Geoengineering’s role in reducing future Antarctic mass loss is unclear

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Geoengineering’s role in reducing future Antarctic mass loss is unclear

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Key Points:

• Idealised geoengineering is unable to prevent significant loss from Antarctica regardless of emissions pathway or year of implementation
• Geoengineering in 2050 under high emissions reduces sea level contribution compared to stabilisation but geoengineering in 2100 increases it
• Surface mass balance gains initially offset loss under stabilisation, but this may be negated in future by accelerating dynamic loss

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Abstract
Using the BISICLES ice sheet model, we compare the Antarctic ice sheet’s response over
the 22nd century in a scenario where idealised large scale, instantaneous geoengineer-
ing is implemented in 2100 or 2050 (geoengineering), with scenarios where the climate
forcing is held constant in the same year (stabilisation). Results are highly climate model
dependent, with larger differences between models than between geoengineering and sta-
bilisation scenarios, but show that geoengineering cannot prevent significant losses from
Antarctica over the next two centuries. If implemented in 2050, sea level contributions
under geoengineering are lower than under stabilisation scenarios. If implemented in 2100,
under high emissions, geoengineering produces higher sea level than stabilisation scenar-
ios, as increased surface mass balance in the warmer stabilisation scenarios offsets some
of the dynamic losses. Despite this, dynamic losses appear to accelerate and may eventu-
tally negate this initial offset, indicating that beyond 2200, geoengineering could eventu-
tally be more effective.

Plain Language Summary
Sea level will keep rising well into the next century as oceans and ice sheets take
decades to respond to atmospheric temperature changes, even if aggressive greenhouse
gas reduction policies were immediately implemented. Consequently, geoengineering has
been proposed as a more rapid measure. Geoengineering refers to the manipulation the
climate system to lessen the impacts of human induced warming. We use an ice sheet
model to predict Antarctica’s response to geoengineering in 2200, as it is one of the most
uncertain sea level contributors. We find that, although the results depend strongly on
which climate model is used to drive the ice sheet model, geoengineering cannot prevent
sea level contribution from Antarctica. However, implementing geoengineering in 2050
produces smaller sea level rises compared with a scenario where the climate is stabilised
in the same year. If geoengineering is delayed to 2100, sea level rise is worse under geo-
engineering, because stabilising the climate in 2100 creates a warmer climate where the
air can hold more moisture, increasing snowfall on Antarctica and offsetting some mass
loss. However, stabilising the climate also produces progressively bigger increases in ice
discharge compared with geoengineering. This suggests that geoengineering may be more
effective in future.

1 Introduction
The Antarctic ice sheet is the largest ice mass on the planet, containing the equiv-
alent of 58m of sea level rise (Morlighem et al., 2020). It is also the most uncertain sea
level contributor. Projected sea level contributions for Antarctica from the IPCC Sixth
Assessment Report are 0.03-0.27m to 0.03-0.34m for 2100 for the low and high emission
scenarios (SSPs: Shared Socioeconomic Pathways) SSP1-2.6 and SSP5-8.5, respectively
(IPCC, 2021). Beyond 2100, projections for the ice sheet become even more uncertain,
in part due to a relative lack of projections, but also due to remaining uncertainties in
ice loss mechanisms, solid earth feedbacks, ice shelf rheology, and others (Bulthuis et al.,
2019; Lowry et al., 2021).

