Chapter 5

Advances in numerical modelling of the Antarctic ice sheet

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5.1 Introduction and aims

In the first edition of Antarctic Climate Evolution, Siegert (2008a) provided a basic assessment of (1) the function of numerical ice sheet modelling, (2) the data needed as input, (3) inter-comparison and calibration exercises and (4) examples of how models have been used to constrain the dynamics and form of past ice sheets. In this chapter, we examine progress made in the last 10 years in each of these areas.

Ice sheet modelling has advanced considerably in the last decade, with substantial improvements in performance and resolution. A critical region of the ice sheet to predicting glacial change is the grounding zone. Our ability to model this part of the ice sheet has improved markedly through better knowledge of the physical processes at play here, and also with anisotropic or adaptive grids that offer high resolution where it is needed most.

In 2008 the bed elevation of Antarctica was poorly constrained in several places, which hindered the usefulness of ice sheet models. In 2013 a revised bed elevation, Bedmap2, was introduced as a consequence of imaginative interpolation procedures and new bed data. Bedmap3 is in the process of being configured, which would be the first full appreciation of continent-wide Antarctic topography without major data gaps. In addition, there have also been attempts to determine the paleotopography of Antarctica, which would allow better appreciation of former ice sheets through numerical modelling (Siegert, 2008b).

Ice sheet model intercomparison has also improved in recent years, with it being acknowledged as a critical way to advance coupled systems. The ISMIP6 (Ice Sheet Modelling Intercomparison Project - Phase 6)

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programme, used in the CMIP6 (Coupled Model Intercomparison Project - Phase 6) project (Nowicki et al., 2016), allows coupled and stand-alone ice sheet models to be tested with a set of climate scenarios, adding confidence to model results and better quantification of their uncertainties.

Given the improvements in models, their inputs and intercomparisons, it is hardly surprising that they have been used well in the last few years to examine former Antarctic ice sheets. They have provided useful information to determine the last glacial maximum (LGM), Eemian and Pliocene ice sheet configurations, as well as further back in time. An important idea is the degree to which 'marine ice sheet instability', which takes effect as the grounding line retreats across deepening topography, and 'marine ice cliff instability', which would act following the break-up of large ice shelves, might lead to wide-spread deglaciation in Antarctica.

Ice sheet models from 2008 look primitive compared to today's. This is a reflection of an area of glaciology that is developing quite quickly. That said, ice sheet models have some way to go before they can offer ideas of former and future ice sheets with a high degree of certainty. It is reasonable to conclude that in 10 years time ice sheet models will be better connected to geophysical data, as well as benefiting from other advances, and will make today's models appear similarly old fashioned.

While geological evidence of former ice sheet changes is paramount to evaluating how ice sheets have behaved in the past, ice-sheet models provide the only means by which quantitative knowledge of the flow and form of past ice sheets can be assessed. In the first volume of Antarctic Climate Evolution, Siegert (2008a) presented a summary of ice sheet modelling activities and how they have been used to define past ice sheets. That chapter discussed how ice sheet models work and offered some examples of their use. In this short chapter, rather than replicate the background to ice sheet modelling, we will instead focus on developments in ice sheet modelling over the last decade, and how they have helped us to understand the growth and decay of ice sheets during the glaciated history of Antarctica. The chapter has five sections. The first summarises recent advances in ice sheet modelling. In the second, improvements in the inputs to numerical models are discussed. The third section looks at new model inter-comparison exercises, as a means to better evaluate model performance, and the fourth provides an assessment of several case studies where modelling has been used to define former ice sheets. In the fifth section, the future of numerical ice sheet modelling is discussed, focusing on areas that would make the greatest positive difference to determining the dynamics and growth cycles of former ice sheets.

5.2 Advances in ice sheet modelling

5.2.1 Grounding line physics

A critical zone of the ice sheet is at its marine margin, where grounded ice either terminates in the ocean or transitions to form a floating ice shelf. The physics under which this transition occurs is non-trivial and has been the subject of much concern and research in glaciology. This concern is supported by satellite observations of ice-surface elevation change over the past 30 years, which show the regions where mass is being lost at the greatest rates correspond to locations with submarine grounding lines (Shepherd et al., 2018). Further, particularly in West Antarctica, if upstream migration of the grounding line occurs over a retro-grade sloping bed, a positive feedback may lead to further recession until the bed slope becomes 'normal' to flow (Joughin et al., 2014), so-called 'marine ice-sheet instability' or MISI.

