *grounding line* (the boundary between ice resting on the bed and floating ice shelves). If the grounding line is forced to retreat into the deep basin, ice loss will become faster and faster, leading to marine ice sheet instability (MISI).

Evidence of the long-term history of the West Antarctic ice sheet

There are two lines of evidence that directly bear on the history of the WAIS, (a) geomorphological evidence from mountains protruding through the ice sheet where ice thickness variations can be dated by cosmogenic isotope analysis of bedrock and glacier deposits and (b) marine biological evidence of ocean contacts beneath the ice sheet and between the Ross and Weddell seas.

Geomorphological evidence built up in recent years suggests that the mountain massifs of West Antarctica have been surrounded by an ice sheet for millions of years. In the southernmost Ellsworth Mountains blue-ice moraines related to katabatic winds flowing down the ice sheet surface reflect the persistence of the WAIS for at least 1.4 Ma (Hein et al., 2016). A glacially striated trimline marking the maximum thickness of a coherent ice sheet bounding the higher Ellsworth Mountains has been shown by multi-isotope analysis of a rock core to have formed more than 3.5 Ma ago (Sugden et al., 2017). Since the ice at the upper margin was warm based and thus required a much warmer climate, the age of the trimline has been hypothesised to relate to the mid-Miocene optimum at ~14–15 Ma when tundra vegetation last existed in Antarctic mountains (Lewis et al., 2008). There is less information for the Ross Sea and Amundsen Sea catchments of the WAIS. However, on Mt. Waesche in the Marie Byrd Land massif, moraines have been exposed for over 500 ka (Ackert et al., 2013), while on Mt. Moulton the volcanic ash layers exposed at the ice surface demonstrate continuous ice sheet presence for nearly 500 ka (Dunbar et al., 2008). The above evidence implies that the WAIS survived in the core mountain areas during at least the last few interglacial cycles and probably the warm Pliocene epoch too.

The biological evidence is different in that it points to a marine seaway between the Ross and Weddell seas in the last few glacial cycles of the Pleistocene. Marine diatoms occur in sediment beneath an ice stream flowing into the Ross Ice Shelf (Scherer et al., 1998) and their age implies open sea water inland of the grounding line at some stage in the Quaternary. Genetic similarities between the octopus, *Pareledone turqueti,* in the Ross and Weddell seas are best explained by a marine seaway between the two in the Pleistocene (Strugnell et al., 2012). Modern bryozoan assemblages in the Ross and Weddell seas are so similar that they point to a seaway between the two during recent interglacial cycles (Barnes et al., 2010).

This contrasting evidence is in agreement with ice-sheet models of West Antarctica under warmer conditions (Pollard et al., 2015; Hein et al., 2016; Jamieson et al., 2010; Gilford et al., 2020). In such simulations sub-continental ice sheets remain over the main mountains of the Ellsworth and Marie Byrd Land massifs while a seaway opens up between the Amundsen Sea and around the northern end of the Ellsworth Mountains to the Weddell Sea. Models suggest the lost ice is equivalent to about 3 m of global sea level. In summary, the long term view suggests that loss of the marine portion of the WAIS in a warming world is possible, even likely.

Current behaviour of WAIS

Recent developments in satellite observing techniques have revealed clear signs of rapid change in West Antarctica, including changes in ice thickness, rates of ice movement, and the extent of fringing ice shelves. Ice-surface elevation data show that much of the Antarctic Ice Sheet is undergoing slight thickening as a result of increased snowfall (Shepherd et al., 2001; Smith et al., 2020; Figure 2). The largest exception to this trend is the Amundsen Sea Sector of the West Antarctic Ice Sheet which is thinning rapidly, in some places by many metres per year. This thinning cannot be explained by increased surface melting: despite recent warming, continental Antarctica remains too cold. Instead, the thinning is caused by increased rates of ice flow, which evacuates ice from the continent faster than it can be replaced by snowfall (Pritchard et al., 2009; Rignot et al., 2002). The changes in flow speed are dramatic: ice discharge from the sector increased by 77% between 1973 and 2013 (Mouginot et al., 2014), and net ice losses from the West Antarctic Ice Sheet now total ~160 Gigatonnes per year (Shepherd, 2018).

