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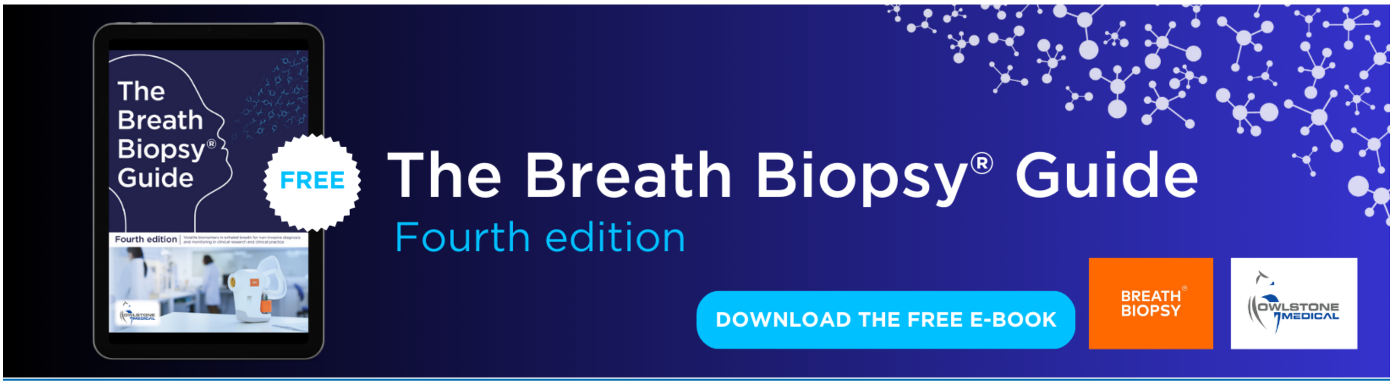

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LETTER

# Reversibility of Greenland ice sheet mass loss under artificial carbon dioxide removal scenarios

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**Keywords:** Greenland ice sheet, sea level rise, climate change, tipping point, anthropogenic carbon emissions, Earth system, artificial carbon removal

## Abstract

With ongoing anthropogenic $CO_2$ emissions, the Greenland ice sheet (GIS) approaches critical thresholds of inevitable, long-term mass loss. Future technologies might be able to efficiently remove $CO_2$ from the atmosphere and thereby cool down our planet. We explore whether and to what extent a realization of this concept could lead to a regrowth of the GIS once it has partly melted. Using the fully coupled Earth system model of intermediate complexity CLIMBER-X, emission pulses between 0 and 4000 GtC are released into the atmosphere, and after 1 kyr, 2 kyr, and 5 kyr, the atmospheric $CO_2$ concentration is reduced back to its pre-industrial value. We find that independent of a specific trajectory, once the southern part of the GIS has partly melted with a total mass loss of more than 0.4 m sea level equivalent, regrowth is inhibited. Uncertainties preclude determination of precise thresholds, but model results indicate that cumulative industrial-era emissions approaching 1000–1500 GtC and beyond increasingly risk irreversible mass loss of the GIS. Once this threshold is passed, artificial atmospheric carbon removal would need to be utilised within the next centuries at massive scale. Beyond that, artificial atmospheric carbon removal has limited abilities to avoid long-term mass loss of the GIS. In conclusion, keeping cumulative anthropogenic emissions below 1000–1500 GtC is the only safe way to avoid irreversible mass loss of the GIS.

## 1. Introduction

Negative anthropogenic atmospheric $CO_2$ emissions, also termed artificial carbon removal, is a possible component to remain below critical temperature thresholds (e.g. Tavoni and Socolow 2013, Lomax *et al* 2015, Carton *et al* 2020). Relying on this concept is however risky since it is not clear whether efficient carbon removal techniques will be deployed in the future, and it could lead to extreme global warming if humans fail to remove carbon from the atmosphere in large quantities (e.g. Fuss *et al* 2014, Anderson and Peters 2016, Williamson 2016). Furthermore, there is the risk that critical thresholds in the Earth system (also termed tipping points) will be crossed before realising net negative emissions (e.g. Shue 2017). Due to the non-linearity of the Earth system, changes could be irreversible, even if the atmospheric $CO_2$ would eventually successfully be reduced to pre-industrial levels.