The relevance of MISI to the potential collapse of the West Antarctic Ice Sheet (WAIS) under anthropogenic global warming has been understood for over 40 years (Mercer, 1978) – the key issue being that ocean warmth could melt marine sections of the ice sheet, triggering ice-sheet collapse through MISI. Clearly, this is a problem that numerical ice-sheet models would be well-suited to investigate, yet until quite recently models treated the grounding line casually and without appreciation of the physics and processes operating in this key location.

A mathematical simplification of grounding line physics was described in a seminal work by Schoof (2007), who demonstrated how it may be parameterised using a simple flux condition that could be incorporated into continental scale ice sheet models. Adoption of this approach has been widespread in the ice-sheet modelling community, particularly among more traditional fixed-grid models (e.g., Pollard and DeConto, 2009). This advance has allowed such models to provide a better appreciation of the evolution of marine sections of the Antarctic ice sheet in the past, and projections of its change over the coming centuries. Models that do not incorporate this Schoof-based flux adjustment have instead chosen to implement other methods, such as sub-grid calculations of the grounding line stress field (Feldmann et al., 2014).

While these advances have been important, they have not led to full resolution of the problem around grounding lines. Aside from the challenges in oceanographic modelling to describe how ocean heat is supplied to the ice-sheet margin, grounding lines represent one of the most challenging places to undertake glaciological research, due to ice-surface crevassing and inaccessibility of the ocean–ice interface. Hence, there is a dearth of measurements from even the most vulnerable marine ice-sheet margins with which to guide ice-sheet models. Moreover, far from being a simple transition between grounded and floating ice, we now appreciate the grounding line resembles more of a 'zone' in many places, heavily influenced by tides that lift and lower significant sections of ice streams and ice rises (Jeofry et al., 2018a) allowing episodic incursions of warm ocean water into subglacial cavities (Milillo et al., 2019). As a consequence, while advances in our ability to model grounding lines have been made, there is much that is needed to be done before we can model their function and change in the detail necessary for reliable forecasting.

5.2.2 Adaptive grids

The first Antarctic ice sheet models ran using a regular sized (fixed resolution) grid with a cell width of 50 km (Budd and Smith, 1982). While slow flow at the centre of the ice sheet can be approximated reasonably well by such a grid – i.e. averaging little change over long distances – as gradients in speed, surface slope, basal conditions and ice dynamics increase coarse grids are unable to simulate realistic ice flow. One solution is to decrease the cell width uniformly across the ice sheet but with a downside of significantly increasing computer running time. By the early 1990s, the Antarctic ice sheet was being modelled with a cell width of 20 km (Huybrechts, 1990), but while this increased resolution led to more plausible ice sheets, the same limitations existed across grounding zones and shear margins. This problem was compounded by the discovery that ice streams are fed by tributaries that stretch well into the ice sheet interior (Bamber et al., 2000), meaning that slow interior ice flow averaged across large distances results in missing key ice stream processes. The numerical solution is to design an approach where grid-cell size can 'adapt' in recognition of where gradients are steep – such as at grounding zones and ice-stream shear margins – allowing ice processes to be accounted for appropriately, while minimising computer running time. This is non-trivial compared to the numerical treatment of a fixed grid, however.

It is fairly straight forward to consider a fixed 'nested' grid of varying cell widths, where resolution is applied to the ice-sheet regions that require it. The more challenging issue is how to allow the grid to 'adapt' as glaciological circumstances change – such as grounding line or shear margin migration.

The first person to consider adaptive grids in ice sheet models was Andrew Starr – a PhD student from Aberystwyth University in the UK (Starr, 2001). He used a 'quad-tree' grid approach as it led to simple modification of the grid. He based his work around a simple shallow-ice approximation model, using rule-based adaptation criteria. Studies included using the EISMINT (European Ice Sheet Modelling Initiative) inter-comparison standards (Huybrechts et al., 1996) to ensure the adaptation was performing appropriately and then application of the validated model to the case of the Loch Lomond Stadial ice sheet of Scotland (Starr, 2001). The adaptive grid model delivered similar accuracy as the fixed grid model but with reductions in computational load of between 40% and 90%. Although this work demonstrated the utility of adaptive grids in glaciology, it only considered the numerical treatment of the adaptation and not how to apply specific glaciological processes associated with the change in resolution. Hence, while the model ran faster than a fixed-grid model, it was not necessarily any better in terms of glaciological processes.