Multiple lines of evidence show that the flow acceleration and mass loss are caused by changes at the ocean boundary of the ice sheet. Incursions of warm water from the Pacific Ocean are melting the ice from beneath, causing thinning and break-up of fringing ice shelves and retreat of glacier grounding lines (Arndt et al., 2018; Christie et al., 2016; Jeong et al., 2016; MacGregor et al., 2012; Milillo et al., 2019; Rignot et al., 2014; Shepherd et al., 2004). In turn, this reduces the resistance to ice flow due to friction beneath the

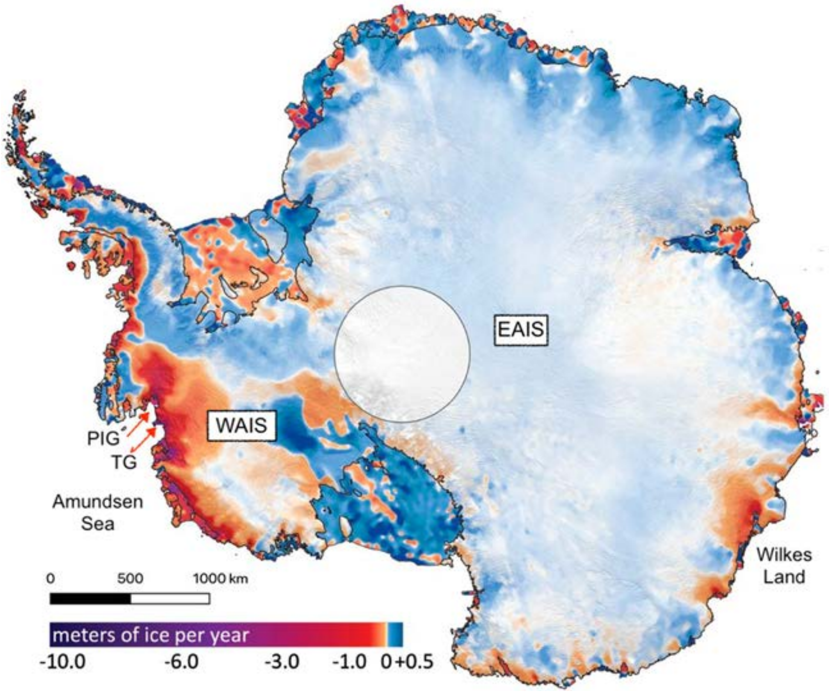

Figure 2. Elevation changes on the Antarctic Ice Sheet showing slight thickening over most of the continent and rapid thinning in the Amundsen Sea Sector od WAIS and in Wilkes Land. PIG: Pine Island Glacier; TG: Thwaites Glacier (From Smith et al., 2020).

glacier margins, leading to faster ice flow and drawing down ice from the interior. The most dramatic changes are occurring at Pine Island Glacier and Thwaites Glacier, the largest ice streams in the Amundsen Sea Sector. Both glaciers are now far from dynamic equilibrium (Shepherd et al., 2019; Wingham et al., 2009), and it is widely accepted that marine ice sheet instability is underway (Joughin et al., 2014; Rignot et al., 2014). Analysis of climate data has shown that the root cause of these changes is a shift in wind patterns over the Antarctic continental shelf, which encourages the transport of warm water towards the ice sheet margins, a shift that can be directly attributed to anthropogenic climate change (Holland et al., 2019). It is clear that the WAIS is still catching up with recent climate change, and that even without additional warming mass loss will continue. We are already committed to further sea-level rise.

Although most of the EAIS rests on bedrock that lies above current sea level, deep basins do occur beneath some parts of the ice sheet. The largest of these is in Wilkes Land, where the beds of Ninnis and Denman Glaciers slope inland, in the latter case to depths of over 3500 m (Morlighem et al., 2020). Glaciers in Wilkes Land have also undergone recent thinning and acceleration, and there are concerns that they are also vulnerable to marine ice sheet instability (Miles et al., 2020; Smith et al., 2020; Figure 2).