A major issue concerning the recovery of pre-industrial conditions by removing atmospheric $CO_2$ is the associated recovery of the sea level. The reason for this is twofold: First, the sea level changes with a substantial time lag after changes in the atmospheric $CO_2$. In fact, thermosteric sea level rise is not reversible on timescales of several centuries even with large net negative emissions (Solomon *et al* 2009, Zickfeld *et al* 2013, Tokarska and Zickfeld 2015). Secondly, sea level change due to melting and regrowth of ice sheets is strongly non-linear: due to positive feedback mechanisms such as the ice-elevation feedback, a substantial melting of an ice sheet may inhibit its regrowth on long timescales even if the atmospheric $CO_2$ concentration is substantially reduced (e.g. Solgaard and Langen 2012, Pattyn *et al* 2018).

One of the main contributors to global sea level rise is melting of the Greenland ice sheet (GIS, Aschwanden *et al* 2019, Goelzer *et al* 2020, Muntjewerf *et al* 2020, Van Breedam *et al* 2020, Box *et al* 2022). Previous studies have shown that the GIS features multiple equilibrium states within a global temperature anomaly of 2 K (e.g. Charbit *et al* 2008, Ridley *et al* 2010, Robinson *et al* 2012, Bochow *et al* 2023, Höning *et al* 2023), which may be approached depending on the initial ice volume. Specifically, for increasing atmospheric $CO_2$ starting from pre-industrial conditions, the equilibrium ice volume would first decrease only by a small extent, but if a bifurcation point is crossed, it would decrease substantially (e.g. Gregory *et al* 2004, Gregory and Huybrechts 2006, Irvalı *et al* 2020, Armstrong McKay *et al* 2022). Due to the hysteresis behaviour, if atmospheric $CO_2$ would then be reduced again, the GIS would not return to its initial state even in the long-term; instead, an atmospheric $CO_2$ concentration below its pre-industrial value may be required to grow the ice sheet back to its pre-industrial state. In Höning *et al* (2023), we found two critical thresholds of the GIS and explored the critical cumulative $CO_2$ emission that would lead to a crossing of these thresholds: a cumulative emission of more than 1000 GtC would cause long-term mass loss of the southern part of the GIS associated with a global long-term sea level rise of 1.8 m. For a cumulative emission of more than 2500 GtC, the entire ice sheet would melt in the long term, associated with a global sea level rise of ≈7 m.

In particular the first threshold is of immediate importance as half of the critical cumulative $CO_2$ emission to cross this threshold—about 500 GtC—have already been released into the atmosphere. If the current annual anthropogenic emission rate of ≈10 GtC $yr^{-1}$ remains constant in the future, this critical threshold would be crossed in ≈50 years.

The southern part of the GIS would not melt instantaneously as temperature rises. If future technologies allow for atmospheric carbon removal at the scale of many gigatons carbon per year, it might be possible to bring the atmospheric $CO_2$ concentration back to its pre-industrial level. However, whether or not long-term mass loss of the GIS would thereby be avoided not only depends on the cumulative carbon emission but also on the elapsed time until the pre-industrial level of atmospheric $CO_2$ is restored.

In this paper, we investigate how mass change of the GIS would respond to different anthropogenic cumulative $CO_2$ emissions followed by artificial carbon removal. We explore different cumulative $CO_2$ emission scenarios as well as different time spans of elevated atmospheric $CO_2$ concentrations before artificial carbon removal. Specifically, we focus on the question of to what extent the GIS could be melted so that it would still regrow in case future technologies were able to reduce the atmospheric $CO_2$ concentration back to its pre-industrial level.

## 2. Methods

As in Höning *et al* (2023), we use the fully coupled Earth system model of intermediate complexity CLIMBER-X (Willeit *et al* 2022, 2023a, 2023b). The model includes the 3D polythermal ice sheet model SICOPOLIS v5.1 (Greve 1997), which is applied to the GIS at a horizontal resolution of 16 km. Due to the relatively coarse resolution of the ice sheet, we include a parameterization for ice discharge into the ocean (Calov *et al* 2015). The interface between the ice sheet and the atmosphere is modelled using the surface energy and mass balance scheme SEMI (Calov *et al* 2005). A representation of the global carbon cycle is also included (Willeit *et al* 2023a).

A characteristic feature of CLIMBER-X is the fully coupled climate-ice sheet-carbon cycle model setup and the use of a physically based surface energy and mass balance interface. In Höning *et al* (2023), we compared the SMB from historical runs with CLIMBER-X using prescribed ice sheets with regional climate models and found differences in the spatial patterns but good agreement of the integrated SMB. For more details, the reader is referred to Höning *et al* (2023).