An ice sheet’s contribution to sea level is dictated by the difference between its sur-
face mass balance (SMB) and ice dynamics. Surface mass balance processes encompass
all gains and losses on the ice sheet’s surface, including snow deposition, surface melt-
ing, runoff, and evaporation, and are primarily controlled by atmospheric changes (Hanna
et al., 2013). Ice dynamics refer to losses through the calving and melting of ice shelves
into the ocean, and are driven by oceanic changes. The combination of SMB and ice dis-
charge make up an ice sheet’s total mass balance. A positive mass balance indicates a
net gain in ice mass, while a negative value indicates net mass loss and therefore a con-
tribution to sea level. Currently, mass loss is primarily driven by ocean interactions (Pattyn
& Morlighem, 2020). In particular, upwelling of circumpolar deep water (CDW), a water mass over 4°C warmer than the freezing point at the base of an ice shelf, is widely accepted as a key driver of current basal melting in the Amundsen Sea (Jacobs et al., 2011; Pritchard et al., 2012; Rignot & Jacobs, 2002). Understanding the impacts of future climate change is difficult as ocean and atmospheric warming can produce contrasting effects (Payne et al., 2021; Edwards et al., 2021). Ocean warming amplifies mass loss through increased ice discharge, and while atmospheric warming increases the moisture holding capabilities of the air, leading to more precipitation and mass gain, it can also increase ice discharge through melting and runoff, which can lead to ice shelf breakup (Kittel et al., 2020).

Even if stringent emissions reduction policies were immediately implemented, sea level rise is projected to continue beyond 2200 due to the delayed response of the oceans and cryosphere to atmospheric temperature changes (climate inertia (IPCC, 2021)). To try and ameliorate some of these lagged climate responses, geoengineering has been proposed as a more extreme measure. Geoengineering describes a deliberate modification of the climate system to help mitigate the impacts of anthropogenic warming (Lockley et al., 2020). Geoengineering methods are broadly comprised of two types; carbon dioxide removal (CDR) and solar radiation management (SRM). CDR removes carbon dioxide from the atmosphere and stores it in long term sinks, while SRM increase the earth’s albedo (Irvine et al., 2018). While SRM does not target the source of anthropogenic warming, its impacts would be felt more rapidly than CDR methods.

Geoengineering experiments are essential for understanding whether Antarctic mass losses would be irreversible, and if implementation could prevent the crossing of critical thresholds such as the initiation of marine ice sheet instability (MISI). MISI refers to the mechanism by which marine ice sheets could rapidly retreat via a destabilising of their grounding lines (Weertman, 1974). It can only occur in marine ice sheets where the bedrock in the interior is more depressed than the coasts, resulting in a retrograde slope (Pattyn & Morlighem, 2020). If an ice shelf thins, its buttressing capabilities on the ice sheet are reduced, accelerating ice flow and causing grounding line retreat (Schoof, 2007). As ice flux is a function of ice thickness at the grounding line, the retreat of the grounding line to deeper portions of the bed leads to a higher ice flux (Weertman, 1974). This creates a positive feedback of mass loss which can only be stabilised when the bed slope reverses or buttressing increases (Weertman, 1974; Gudmundsson, 2013).

Few studies have been done regarding geoengineering’s impact on Antarctic mass loss. Garbe et al. (2020) show with equilibrium experiments that regrowth of the Antarctic ice sheet is much slower than deterioration (i.e. hysteresis), suggesting slow implementation of CDR may be ineffective. DeConto and Pollard (2016) showed that for high emission scenarios, implementing CDR in 2500 could reduce the sea level contribution from Antarctica more effectively than a natural reduction of CO$_2$ begun in the same year, but sea level rise remained very high: at 9.55m and 4.7m for high and mid emissions scenarios, respectively, even after 5000 years. These experiments were limited in scope, however, with a very late drawdown of CO$_2$, no ocean cooling, and were driven by a model that includes a mechanism of sustained ice front retreat known as marine ice cliff instability (MICI) and thus loses ice more rapidly than other models (IPCC, 2021, 2019). Sutter et al. (2023) find that SRM cannot prevent a collapse of the West Antarctic Ice Sheet under a high emissions scenario due to committed warming in the Southern Ocean, but that under a mid emission scenario, if implemented by mid century, collapse could be prevented.