Computer models of ice sheet instability

Study of the past has demonstrated the vulnerability of the West Antarctic Ice Sheet in warm climates, and observations of current ice-sheet behaviour have uncovered clear signs that marine ice sheet instability may have begun. To answer the questions of how much ice will be lost, and how quickly, glaciologists use computer models that represent the dynamics of the ice with systems of equations (Pattyn et al., 2017; Pattyn, 2018). Experiments can then be performed with these ‘virtual glaciers’ to investigate how the ice will respond to changing environmental conditions. When Mercer issued his warning over 40 years ago, ice-sheet models were rudimentary and represented the ice in simplified one- or two-dimensional form. These models were sufficient to illustrate many of the key physical processes, but too simple to provide reliable guides to either the magnitude or the rate of ice sheet response to climate change (e.g. Thomas & Bentley, 1978; Weertman, 1974). A long-standing issue was how to calculate the forces acting on the ice at the grounding line, particularly how the floating and non-floating parts of the ice sheet affect each other and influence rates of ice flow. When the ‘grounding line problem’ was finally solved (Schoof, 2007) it provided mathematical proof that the theory of Marine Ice Sheet Instability (MISI) was correct and prompted focused effort to use rapidly developing computing capability to develop realistic and reliable forecasting tools.

Modern glaciological models represent ice sheets in three dimensions and include routines to simulate many important processes, such as melting beneath ice shelves and migration of the grounding line. Several slightly different models of the Antarctic Ice Sheet have been developed by groups around the world, each with advantages and disadvantages. Despite disagreements in detail, however, the results agree that MISI is underway in the Amundsen Sea Sector of WAIS (e.g. Joughin et al., 2014). There is also wide agreement that this part of the ice sheet is highly sensitive to melting at the grounding line and loss of floating ice shelves, and that ice loss will accelerate if the oceans and atmosphere continue to warm. The models disagree, however, when it

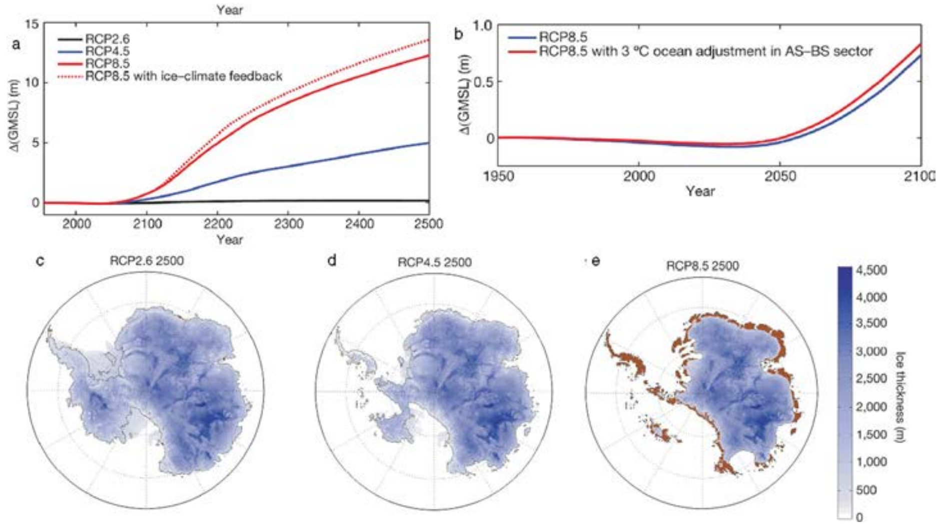

Figure 3. Predicted sea level rise and mass loss from the Antarctic Ice Sheet under IPCC CO_2 emission scenarios RCP2.6 (low), 4.5 (medium) and 8.5 (high), using a model with a simple representation of the ice cliff instability. (a) Sea level rise until 2500. (b) twenty-first Century sea level rise under RCP 8.5 (continued growth of CO_2 emissions). (c-e) Configuration of Antarctic Ice Sheet in 2500, in alternative carbon futures. From: DeConto & Pollard, 2016.