The next step was to incorporate improved ice flow processes into numerical ice sheet models, using adaptive grids to determine where to employ them. The optimal outcome is a model that runs efficiently, applies processes where needed and avoids unnecessary calculations. Cornford et al. (2013) produced the first such model, BISICLES (Berkeley Ice Sheet Initiative for Climate at Extreme Scales), and applied it to the West Antarctic ice sheet. In their model, a 'block-structured finite volume method with adaptive mesh refinement' was used to apply enhanced resolution at the grounding line within a three-dimensional ice sheet model. As in Starr (2001), the model was compared against fixed-grid alternatives revealing a similar overall function but with reduced computation time. However, the major advantage was that grounding line physics was included, and with adaptation of the grid around the grounding line, its migration was able to be modelled appropriately and in relatively small increments, rather than in jumps dictated by a fixed grid size.

5.2.3 Parallel ice sheet model – PISM

Adding functionality to ice sheet models such as three-dimensional flow, longitudinal stresses, thermodynamics and grounding line physics adds to computational time. This is a major issue if ice sheet evolution is being investigated over long time periods, such as glacial cycles. In addition to adaptive grids, a further improvement in numerical methods is exemplified by the Parallel Ice Sheet Model (PISM). This model uses an approach whereby the 'shallow ice approximation', which calculates the flow of ice frozen to the bed well, and the 'shallow shelf approximation', which determines flow driven by longitudinal stresses such as in floating ice shelves, are calculated across the ice sheet – meaning a realistic ice flow field can be derived without boundaries between flow systems (Winkelmann et al., 2011).

Since it was launched, PISM has been used in over 100 published studies of both the Greenland and Antarctic ice sheets in a variety of settings from deep geological time to predictions of future change. One recent application of PISM was to model Antarctica over several glacial cycles (Albrecht et al., 2020a), to determine the influence of boundary conditions and parameter choices in model output – the issue being that modelling is being significantly hampered by a lack of reliable input data in some key areas that make the use of sophisticated ice sheet models unsuitable.

5.2.4 Coupled models

Having established more sophisticated numerical methods in ice sheet models, a final improvement has been in the coupling of the ice sheet system to other models (atmosphere, ocean and solid earth). Most numerical models now couple ice sheet and ice shelf components to achieve realistic ice dynamic simulations across the grounding zone (e.g., Bueler and Brown, 2009; Huybrechts, 1990; Martin et al., 2019; Pollard and DeConto, 2009;

Sato and Greve, 2012). However, major advances have also been made in terms of coupling either models, or model outputs, from atmosphere–ocean general circulation models (GCMs) into ice sheet models run over long time periods. Pollard and DeConto (2009), for example, did this by forming a library of GCM solutions for a variety of ice sheet scenarios and were able to then select the most appropriate to drive ice sheet change through the model run. While this is clearly a simplification, the outcome was that the ice sheet model could be accompanied for the last 5 million years by relatively detailed inputs of air temperature and precipitation.

In the last few years, other components of the earth system have been coupled to ice sheet models, such as interactions with the solid earth and with spatially varying sea level (Gomez et al., 2010, 2015, 2018), improving the robustness of the simulations. However, full integrated coupling of the entire Earth system has yet to be achieved in a manner that allows reliable prediction of future ice sheet change over centennial or longer timescales (Siegert et al., 2020). Parameterisation remains a more appropriate choice in many circumstances, to avoid computational time burdens and unrealistic scenarios (where attempts to incorporate basal processes lead to ice-sheet outcomes that are unlikely).

5.3 Model input – bed data

Regardless of their sophistication, and improvements in their capabilities, numerical ice-sheet models require reliable and sufficiently detailed boundary conditions and input data in order to yield plausible results. The most essential of these is the subglacial topography of Antarctica, which has been the subject of substantial research in the last decade. Bed topography is a major control on ice dynamics, and so unless it is known well ice-sheet models run the risk of significant mistakes regarding ice-sheet flow and change.