Under an earlier application of CDR, DeConto et al. (2021) still show sustained sea level contribution from Antarctica. They see a distinct increase in contribution between CDR deployment in 2060 and 2070, suggesting the existence of a critical threshold of ice sheet loss. The authors attribute this to marine ice instabilities being triggered
due to the deterioration of ice shelves that cannot recover, even with rapid CDR, due
to the ocean’s slow response time.

Here, we also perform idealised CO$_2$ drawdown experiments to mimic an instan-
taneous application of geoengineering, but using an ice sheet model that does not invoke
MICI processes. We compare the Antarctic ice sheet’s response to a scenario where ide-
alised, large scale CDR is immediately implemented in either 2100 or 2050 by instantly
returning the climate to present day forcing, with ones where the climate is held con-
stant in the same year. In doing so, we aim to improve understanding of reversibility and
long term commitments of mass loss from Antarctica.

2 Methods

2.1 The BISICLES ice sheet model

This study used the Berkeley Ice Sheet Initiative for Climate at Extreme Scales (BISI-
CLES) (Cornford et al., 2013). This model was chosen due to its adaptive mesh refine-
ment capabilities, allowing it to better capture ice dynamics around grounding lines and
ice streams. Modelling ice sheets requires fine spatial resolution (<1km) for these pro-
cesses, but as interior changes are slower and on larger spatial scales, they do not require
such high resolution. By using adaptive mesh refinement, high resolution is only used
where it is necessary, reducing computational costs and allowing more simulations. Here,
we apply a finest spatial resolution of 1km, reducing down to 8km in the interior.

2.2 Forcing scenarios

This work is based on extending Antarctic projections from the Ice Sheet Model
Intercomparison Project for CMIP6 (ISMIP6), which compared a range of stand-alone
ice sheet models to provide the most up to date understanding of ice sheet response to
the climate system for the Climate Model Intercomparison Project Phase 6 (CMIP6) (Nowicki
et al., 2016; Seroussi et al., 2019; Payne et al., 2021; J. O’Neill et al., 2024). Five exper-
iments (experiments 5-8 and B7) were chosen to extend beyond 2100 from O’Neill et al.
(2024). Three experiments are high emission scenarios under RCP8.5, and use GCMs
NorESM1-M (NorESM1 8.5), MIROC-ESM-CHEM (MIROC 8.5) and CCSM4 (CCSM4
8.5). The other two experiments are low emission scenarios forced by NorESM1-M un-
der RCP2.6 (NorESM1 2.6) and CNRM-CM6-1 under SSP1-2.6 (CNRM 1-2.6). These
GCMs were selected for ISMIP6 via a thorough analysis process (Barthel et al., 2020),
based on their ability to simulate present day Antarctic climate, in addition to sampling
a range of atmospheric and ocean forcings, and the availability of both RCP8.5 and RCP2.6.
CNRM was selected due to availability only, to provide an additional low forcing scenario
(Payne et al., 2021).

The ice sheet model experiments were driven by both atmospheric and ocean forc-
ing, both of which were provided by ISMIP6 directly from GCM output. The atmospheric
projections consist of yearly SMB and surface temperature anomalies relative to a refe-
rence period of January 1995 to December 2014. Oceanic projections consist of ther-
mal forcing anomalies (calculated from temperature and salinity) relative to 1995-2014,
which were then added to an observed climatology (1995-2017) in order to calculate basal
melt rates using the ISMIP6 melt parameterization (Jourdain et al. (2020)).

Climate forcings were extended beyond 2100 to 2200 by either repeating the cli-
mate forcing between 2091-2100 (simulating a stabilisation scenario with no geoengineer-
ing), or instantly returning to present day forcing of 2015-2024 (simulating an instant,
large scale geoengineering application scenario). A second set of scenarios was generated
using the same method but extending the climate forcing from 2050, to understand the
effects of an earlier geoengineering implementation. In this case, the repeated time pe-
riod for the stabilisation scenario was 2051-2060. We refer to these as the 2100/2050 stabilisation and geoengineering scenarios, respectively.