comes to predicting exactly how quickly ice will be lost under specified conditions. Some models indicate that MISI will unfold relatively slowly, with collapse of WAIS taking centuries to millennia (Favier et al., 2014; Feldmann & Levermann, 2015; Ritz et al., 2015). Others, however, suggest that collapse may be very rapid (decades to centuries), especially under high-carbon scenarios.

The crucial distinction between models that predict slow *versus* rapid collapse is how they represent the breakaway of icebergs, a process known as calving. Calving is a complex process, and considerable ingenuity has been applied over the years to find ways of representing it in ice sheet models, with mixed success (Benn & Åström, 2018). The problem is particularly acute for the case of WAIS, because ice retreat into very deep water will expose ice cliffs far higher than any that currently exist, meaning that there are no observations to help us understand how they might behave. Theoretical considerations indicate that above a certain height ice can no longer support its own weight, placing a limit on ice cliff stability (Bassis & Walker, 2012). This consideration led Pollard et al. (2015) to propose that rapid ice sheet collapse could occur by a process of Marine Ice Cliff Instability (MICI), with ice loss at rates far greater than in MISI, which is driven largely by grounding-line dynamics. Numerical models that incorporate simple representations of the MICI process indicate that collapse of parts of WAIS could be imminent, leading to sea level rise of tens of centimetres by 2100 and several metres in the ensuing centuries (DeConto & Pollard, 2016) (Figure 3). The concept of MICI is controversial, however, and for various reasons many researchers remain sceptical (e.g. Clerc et al., 2019; Edwards et al., 2019). The race is on to determine the circumstances under which MICI might occur, and to develop accurate predictive models of this potentially catastrophic process (Crawford et al., in review).

Conclusions

In the 40 years since Mercer's warning, much has been learned about the response of ice sheets to climate change, but the message remains the same. Human emissions of greenhouse gases are putting large parts of the West Antarctic Ice Sheet at risk of collapse. In the relatively recent geological past, marine-based portions of the Antarctic Ice Sheet did not survive climates that were only slightly warmer than present. The Amundsen Sea Sector of WAIS is currently undergoing rapid ice thinning and acceleration, grounding line retreat, melting and break-up of ice shelves. These changes are occurring in response to greenhouse gas emissions to date. Numerical modelling studies confirm that MISI is ongoing, and that MICI is perhaps imminent in some areas. Parts of the WAIS have already crossed the threshold into MISI, and the threshold for MICI might be close. The rate of collapse is sensitive to the amount of atmospheric and oceanic warming - the greater the warming, the more rapid the collapse. If emissions continue to increase at current rates, the additional global mean sea level rise from WAIS could be several tens of centimetres by the end of this century, and two to three metres in the centuries to come.

Ongoing scientific work emphasises the importance and complexity of the problem. The International Thwaites Glacier Collaboration, jointly funded by research councils in the UK and USA, has brought together a large team of scientists to understand the past, present and future of Antarctica's most vulnerable glacier, collecting data from the ice sheet and the adjacent seas and developing the next generation of computer models (Scambos, 2017; https://thwaitesglacier.org). Other research groups throughout the world are racing to solve the wider problems of how marine-based ice sheets respond to climate change, and how the impact of greenhouse warming on a distant ice sheet will affect humanity for generations to come unless emissions are urgently reduced.

Acknowledgement

DIB's contribution to this work is from the DOMINOS project, a component of the International Thwaites Glacier Collaboration (ITGC). Support for DIB was provided by the Natural Environment Research Council (NERC: Grant NE/S006605/1). ITGC Contribution No.ITGC:025.

Disclosure statement

No potential conflict of interest was reported by the author(s).

ORCID

Douglas I. Benn http://orcid.org/0000-0002-3604-0886

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