For the sake of simplicity, the orbital configuration is kept constant at its present-day state. We initialize the GIS using present-day observations and an ice temperature of $-10\,^\circ$C and let the model run for 10 kyr, allowing the ice sheet to reach a quasi-equilibrium. We then force the fully-coupled climate–ice sheet–carbon cycle model with different $CO_2$ emission pulses with cumulative emissions between 0 and 4000 GtC, evenly spread throughout a time interval of 100 yr. $CO_2$ is an interactive part of the system and we let the system respond to the elevated atmospheric $CO_2$ concentration for a fixed period of 1, 2, and 5 kyr. After that, we mimic net carbon removal by prescribing the atmospheric $CO_2$ concentration to exponentially decrease towards zero and keep it constant as soon as it reaches its pre-industrial value after 1 kyr. In addition, we test a rapid $CO_2$ removal scenario starting 100 yr after the emission pulse and with a duration of 500 yr. Compared to applying a negative emission pulse, our approach has two significant advantages: First, it bypasses the problem that the carbon removal rate would be required to be continuously adjusted to keep the $CO_2$ level at pre-industrial values as $CO_2$ keeps being released from the oceans and other Earth system components over long timescales. Secondly, it avoids the problem that if carbon removal is applied at a too high rate, the atmospheric $CO_2$ concentration could temporally be smaller than its pre-industrial value.

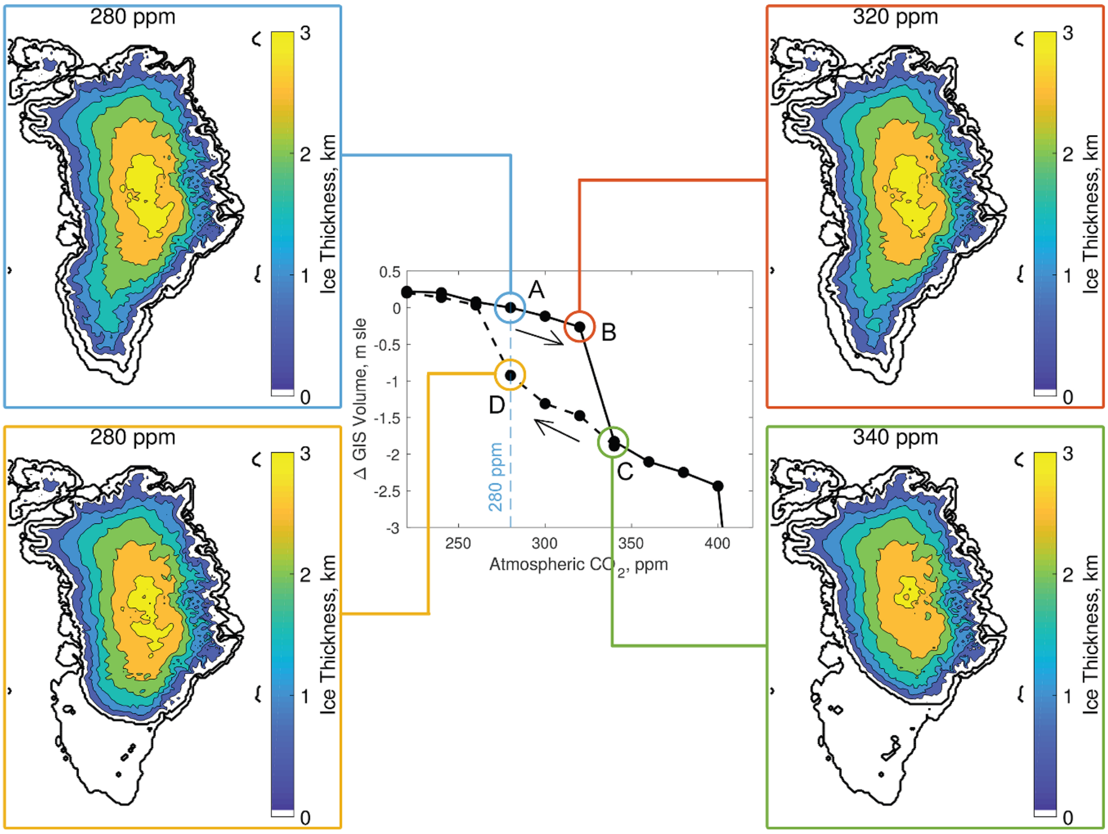


**Figure 1.** Equilibrium states of the GIS volume for fixed atmospheric $CO_2$ concentrations starting from pre-industrial GIS following the path of increasing $CO_2$ (solid black curve) and from point B following the path of decreasing $CO_2$ (dashed curve). States A and D both refer to equilibrium states of the GIS at pre-industrial atmospheric $CO_2$, of which state D is reached when starting from the ice sheet at point C reducing atmospheric $CO_2$. The hysteresis diagram covers the upper part of the hysteresis diagram in figure 1 of Höning *et al* (2023).