At the time of the first Antarctic Climate Evolution volume (Florindo and Siegert, 2008), the most complete assembly of bed data was known as Bedmap (Lythe and the BEDMAP Consortium, 2000) – the first compilation of bed data since the Antarctic Geophysical Folio in the 1980s (Drewry, 1983). While Bedmap was an advance on the ‘Folio’, and contained detailed bed information from several key places such as the Siple Coast in West Antarctica, it still left several large (100s km wide) regions without any bed data to constrain the subglacial landscape.

In the last two decades, a number of teams of glaciologists have been acquiring new data from, primarily, airborne radio-echo sounding missions. The data-free regions in Bedmap have been a major focus of geophysical exploration, allowing discovery of uncharted mountains and lowlands, lakes and sedimentary basins – each of which would be influential on ice flow and so critical as modelling boundary conditions. For example, the Chinese Antarctic programme and the AGAP (Antarctica’s GAmburtsev Province) programme mapped the enigmatic Gamburtsev Subglacial Mountains (Rose et al., 2013; Sun et al., 2009), revealing upland glacial landforms that show it as the birthplace of the modern Antarctic ice sheet. In addition, the ICECAP (Ice and Crustal Evolution of the Central Antarctic Plate) collaborative undertook several seasons of fieldwork to characterise the landscape of the Aurora and Wilkes subglacial basins (Wright et al., 2012), revealing how water could run from the ice sheet interior to its margin, and discovering ice-cut fjords deep within the ice sheet interior as evidence of a former, smaller, dynamic ice sheet (Young et al., 2011).

These, and many other smaller datasets, led to an updated compilation of bed topography, named Bedmap2 (Fretwell et al., 2013). Indeed so much new data was included in Bedmap2 that the difference between it and Bedmap was far greater than between Bedmap and the 'Folio'. This was a major boost to ice-sheet modelling, and hundreds of projects and papers have subsequently taken advantage of it. However, several data issues remain in Bedmap2, in three forms. The first is substantial geographical regions devoid of basal measurements, including upstream of Recovery Ice Stream, Princess Elizabeth Land and South Pole. The second is data-free zones between existing geophysical transects, some of which are spaced 50 km apart. The third is a reliance on 1970s analogue data, recorded every $\sim$2 km with navigation inaccuracies of up to 5 km.

On the first issue, since 2013 there have been several new airborne geophysical surveys targeted at filling the remaining data gaps (e.g., Paxman et al., 2019a,b) for the vicinity around South Pole; Humbert et al. (2018) for the Recovery system; and Cui et al. (2020) under the second phase of ICECAP for Princess Elizabeth Land. On the second issue, data-free zones between transects is a continuing problem. To create a bed surface between irregular sets of data, an interpolation procedure is needed. Bedmap2 and many other bed surface products use 'krigging'. However, more sophisticated approaches are starting to be used, including 'mass conservation' techniques, where the bed is determined by considering the flux of ice necessary to yield measured surface velocities. Morlighem et al. (2017, 2019) used this approach for the most up-to-date subglacial bed surfaces in Greenland and Antarctica; and Jeofry et al. (2018b) used it for the Weddell Sea sector in West Antarctica. In addition, Graham et al. (2017) calculated a 'synthetic' bed surface at 100 m resolution by utilising roughness measurements within Bedmap and new radio-echo sounding (RES) data and assimilating the results into Bedmap2; the result is a bed product that contains morphological information in fine detail as well as large-scale topography. The third issue is being addressed by the recent digitisation of historical analogue records (Schroeder et al., 2019), allowing along-track data between the officially logged recordings to be introduced, navigation to be improved at cross-overs with new data and, importantly, a times series of $>$40 years in RES measurements to be established for $\sim$40% of the continent. As a consequence of these recent improvements, a new international project – Bedmap3 – is being set up by the Scientific Committee on Antarctic Research (SCAR) to provide the first complete observation-based bed surface of subglacial Antarctica.