3 Results

3.1 Total sea level contribution

Figure 1 shows the projected Antarctic sea level contribution for all experiments. Total sea level contribution is the change in volume above flotation (VaF) for grounded ice, calculated by

\[ V_{af} = \min((Z - S), 0) \times \frac{\rho_{\text{ocean}}}{\rho_{\text{ice}}} + H \] \( dx \ dy \)

where \( Z \) is topography, \( S \) is sea level, \( \rho_{\text{ocean}} = 1028 \text{ kg m}^{-3} \) and \( \rho_{\text{ice}} = 910 \text{ kg m}^{-3} \) are the densities of ocean water and ice respectively, and \( H \) is ice thickness. Table B1 summarises the projected changes for key variables at 2200 relative to 2012 for all experiments.

Regardless of scenario, Antarctica will contribute considerably to sea level rise over the next two centuries: up to 172mm. There is no clear distinction between high and low emission scenarios, with a large range in sea level contributions between models for the same scenario, indicating that the results are highly model dependent (Figure 1). For instance, in the 2050 scenarios, NorESM1 2.6 stabilisation has a sea level contribution almost 70mm higher than CCSM4 8.5 stabilisation.

Under RCP2.6/SSP1-2.6, geoengineering results in marginally lower sea level contributions than stabilisation for both 2050 and 2100 implementation. The difference in sea level contribution between the models’ geoengineering and stabilisation scenarios (G-S difference) is smaller for the 2100 scenarios (<1-4mm) than the 2050 scenarios (3-11mm, B1).

The 2050 RCP8.5 scenarios show that, with the exception of CCSM4 8.5, geoengineering would result in a smaller sea level contribution than stabilisation. For CCSM4 8.5, geoengineering increases sea level by 2200, though the trajectory indicates that there may be recovery in future decades (Figures 1 and B1). G-S differences are higher than for low emissions, between 14-24mm (Figure B1).

The 2100 RCP8.5 emission experiments have more disagreement between models on the effectiveness of geoengineering. Geoengineering has a higher sea level contribution than stabilisation for NorESM1 8.5 and CCSM4 8.5 by 2200. However, both geoengineering trajectories appear to slow, while the stabilisation scenarios accelerate, suggesting that post 2200, geoengineering could eventually be more effective, with their G-S differences peaking and beginning to decrease (Figure B1). MIROC 8.5 also initially shows a higher sea level contribution under geoengineering, but this reverses in ~2185. CCSM4 8.5 has a much larger G-S difference than the other two models.

In the following two sections, the two components that make up total sea level contribution (SMB and ice dynamics) are discussed.

3.2 Surface Mass Balance

Table B1 shows the integrated SMB sea level contribution in 2200. Values are negative as the data is shown in terms of sea level contribution. As with total sea level contribution, there is overlap between RCP8.5 and RCP2.6/SSP1-2.6 scenarios and a large spread in model projections. NorESM1 consistently shows the weakest increases in SMB.
Figure 1. Total sea level contribution relative to 2012 shown in SLE (mm) for 2050 (top) and 2100 (bottom) for RCP2.6/SSP1-2.6 (left) and RCP8.5 (right) emission scenarios. Line types show different model experiments. NorESM1: solid line, MIROC: dotted line, CCSM4: dashed line, CNRM: dash dotted line. Red lines indicate stabilisation scenarios, blue lines indicate geo-engineering scenarios.

Figure 2a-d shows the G-S differences for SMB. Under low emissions, CNRM 1-2.6 shows that geoengineering results in smaller SMB gains (negative G-S difference). In contrast, NorESM1 2.6 has higher SMB under geoengineering for the 2050 scenario (positive G-S difference) and a negligible difference for the 2100 scenario. All show smaller G-S differences and the largest differences are between the models themselves.