The exponentially-shaped decline towards the pre-industrial level is motivated by the fact that carbon removal is more efficient at higher atmospheric $CO_2$ concentrations (e.g. Tokarska and Zickfeld 2015). We neglect changes in short-lived greenhouse gases like methane in our study, since these are less relevant on the timescale associated with melting of the GIS. Consideration of non-$CO_2$ greenhouse gases would influence our quantitative results, but not to such an extent that our qualitative conclusions would change.

## 3. Results

To explore the response of the GIS volume to changes in the atmospheric $CO_2$ concentration, we first focus on equilibrium states of the GIS (figure 1), adapted from Höning *et al* (2023). These states have been derived by running the model at constant atmospheric $CO_2$ concentration until the GIS volume changes at rate smaller than 1 mm kyr$^{-1}$. Starting from the pre-industrial GIS (state A) and increasing atmospheric $CO_2$, the GIS follows the solid black curve and passes through a bifurcation point between B and C, thereby melting its southern part. If, starting at point C, the atmospheric $CO_2$ is reduced again, the GIS follows the dashed black curve and reaches state D at 280 ppm where still a large part of the south remains melted. We note that these states are equilibrium states and that even a short overshoot of a bifurcation point would not necessarily cause the system to irreversibly transition to another stable state.

In our model runs with interactive $CO_2$, cumulative emissions between 0 and 4000 GtC result in an elevated atmospheric $CO_2$ concentration that naturally starts declining shortly after the end of the pulse (figure 2(a)). After 1 kyr (solid), 2 kyr (dashed), and 5 kyr (dashed-dotted curves), the atmospheric $CO_2$ concentration is set to exponentially decrease until it reaches its pre-industrial value throughout an additional time interval of 1 kyr, thereby mimicking net negative emissions. The atmospheric $CO_2$ concentration controls the global mean temperature (figure 2(b)). The global mean temperature anomaly temporally rises up to 6°C for cumulative emissions of 4000 GtC and then continues to follow the fate of declining atmospheric $CO_2$. Elevated temperatures

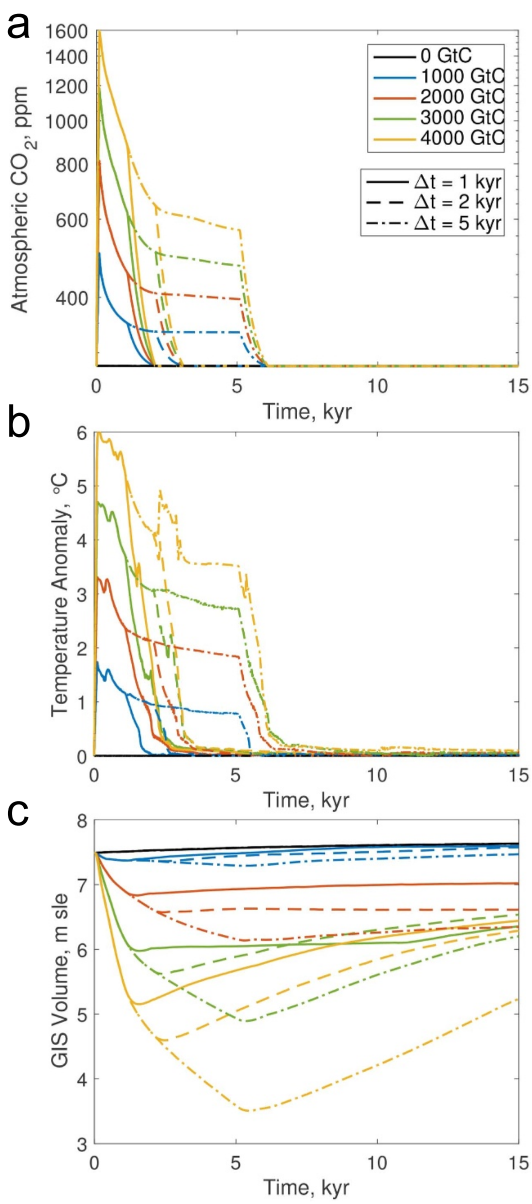


**Figure 2.** Simulated (a) atmospheric $CO_2$ concentration, (b) global mean temperature anomaly relative to pre-industrial, and (c) GIS volume as a function of time after cumulative emission pulses of 0 (black), 1000 GtC (blue), 2000 GtC (red), 3000 GtC (green), 4000 GtC (yellow). After a time span $\Delta t$ of 1 kyr (solid), 2 kyr (dashed), and 5 kyr (dashed-dotted), the atmospheric $CO_2$ concentration is exponentially reduced until it reaches its pre-industrial value after a time interval of 1 kyr and then kept constant.