Interestingly, the geophysical data that have been acquired to form the Bedmap products allow closer inspection of subglacial morphology, which has in places revealed planation surfaces that are likely relics from preglacial times (Rose et al., 2015). Further, using Bedmap2, new data and sedimentary back-filling, it is possible to provide assessments of former Antarctic landscapes that are crucial to our ability to model ancient ice-sheet evolution (as we can be certain that the modern bed topography reduces in relevance with past time). Sugden and Jamieson (2018) provide an overview of the preglacial landscape of Antarctica, while Paxman et al. (2019a,b) have revealed the role of lithospheric flexure and erosion in determining landscape evolution; hence, it is now becoming possible to run numerical ice-sheet models over beds more representative of ancient periods than the Bedmap products.

Naturally, ice sheet models require more inputs than merely bed topography, and a good example of how they can be set up to model past ice sheets is provided by Albrecht et al. (2020b) for their assessment of Antarctica at the LGM using PISM.

5.4 Advances in knowledge of bed processes

Most ice sheet models are validated by comparing outputs against the modern Antarctic ice sheet. Commonly, model initialisation is optimised in such a way as to yield the best match between simulated and satellite-observed surface ice velocities, either by modifying basal drag or other ice flow parameters. While ice sheet models are capable of calculating basal processes (melting, sliding, for example) to dictate the flow of ice, such models are rarely capable of mimicking the real flow. Hence, basal conditions (such as the rheology and saturation state of sediments, or the plasticity of substrate deformation) often need to be parameterised. This approach is valid if the modern ice sheet is being assessed, but where the ice sheet evolves significantly in modelling experiments, the approach is less appropriate.

Geophysical data used to obtain ice thickness and bed topography often contain information that can resolve basal conditions and processes, but these are rarely assessed in numerical modelling investigations (Jeofry et al., 2019). The problem is twofold; first the modelling community often fails to see the benefit of geophysical data in refining basal processes and, second, the geophysical community often fails to provide the information needed to improve models. Furthermore, it is not always clear how local-scale or point geophysical interpretations can be meaningfully integrated into much larger-scale (for example, whole continent) ice sheet simulations.

In the last 10 years, there have been several key papers that have advanced our knowledge of bed processes in Antarctica, both now and in the past, and such information should be assimilated into numerical modelling procedures if they are to advance to become process-oriented, capable of predicting glaciological change. The most obvious areas in which ice sheet modelling can improve are in its consideration of basal hydrology and bed conditions, and their combined role in modulating the flow of ice above. Here there have been some notable geophysical advances.

Glacier hydrology has been an active area in glaciology for over 50 years (e.g., Nye, 1969). We know that basal water lubricates the bed, especially in the presence of weak unconsolidated sediments, and that fast flow within ice streams is controlled by that water (among other things, such as topography and geology). Clearly, as the ice sheet changes, so too does the subglacial hydrological regime. Hence process-based ice sheet models must advance by learning, from geophysical measurements, of the basal environment. To that end, some ice sheet models now include basal hydrological components. For example, in PISM, basal resistance evolves from an initialisation state depending on the availability and transport of subglacial water (Bueler and Brown, 2009; Bueler and van Pelt, 2015). This time-evolving scheme allows ice streams to switch on and off entirely naturally within the model, without specific prescription of where or when rapid sliding should occur (Golledge et al., 2015; van Pelt and Oerlemans, 2012).

Across Antarctica, the last decade has seen significant ideas for how water flows beneath the ice. This is critical in glaciology, as work on valley glaciers over many years has shown how specific hydraulics affect ice flow. For Thwaites Glacier in West Antarctica, which is a priority for investigation given it is losing mass and susceptible to MISI, Schroeder et al. (2013) used a novel data processing procedure, involving the 'angular distribution of energy in radar bed echoes' to decipher precisely where basal water exists. They used this technique to reveal basal canals within which water can flow and showed that different hydrological systems exist, which are related to gross basal topography. In one location, the canals are distributed and thus conducive to high water pressures, ponding and reduced basal friction, but across a bedrock ridge this transitions to a system of more concentrated well-organised channels in which water flow to the margin is more efficient. This pioneering study was supported by Le Brocq et al. (2013), who showed how channels carved upwards into floating ice shelves at the grounding line were caused by channelised flow of basal water upstream. Later, similar channels were explained by subglacial eskers (Drews et al., 2017) upstream of the Roi Baudouin Ice Shelf in East Antarctica, and water flow alongside large flow-parallel bedrock landforms in Foundation Ice Stream in West Antarctica (Jeofry et al., 2018a). Thus, there is emerging but convincing geophysical evidence for widespread channelised flow of basal water from several sites in Antarctica. Uptake of this knowledge within ice sheet models, and 'training them' to match the data, is possible in coming years. We know this would be useful, as measured discharges from subglacial lakes have been shown to influence the flow speed of outlet glaciers (Stearns et al., 2008). Water flow into and out of hydraulically 'active' subglacial lakes may be more complex than thought initially (e.g., Wingham et al., 2006), but geophysical evidence is now able to measure the topographic conditions that bound them (Siegert et al., 2014), offering the possibility of being able to model them. Basal water channels in ancient glaciological settings (i.e. not possible to form them in today's ice sheet configuration) have also been identified (Rose et al., 2014), though the timing of when they formed is not yet known.