All high emission simulations show smaller SMB gains under geoengineering than stabilisation. SMB gains and G-S differences are larger in the 2100 simulations. The 2100 scenarios also have a clearer distinction between geoengineering and stabilisation as there is no overlap between scenarios. CCSM4 8.5 has the strongest SMB response, showing the largest gains for both the 2050 (991mm) and 2100 (1116mm) experiments under stabilisation, as well as the largest G-S differences (85mm and 156mm).

3.3 Ice Dynamics

Estimates of ice dynamics sea level contribution were calculated by subtracting the integrated SMB from the total sea level contribution, to better understand changes in Antarctic ice sheet volume not directly due to SMB. This calculation produces an ice dynamics contribution that can be attributed to both grounding line retreat and increased flux across the grounding line.

Figure 2 (panels e-h) shows the G-S differences for ice dynamics. Under RCP2.6/SSP1-2.6, NorESM1 2.6 has negligible G-S differences for both 2050 and 2100 scenarios. CNRM 1-2.6 has G-S differences of 18mm and 14mm respectively, with geoengineering producing a smaller sea level contribution from ice dynamics than stabilisation. Both models have higher ice dynamics contributions for the 2100 experiments (Table B1).

Under RCP8.5, geoengineering results in smaller ice dynamics sea level contributions, whether implemented in 2050 or 2100, shown by the negative G-S differences. For the 2050 experiments, CCSM4 has the largest G-S difference of 67mm, with NorESM1
Figure 2. Difference between geoengineering and stabilisation scenarios (geoengineering minus stabilisation) for cumulative SMB (panels a-d) and ice dynamics (e-h). RCP2.6/SSP1-2.6 scenarios are shown in the left panels, and RCP8.5 scenarios are shown on the right. Line types show different model experiments. **NorESM1** – solid line, **MIROC** – dotted line, **CCSM4** – dashed lined, **CNRM** – dash dotted line. Positive (negative) values indicate that geoengineering has a larger (smaller) SMB or ice dynamics value than stabilisation.
having the smallest G-S difference of 30mm. For the 2100 experiments, the G-S difference is more pronounced for all models (76-97mm), and the ice dynamic sea level contribution is greater than compared with the 2050 experiments. G-S differences also appear to increase at an accelerating rate compared with the 2050 experiments’ more linear response (with the exception of CCSM4 8.5). The acceleration in G-S difference is due to the sea level contribution from ice dynamics increasing at a faster rate under a stabilisation scenario than under geoengineering.

3.4 Spatial patterns of mass loss

Figure 3 presents spatial patterns of G-S differences for ice thickness. Geoengineering is helpful in reducing mass loss for the Amery and West ice Shelves, the Amundsen Sea Embayment, and Totten Glacier. The Ross and Ronne-Filchner ice shelves are more model dependent. All models show greater thickening in the interior under stabilisation compared with geoengineering. Though geoengineering does prevent some thinning, there are still large losses in these regions, under both geoengineering and stabilisation (B2).

Similar results are observed in the 2100 simulations, with losses observed in the same areas but with greater severity (Figure B3). The north coast of Queen Maud Land also experiences significant losses. The G-S difference is larger in the 2100 experiments (Figure 3), as is the inland thickening under stabilisation because of the increased SMB, and there is strong model agreement on geoengineering being beneficial to the Ross ice shelf.

Losses are smaller under RCP2.6/SSP1-2.6, but spatial patterns of thinning are similar (Figures B2 and B3). Though there is some thickening in the interior, G-S differences are much smaller for RCP2.6/SSP1-2.6 than under RCP8.5, indicating smaller SMB changes (Figure B4). All simulations demonstrate that geoengineering is less effective for the Ross ice shelf but is otherwise useful in many similar regions as the RCP8.5 experiments.

4 Discussion

All models agree that regardless of scenario, Antarctica will contribute considerably to sea level over the next two centuries. SMB plays an important role in driving changes across all scenarios, with ice dynamics also contributing significantly to the 2100 RCP8.5 emissions scenarios.