cause a melting of the GIS (figure 2(c)): while small cumulative emissions (1000 GtC, blue curve) lead to only limited mass loss, if at all, higher emission pulses cause significant mass loss, in particular if a long time passes until the atmospheric $CO_2$ concentration is reduced to its pre-industrial value. It also becomes apparent that once the GIS loses mass to a certain extent (by $\approx$1 m sea level equivalent sle, such as for 2000 GtC and $\Delta t = 2$ kyr, dashed red curve), the ice sheet does not regrow to its pre-industrial state even after the atmospheric $CO_2$ is reduced accordingly.

The combination of cumulative $CO_2$ emission and time interval $\Delta t$ before negative $CO_2$ emissions are applied controls the total mass loss and regrowth of the GIS (figure 3). The fact that the points corresponding to different combinations (colors and shapes of the points in figure 3) lie on the same single line indicates that regrowth of GIS depends on the total mass loss prior to $CO_2$ removal, rather than on a specific trajectory. Therefore, the two parameters—cumulative $CO_2$ emission and time span $\Delta t$—can be reduced to single one: the total mass loss before negative $CO_2$ emission. If the total mass loss before $CO_2$ reduction is small due to small cumulative emission and/or small $\Delta t$ (i.e. points plotted on the left, light red area in figure 3), the GIS can efficiently regrow (small y-values in figure 3(d)). However, once the ice volume crosses a