A new frontier in subglacial hydrology lies beneath the ice–water interface as groundwater (Siegert et al., 2018), especially within large sedimentary basins (Siegert et al., 2016), and has the potential to contribute significantly to the water supply to ice stream beds (Christoffersen et al., 2014) and the distribution and exchange of basal heat (Gooch et al., 2016) – both having the potential to significantly influence the flow of ice above. While our ability to model such systems is not yet possible due to a lack of data, several plans exist to identify, measure and assess Antarctic groundwater making it a potential new element for ice sheet models of the future.

5.5 Model intercomparison

For many years in the early history of ice-sheet modelling, a number of models were built and run independently. While these used the same glaciological knowledge, differences in numerical schemes, resolution and process-prioritisation led to differences in past ice-sheet reconstructions depending on the model used. To help resolve this, formal model intercomparison exercises were established, to show where consistencies exist and how differences occur. The first, as reported in Siegert and Payne (2001), was the EISMINT (European Ice Sheet Modelling Intercomparison) exercise. In the last decade, new intercomparison exercises have accompanied enhanced numerical modelling sophistication, focusing on key components of the ice-sheet system. For example, Pattyn et al. (2012) formed the MISMIP (Marine Ice Sheet Model Intercomparison) project, to investigate how different models can reproduce marine ice sheet dynamics and change. This is especially relevant to knowledge of how the WAIS has changed in the past, and will change in the future, and underlined the importance of the appropriate adoption of grounding line physics. More recently, ISMIP6 has allowed ice-sheet models to be intercompared with respect to IPCC scenarios, in order to improve estimates of future ice sheet contributions to sea level. Importantly, this allows ice-sheet models that are coupled into Earth System models, as well as standalone models, to be inter-compared and assessed. The first output from this exercise identified how models of Antarctica should be set up and initialised (Seroussi et al., 2019), with subsequent work presenting the scenario-based projections (Edwards et al., 2021; Seroussi et al., 2020). Additional projects have been established to inter-compare models from specific periods in the past, such as the Pliocene (Haywood et al., 2013), or to investigate the way in which particular processes, such as MISI, are captured (Sun et al., 2020).

5.6 Brief case studies

Now that we have covered how the last decade has seen advances in ice sheet modelling, input data, geophysical evidence and model intercomparison exercises, we can examine how models have been used to reconstruct former Antarctic ice sheets. The discussion will be brief, as it will be provided in detail in other chapters, but key outcomes from such numerical modelling exercises are worth stating for the LGM (Siegert et al., 2021), the mid-Pleistocene (Wilson et al., 2021) and the Pliocene (Levy et al., 2021).

For the LGM, Kusahara et al. (2015) produced a simulation of the LGM Antarctic climate system to understand relationships between the atmosphere, ocean, sea-ice and ice shelves. They showed that ice shelf cavities were shaped very differently from today — being much larger for one thing, but also with thicker floating ice in many places. Because the ice shelf margins were closer to the continental shelf edge, warmth from Circumpolar Deep Water could readily flow into the cavity, causing far more ice-shelf melting than today. Further, the modelling revealed that the winter sea ice limit was around 7° further north than today, and that in summer the Atlantic sector retained sea ice cover with limited amounts elsewhere. Golledge et al. (2012) produced a numerical model of the LGM ice sheet, focusing on how ocean heat led to its subsequent retreat. They examined whether ocean heat, or eustatic sea level rise, could be responsible for the retreat measured in the geological record. They found that while these drivers led to some change to the ice margin, once this had been triggered an impact was felt on ice sheet dynamics. Modification to the flow of ice, and in particular increased flow in ice streams, led to drawdown of ice from the ice-sheet interior and, hence, further ice loss to the ocean. They suggest that this finding has obvious consequences for today's ice sheet that is presently losing mass in several places due to ocean warming (Shepherd et al., 2018).