Scenarios with the most warming show the largest SMB gains as warmer climates lead to increased precipitation. This is seen in the forcings (Figures A1 and A2), where for all models, the repeated decadal SMB forcing under stabilisation is higher than under geoengineering. This difference in climate forcing produces the large negative G-S differences for SMB seen for the RCP8.5 emissions scenarios, particularly for the 2100 simulations, indicating that geoengineering tends toward smaller SMB increases due to the reduced warming. For the 2100 RCP8.5 stabilisation scenarios, this increased SMB partially offsets some of the losses from Antarctica, resulting in smaller sea level contributions compared with geoengineering. This contrasts to what is seen in the 2050 RCP8.5 scenarios and all RCP2.6/SSP1-2.6 emission scenarios, as here the small forcing difference between geoengineering and stabilisation does not produce a SMB increase large enough to partially offset dynamic losses. CCSM4 8.5 however, has a very large SMB increase, which is why this is the only 2050 experiment where sea level contribution under geoengineering is higher than under stabilisation: geoengineering dampens the SMB, while dynamic losses continue.

Though the 2100 RCP8.5 scenarios initially show larger sea level contributions under geoengineering, all geoengineering trajectories begin to slow, while the stabilisation trajectories accelerate (Figure 1), leading to the possibility of the scenarios eventually
Figure 3. Spatial patterns of ice thickness difference in meters between geoengineering minus stabilisation for RCP8.5 experiments at 2200. 2050 experiments are shown on the left and 2100 shown on the right. Where values are negative (red), geoengineered ice thickness is less than the stabilisation experiments. Where values are positive (blue), geoengineered ice thickness is more than stabilisation experiments. Values higher than 50m or lower than -50m are shown in black.
converging. G-S differences peak and then decline (Figure B1), with MIROC’s sea level contribution under stabilisation overtaking geoengineering in ~2185 (Figure 1). Initially, increased SMB from warmer atmospheric temperatures in the stabilisation scenarios compensates for some of the losses; however, over time, the ice dynamic contribution increases substantially relative to the geoengineered scenarios. At this point, SMB increases are no longer enough to compensate for the dynamic losses. This has been found in previous work (Winkelmann et al., 2015; Golledge et al., 2015) and is seen here in Figure 2, where the 2100 RCP8.5 scenarios show an accelerating increase in G-S difference for ice dynamics, while the SMB G-S difference increases linearly.

The large rise in sea level contribution from ice dynamics under the high emission stabilisation scenarios is explained by the basal melt (Figure B5), which greatly increases compared to geoengineering. Figure 3, also shows thinner ice shelves under stabilisation, reducing buttressing and increasing ice flow. The G-S difference for the grounded area also accelerates because the grounded area under stabilisation continues to decrease, while it begins to plateau under geoengineering (Figure B6). All other scenarios show a stabilisation for both geoengineering and stabilisation. The 2100 RCP8.5 stabilisation scenarios could therefore point to a possible instability in grounding line retreat being triggered, which geoengineering could help to mitigate.

The Amery ice shelf, Totten and Amundsen Sea Embayment glaciers appear to be more unstable than others, as they continue to thin even when ocean thermal forcing reverts to present day under both low and high emissions scenarios. Observed rates of thinning and grounding line retreat are highest in the Amundsen and Bellingshausen Sea areas and around Totten Glacier, and several Amundsen Sea Embayment glaciers have been stated as being compatible with the onset of MISI, though this is still uncertain (IPCC, 2021, 2019)

The lagged response of the ice sheet to past warming means that geoengineering is unable to prevent mass loss, even in this idealised case where ocean forcing is instantly decreased. In reality, sea level contributions would likely be even higher as the additional ocean inertia would mean that ocean thermal forcing would remain at 2050 or 2100 levels for decades, even if atmospheric temperatures were immediately reduced. CDW, for example, is a relatively old (Matsumoto, 2007) and deep (Jacobs et al., 2011) water mass. This means it is not in frequent contact with the atmosphere, and that these deeper waters take time to adjust to atmospheric changes as they penetrate down from the surface. The ocean’s lagged response time has been previously proposed as the reason Antarctica will have committed sea level rise, even if atmospheric temperatures were stabilised (DeConto et al., 2021).