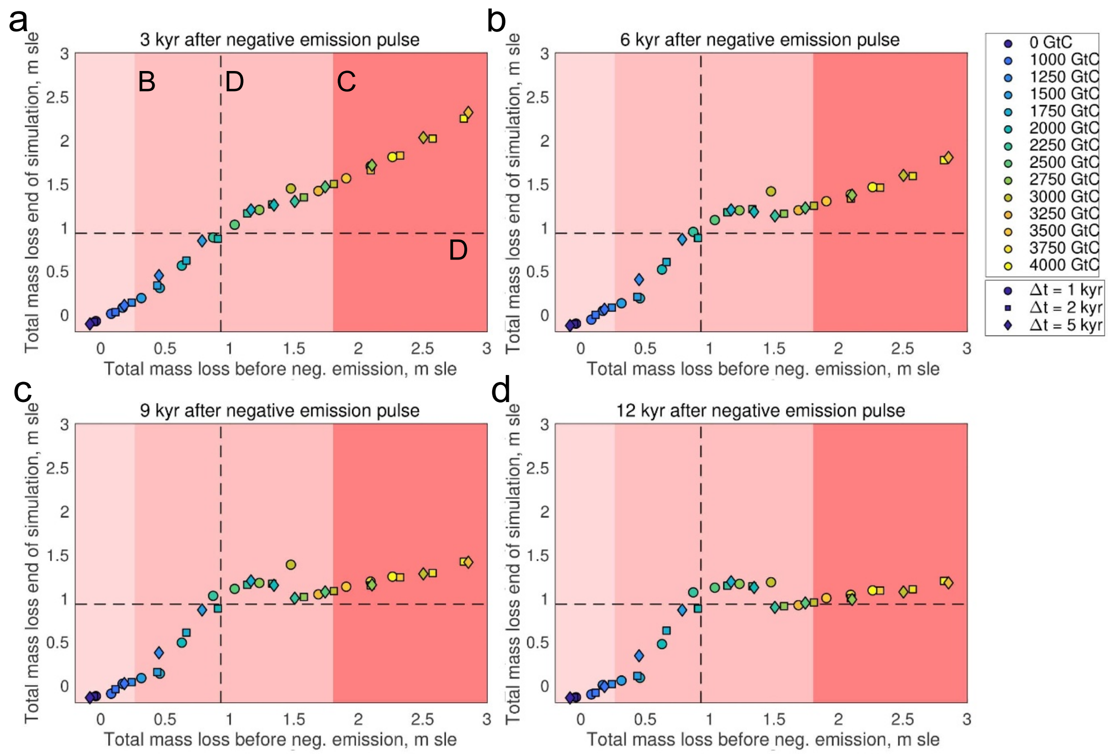


**Figure 3.** Total GIS volume anomaly (relative to pre-industrial) at the end of the simulation ($y$-axes) as a function of total GIS volume anomaly right before negative emissions are applied ($x$-axes). End of simulation is (a) 3 kyr, (b) 6 kyr, (c) 9 kyr, and (d) 12 kyr after the pre-industrial atmospheric $CO_2$ level has been restored. Model simulations include cumulative emission pulses between 0 (blue) and 4000 GtC (yellow) and the time span $\Delta t$ between the positive emission pulse and the reduction of $CO_2$ to pre-industrial is 1 kyr (circle), 2 kyr (square), and 5 kyr (diamond). In the left, light-red column of each sub-figure, the southern part of the GIS is frozen, in the centre column it is partly melted, and in the right, dark-red column, it is completely melted. The transitions between these columns of 0.26 m sle and 1.8 m sle refer to points B and C in figure 1. The dashed, black lines of 0.93 m sle refers to state D, which is the equilibrium GIS volume anomaly (relative to pre-industrial) for an atmospheric $CO_2$ concentration of 280 ppm if started from point C and subsequently reducing atmospheric $CO_2$ (dashed curve in figure 1).

critical threshold (near the transition to the mid-red column), complete GIS regrowth is inhibited. This transition is termed point B and separates an ice-covered and a partly melted southern part of the GIS. The transition towards the right, dark-red column is termed point C and indicates the transition towards a completely melted southern part of the GIS. The vertical dashed black line (point D) depicts the equilibrium GIS volume anomaly at 280 ppm if started from point C reducing $CO_2$. We also plot this value as a horizontal black dashed line, depicting the ice regrow after $CO_2$ reduction. We observe that GIS only regrows to this state: once the southern part of the GIS is (partly) melted, this part will not regrow, even if atmospheric $CO_2$ is reduced to pre-industrial levels.

## 4. Discussion

Future artificial carbon removal from the atmosphere is a potential concept to reduce the atmospheric $CO_2$ concentration in order to limit global warming or even to restore pre-industrial climate conditions. In this paper, we tested this concept with a focus on the crossing of critical thresholds of the GIS that could inhibit regrow. We found that once the GIS has lost mass by more than ≈0.4 m sle, it would not regrow if atmospheric $CO_2$ is reduced to pre-industrial, independent of the particular combination of cumulative $CO_2$ emission and time interval before deploying artificial carbon removal. Once the GIS has lost mass by more than ≈0.9 m sle, artificial carbon removal could only lead to a regrow of the GIS up to this value (0.9 m sle mass loss relative to pre-industrial), but not further. The reason for this is the multistability of the GIS due to positive feedback mechanisms. For example, an increase in surface melt enlarges the area at lower elevations exposed to higher air temperatures, which in turn leads to enhanced melt. If a critical threshold is crossed, the equilibrium ice volume would decrease substantially and would not recover even if global temperature declines again (Charbit *et al* 2008, Ridley *et al* 2010, Robinson *et al* 2012, Solgaard and Langen 2012). In our simulations, the multistability is related to a melting of the southern part of the GIS (compare figure 1).

Theoretically, atmospheric $CO_2$ could be reduced below pre-industrial values, which could allow a regrowth of the GIS despite crossing critical thresholds (compare Höning *et al* 2023). However, we consider this an extremely unlikely scenario, as already bringing down $CO_2$ to pre-industrial levels can be considered a big challenge. Reducing $CO_2$ below pre-industrial levels would also be undesirable as it could trigger a glacial inception over other NH continents, considering that we are at present close to a minimum in NH summer insolation and it has been suggested that at pre-industrial $CO_2$ concentrations we were close to the bifurcation point to trigger glacial inception (Ganopolski *et al* 2016, Talento *et al* 2023).