The last interglacial has also been the subject of recent ice-sheet modelling, with several studies concluding that the Antarctic Ice Sheet was smaller than today at that time, probably leading to a sea-level contribution of 2.5–3 m (Clark et al., 2020; DeConto and Pollard, 2016; Sutter et al., 2020).

An interesting use of PISM was made by Sutter et al. (2019) who focused on the mid-Pleistocene transition (1.2–0.9 Ma), which saw a change from glacial cycles paced at a frequency of ~100 ka to ~40 ka. Their simulations covered the last 2 Ma and revealed how the ice sheet form has changed over this time, especially in West Antarctica as this period may have seen it transition to a large and almost entirely marine-based ice sheet. Importantly, the model also revealed sites where little glaciological change had occurred, predominantly in East Antarctica, which has relevance to the preservation of very old ice at the base of the modern ice sheet that can potentially be sampled by coring. The conditions for such ice are quite stringent — it must be thick enough to contain a record, but thin enough so as not to melt at the base. This requirement means that there are relatively few sites in East Antarctica that appear suitable, but some exist around major ice domes.

Further back in time, the Pliocene has also been the subject of considerable ice-sheet modelling activities, not least because the period was influenced by an atmospheric CO_2 concentration of over 400 ppm, which is similar to today's. Thus, the period likely represents an example of how the Antarctic ice sheet may react ultimately to the warming that occurs under such a scenario. Modelling can help reveal the end-state conditions − the maximum effect of the warming on the ice sheet − and the processes responsible. If the rate of climate forcing is also known, simulations can also help constrain rates of ice sheet loss. In terms of forcing, it is essential to recognise that the Antarctic continent was an integral part of Pliocene Earth, not a passive component influenced by external forcing (Dolan et al., 2018; Haywood et al., 2013). One important ice sheet modelling investigation was undertaken by Pollard and DeConto (2009), which revealed that the Pliocene interglacial ice sheet was far smaller than today's; possibly contributing around 5−7 m to a global sea level rise of approximately 20 m, which is consistent with geological records of major eustatic change at this time (Dumitru et al., 2019; Grant et al., 2019; Raymo et al., 2011). More recently, Golledge et al. (2017) specifically focused on a Pliocene interglaciation at 4.23 Ma, when Southern Hemisphere insolation was at its maximum. They used a one-way coupled ice-sheet/climate model to produce a range of ice-sheet scenarios and concluded that Antarctica contributed ~8.6 m to sea level. Given that the WAIS presently contains enough ice to raise sea level by ~3.5 m, sea level contributions above this point to major ice loss from East Antarctica and, specifically through modelling, sedimentary geology (e.g., Aitken et al., 2016; Cook et al., 2013) and glaciological theory from within its deep marine settings such as the Wilkes and Aurora basins. One controversy in recent years has focused on the rates of past ice-sheet change experienced in Antarctica. The motivation for this is to understand how quickly the present ice sheet can respond to greenhouse-gas driven warming. In a well-document study, Pollard et al. (2015) put the case for Antarctic loss driven by 'hydrofracturing and cliff failure'; the marine ice cliff instability (MICI) hypothesis. This, they argue, is possible if ice-shelves disintegrate rapidly under extreme ocean and atmospheric heating and the resulting hydrofacturing of floating ice, which then produces vertical ice cliffs at grounding lines. If the thickness of the vertical wall of ice is over ~100 m above the ocean surface, it was suggested to be unable to support itself mechanically and, thus, collapses. Pollard et al. (2015) suggest through ice-sheet modelling that this was a mechanism responsible for ice loss in the Pliocene and, potentially, for the future Antarctic ice sheet. This is a controversial proposal because the rate of change is far greater (10s−100s vs 1000s years) than shown by other ice sheet models. DeConto and Pollard (2016) argue that the rate of future sea level rise is significantly underpredicted if this process is not taken into account. However, this theory has been rebutted recently by Edwards et al. (2019) who used a statistical reassessment of the original DeConto and Pollard (2016) simulations to show that Pliocene variations were as possible without invoking cliff failure as they were with the mechanism switched on. Furthermore, recently published process-based (rather than parameterised) models have shown that ice cliffs of the height necessary to trigger cliff collapse in the Pollard et al. (2015) scheme are unlikely to develop unless the buttressing ice shelf can be entirely removed in less than an hour (Clerc et al., 2019). Even though MICI is thought (by some) to be unlikely to occur in this century, if it did, there would be significantly higher rates of rise in the sea level than what we have experienced in the last few decades (Siegert et al., 2020) and predicted by models that do not account for it. Hence, under a precautionary principle it should not be discounted. Knowledge of the conditions that may permit MICI is a major area of research in glaciology, and a priority for the INSTANT programme is to evaluate evidence for its influence on past ice sheet changes (Colleoni et al., 2021).