The models show little agreement on sea level contribution, and high and low emission scenarios overlap between models in many cases. Figures A1 andA2 show that SMB and ocean thermal anomalies have large interannual variability, meaning these results depend strongly on the decade chosen to repeat. Particularly for the low emission scenarios, there is considerable overlap between stabilisation and geoengineering input forcings, which may explain why smaller changes are seen between the two, and why the largest differences are seen between models. The model and decade chosen therefore play a comparably large role in determining Antarctic sea level contribution. As these scenarios are highly idealized, we do not focus on projecting absolute sea level contribution. Instead, we focus on understanding whether geoengineering leads to more effective sea level rise mitigation than stabilising climate at 2050 or 2100. The simulations also provide insight into the reversibility of mass loss from Antarctica: that while idealised, large scale geoengineering can mitigate some loss, it cannot reverse it.
5 Conclusion

Although the Antarctic ice sheet will contribute substantially to sea level rise in all cases, implementing geoengineering in 2050 generally results in decreases in sea level contribution compared with stabilising the climate at 2050 or 2100. The climate model CCSM4 under an RCP8.5 scenario is an exception, as its strong SMB response offsets some sea level contribution in the stabilisation scenario. If geoengineering methods are deployed in 2100, outcomes are more uncertain, and under high emission scenarios, geoengineering often initially contributes more to sea level rise than stabilising climate in 2100, due to increased SMB offsetting some of the mass loss. Beyond 2200, however, sea level contribution under stabilisation appears to accelerate, likely as a result of increased losses due to ice dynamics, whilst the geoengineering scenarios’ sea level contribution decelerates. This could indicate that in future, geoengineering may eventually be more effective.

Sea level contributions differ widely between models for the same scenario, with this difference often being larger than the difference between the geoengineering and stabilisation scenarios. Under RCP8.5, models do not all agree that geoengineering in 2050 would be more effective than stabilising the climate. The model uncertainty therefore makes it difficult to quantify the effectiveness of geoengineering, however the results still highlight that Antarctic mass loss is irreversible for the next two centuries due to its delayed response to climate forcings.

More work is needed to understand Antarctica’s response to more realistic geoengineered scenarios, but the results presented here indicate that geoengineering would not be a complete solution to mitigating sea level contribution from the ice sheet, nor reverse it on multi-century timescales. Deployment would be more effective if implemented earlier, and if delayed until the end of the century, would initially be more harmful than stabilising the climate. As substantial mass losses are still seen under a 2050 implementation, it is likely that even an earlier implementation of geoengineering would not be able to fully prevent further sea level contribution. Additional mitigation and adaptation strategies will therefore still need to be investigated.

6 Open research

We use BISICLES version 1.3, revision number 4311 of the public branch, accessible at https://anag-repo.lbl.gov/svn/BISICLES/public/trunk/. BISICLES is written in a combination of C++ and FORTRAN and is built upon the Chombo AMR software framework. More information about Chombo can be found at http://Chombo.lbl.gov.

ISMIP6 atmosphere and ocean forcing data is stored on the University of Buffalo’s CCR transfer server, accessed at sftp://transfer.ccr.buffalo.edu/projects/grid/ghub/ISMIP6. Instructions for accessing the server can be found at: https://www.climate-cryosphere.org/wiki/index.php?title=ISMIP6-Projections-Antarctica#A2.2_Retrieving_dataset_and_Upload_model_output

The data that support the findings of this study are openly available at https://data.mendeley.com/preview/y3vg6c68th?a=d675fa69-5403-40ec-8422-96f347654d63.