Ridley *et al* (2010) used the atmosphere-ocean general circulation model HadCM3 (Pope *et al* 2000) to study the reversibility of mass loss of the GIS and derived its initial state from a single, high-$CO_2$ scenario. They found that after restoring pre-industrial atmospheric $CO_2$ levels, the GIS converges towards three distinct steady states, a pre-industrial GIS, a melted GIS, and an intermediate state. The threshold that prevents the GIS from complete regrowth was found to lie between 80 and 90% of the pre-industrial GIS volume (Ridley *et al* 2010). This range corresponds to a total mass loss of the GIS between 0.75 and 1.5 sle. In contrast, in the present paper, we used a fully coupled climate-ice sheet-carbon cycle model, which allowed us to combine different $CO_2$ emission pulse scenarios with different time intervals during which the climate-ice sheet model responds to the elevated temperatures. This approach yields a variety of mass loss scenarios of the GIS that can directly be traced back to the respective emission scenario. Instead of distinct steady states that the GIS approaches, we found that between 0.4 and 0.9 m sle total mass loss, that GIS mass volume hardly changes after the pre-industrial level of atmospheric $CO_2$ has been restored. This result implies irreversible mass loss of the GIS starting much earlier (for mass loss >0.4 m sle) than found by Ridley *et al* (2010), although a crossing of this threshold would not apply further, inevitable mass loss towards another steady state after restoring pre-industrial atmospheric $CO_2$ but rather inhibited regrowth.

Simulating the emission pulses, we assumed an even distribution throughout a time interval of 100 yr, which allows for a straightforward comparison between different cumulative emission scenarios. While the specific shape of the emission pulse may affect mass loss of the GIS within the first few hundred years, it becomes negligible on a millennia timescale (Charbit *et al* 2008, Höning *et al* 2023), which is the timescale relevant in this paper.

Instead of applying negative $CO_2$ emissions pulses, with the onset of artificial carbon removal, we mimicked the latter by prescribing the atmospheric $CO_2$ concentration to decrease exponentially until it reaches its pre-industrial level over a fixed time interval of 1 kyr and then kept the $CO_2$ concentration constant. Again, the specific shape of carbon removal is not important for the long-term evolution of the GIS, and our choice has the advantage that the carbon sink does not need to be continuously adjusted when oceans and land reservoirs continue to release $CO_2$ into the atmosphere over hundreds of years.

Given the large timescale of several tens of thousands of years needed to simulate mass loss and regrowth of the GIS, we chose a relatively coarse ice sheet resolution of 16 km. Using a finer ice sheet resolution would probably be needed to simulate the fate of the ice sheet on a centennial timescale, but on a timescale >1 kyr as relevant for this study, the choice of the resolution is less important (Aschwanden *et al* 2019).

The choice of the ice sheet model SICOPOLIS could also have an effect on our results. Essential for our findings is the existence of an intermediate stable state where the southern part of the GIS is melted. Using the ice sheet models PISM (Winkelmann *et al* 2011) and Yelmo (Robinson *et al* 2020), Bochow *et al* (2023) explored the response of the GIS to temperature forcing overshooting critical thresholds. While they found several intermediate states between 50% and 90% of the current GIS at 1 °C global mean temperature anomaly with PISM, the ice sheet model Yelmo did not show an intermediate stable state. Both ice sheet models showed a modest sensitivity to warming in the southwest part (Bochow *et al* 2023). Similar to our results, Bochow *et al* (2023) concludes that both peak warming at AD 2100 and a reduction of temperature after centuries are essential to mitigate a critical loss of the GIS.

Another key factor of uncertainty is related to the equilibrium climate sensitivity (ECS). The ECS in the standard model is 3 K, which is the best current estimate (IPCC 2021). However, values of 2 K on the lower end and 4.5 K on the upper end cannot be ruled out. To explore the effect of this uncertainty, we have rerun all simulations mimicking ECS values of 2 K and 4.5 K and show the results in figures 4(a)–(f).

As expected, for an ECS of 2 K (figure 4, top row), the temperature anomaly rises up to 4 °C for an emission pulse of 4000 GtC (compared to up to 6 °C for the reference model with a climate sensitivity of 3 K (figure 4(b)), and melting of the GIS is correspondingly smaller (figure 4(c)). Figure 5 indicates that the total mass loss at the end of the simulation as a function of total mass loss directly before the negative emission pulse follows the same single curve as before, with some outliers at high cumulative