5.7 Future work

While ice sheet modelling, and its use, has developed considerably in the last decade, several areas where improvements could be made remain (see Siegert et al., 2020). Colleoni et al. (2018) point to where attention is needed at the interfaces between well-studied systems such as at ice—ocean and ice—bed boundaries. Such locations are often very challenging to access physically; hence, we rely on remotely-sensed information to guide models. However, in critical locations such as grounding lines and ice shelf cavities, we are only now beginning to understand the complexities that exist there and how simplistic our approach to modelling them has been (Jeofry et al., 2018a; Siegert et al., 2020). Colleoni et al. (2018) argue that greater attention is needed by the modelling community in these places, with targeted geophysical and oceanographic missions to acquire remote and in situ data, if we are to advance ice-sheet modelling still further to meet the ultimate ambition of reliably predicting ice sheet change and reducing uncertainty in future sea-level estimates.

Another area where more work is needed is in the use of geophysical data by numerical ice-sheet models. In other modelling communities, data assimilation and machine learning utilise geophysical measurements to train and improve model performance. An obvious example is in atmospheric models for weather predictions. While this is now beginning in ice-sheet modelling (for example, the ISMIP6 Antarctic Ice Sheet assessment incorporates six data assimilation ice sheet models and 10 that use more traditional spin-up approaches — matching geometry and velocities with remote sensing measurements), there remains much more to be done. Issues with ISMIP6 include the use of ensemble members that cannot simulate the present-day ice sheet, and the need for more consistency and understanding of the important rate limiting processes.

The most obvious geophysical measurement required by ice-sheet models is the bed topography from ice-penetrating radar (Fretwell et al., 2013). However, such data contain a wealth of information about conditions at the ice sheet beds that are rarely utilised, if at all, in modelling schemes. Jeofry et al. (2019) analysed the performance of the BISICLES ice sheet model, which was optimised for surface flow by reducing basal drag, against radar evidence for basal water, sediment and morphology. The results revealed that while the model performs reasonably well in a gross sense, several discrepancies were revealed. Obviously, if the model optimised for present-day conditions cannot replicate actual measurements as well as it might, how can we have confidence in models when they predict ice sheet evolution? Hence, assimilating geophysical evidence, such as hydrological conditions in ice-sheet models, appears to be an obvious next step.

Finally, and most obviously, Bedmap2 – which is used as a basic boundary condition for most Antarctic ice sheet models – contains several large data gaps, and areas where data coverage is relatively sparse. Graham et al. (2017) showed that getting basal topography right in ice sheet models was critical to their performance and provided a 'synthetic' bed elevation grid for models to be tested. Morlighem et al. (2019), using the 'mass conservation' technique, have recently calculated the most accurate depiction of Antarctic bed elevation (Bedmachine Antarctica). The technique works by measuring ice surface velocities from satellite data and, assuming the vertical profile of ice flow, a bed profile that allows ice flux along flowlines to be preserved is established. The technique works best where velocities are greatest, as the bulk of ice flow is from basal processes, and allows bed morphology to be determined in the key area of ice sheet grounding lines, where they have revealed unmeasured deep troughs bounding the ice sheet. However, Bedmachine Antarctica is not a data base and, as discussed above, there may be additional benefits to the modelling community to fully, systematically and accurately measure the base of the Antarctic ice sheet. Plans are in place to update Bedmap2 with new data that cover most of its data gaps (i.e., Bedmap3), and this should appear in the coming years.

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