Figures were created using Matplotlib version 3.7 and Pandas version 1.5.3. Maps were creating using VisIt version 3.1.0, available at https://sd.llnl.gov/simulation/computer-codes/visit/executables
Appendix A  Climate forcing inputs

Appendix A shows all input forcings used, illustrating the repeated decadal timeslices.

Figure A1. SMB anomalies for 2050 (top) and 2100 (bottom) for RCP2.6/SSP1-2.6 (left) and RCP8.5 (right) emission scenarios. Different line types show different model experiments. **NorESM1** – solid line, **MIROC** – dotted line, **CCSM4** – dashed line, **CNRM** – dash dotted line. Red/orange lines indicate stabilisation scenarios, blue lines indicate geoengineering scenarios. The grey vertical dashed lines show the repeated time periods of geoengineered (2015-2024) and stabilisation (2051-2060/2091-2100) climates.

Figure A2. As A1 but for ocean thermal forcing.
Appendix B  Further results and variables

Appendix B contains a table of all 2200 values relative to 2012 for total sea level contribution, SMB, ice dynamics, total melt, and grounded area change (Table B1). It contains timeseries showing the G-S difference for total sea level contribution (B1), absolute sea level contribution from melt (B5) and grounded area change (B6), and spatial patterns of mass loss (B2, B3 and B4).

Figure B1. Difference between the geoengineering and stabilisation scenarios (geoengineering minus stabilisation) for total sea level contribution, for 2050 (top) and 2100 (bottom) for RCP2.6/SSP1-2.6 (left) and RCP8.5 (right) emission scenarios. Different line types show different model experiments. NorESM1 – solid line, MIROC – dotted line, CCSM4 – dashed lined, CNRM – dash dotted line. Where the value is positive, geoengineering has a larger sea level contribution than stabilisation, i.e. that geoengineering is worse than fixing the climate at that point. If the value is negative, then geoengineering has a smaller sea level contribution than stabilisation.

Acknowledgments

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References


Bulthuis, K., Arnst, M., Sun, S., & Pattyn, F. (2019, April). Uncertainty quantification of the multi-centennial response of the Antarctic ice sheet to cli-
Table B1. Projections in 2200 relative to 2012 for total sea level contribution, integrated SMB, integrated ice dynamics, integrated basal melt, and grounded area change, for all experiments, shown in mm sea level equivalent

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<tr>
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Figure B2. Thickness change in meters between 2012 and 2200 for the 2050 experiments. Pink line denotes the grounding line. Red areas represent areas where ice thickness is lower in 2200 compared with 2012. Values higher than 200m or lower than -200m are shown in black.
Figure B3. As B2 but for the 2100 scenarios.
Figure B4. Spatial patterns of ice thickness difference between geoengineering minus stabilisation for RCP2.6/SSP1-2.6 experiments at 2200. Thickness difference shown in meters. 2050 experiments are shown on the left and 2100 shown on the right. Where values are negative (red), geoengineered ice thickness is less than the stabilisation experiments. Where values are positive (blue), geoengineered ice thickness is more than stabilisation experiments. Values higher than 50m or lower than -50m are shown in black.
Figure B5. Cumulative sum of total melt relative to 2012 shown in SLE for 2050 (top) and 2100 (bottom) for RCP2.6/SSP1-2.6 (left) and RCP8.5 (right) emission scenarios. Different line types show different model experiments. *NorESM1* – solid line, *MIROC* - dotted line, *CCSM4* - dashed lined, *CNRM* - dash dotted line. Red lines indicate stabilisation scenarios, blue lines indicate geoengineering scenarios.

Figure B6. Grounded area change relative to 2012 for 2050 (top) and 2100 (bottom) for RCP2.6/SSP1-2.6 (left) and RCP8.5 (right) emission scenarios. Different line types show different model experiments. *NorESM1* – solid line, *MIROC* - dotted line, *CCSM4* - dashed lined, *CNRM* - dash dotted line. Red lines indicate stabilisation scenarios, blue lines indicate geoengineering scenarios.