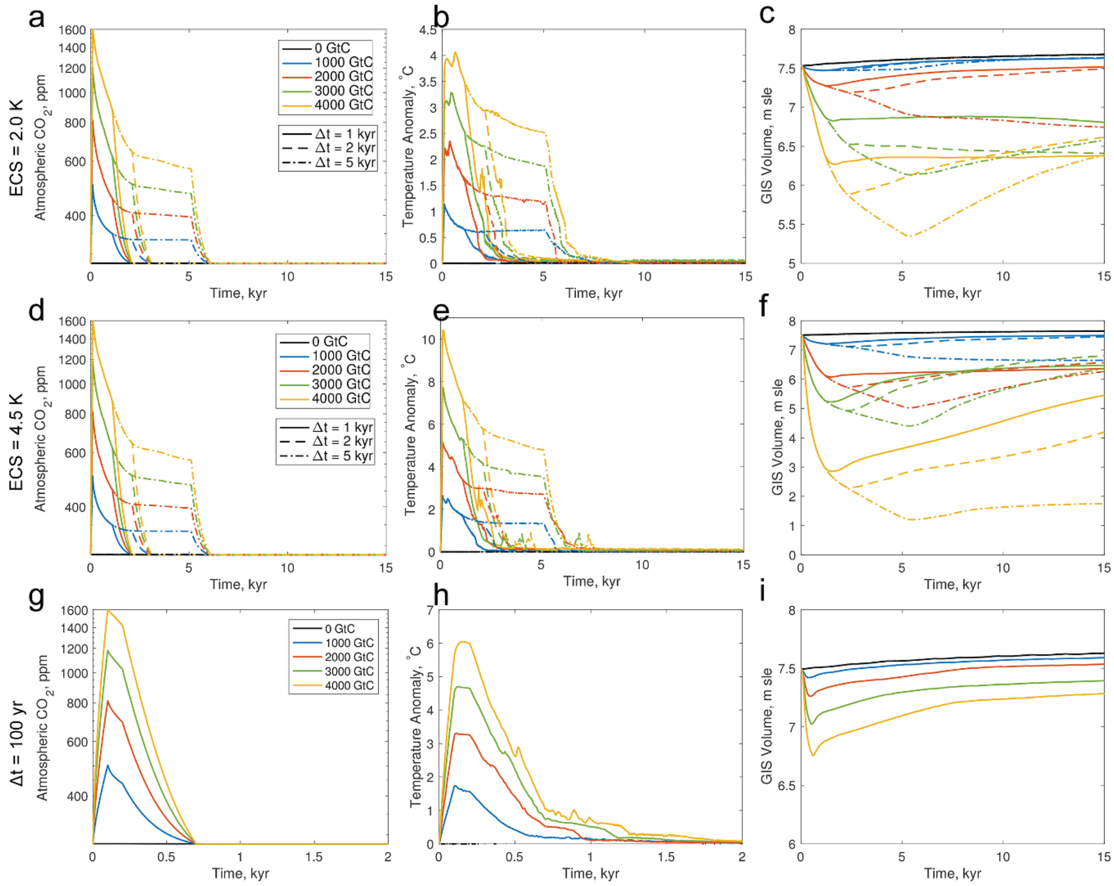


**Figure 4.** Model results using a climate sensitivity of 2 K (top row) and 4.5 K (centre row). The time span before negative emissions are applied is 1 kyr (solid), 2 kyr (dashed) and 5 kyr (dashed-dotted), and as in figure 3, the duration of negative emissions is 1 kyr. The bottom row corresponds a scenario of rapid negative emissions (time span before negative emissions are applied of 100 yr and duration of negative emissions of 500 yr), while the climate sensitivity is 3 K.

emissions, which we attribute to the circulation of the southern ocean (not shown here). For cumulative emissions between 1500 and 2250 GtC (depending on the time span before atmospheric $CO_2$ is reduced), melting of the GIS is so extensive that a complete regrowth is inhibited even if the pre-industrial level of atmospheric $CO_2$ is restored. For a climate sensitivity of 4.5 K (figure 4, centre row), melting of the GIS is irreversible already for cumulative emissions about 1000 GtC for a time span before atmospheric $CO_2$ is reduced of 1 kyr.

Finally, melting of the GIS takes time, and in our reference model, we tested time spans before restoring the pre-industrial level of atmospheric $CO_2$ of 1, 2, and 5 kyr and then reduced atmospheric $CO_2$ throughout an interval of 1 kyr. Certainly, if artificial carbon removal techniques that are able to remove significant amounts of carbon from the atmosphere were deployed in large quantities within the next decades or centuries, pre-industrial levels of atmospheric $CO_2$ might be restored before the GIS has lost significant mass (≈0.4 m sle). Figure 4 (bottom row) shows model results using a time span before atmospheric $CO_2$ is decreased of 100 yr and a time interval throughout which atmospheric $CO_2$ is decreased of 500 yr (figure 4(a)). We find that in this case even high emissions of 4000 GtC are not sufficient to significantly melt the GIS and restoring its pre-industrial state is therefore feasible. However, this endeavour would require to remove hundreds to thousands of Gt carbon from the atmosphere within the next few centuries. Given the long timescales associated with ice sheet mass loss and regrowth, this carbon would then be needed to be stored over millennia, which only leaves a limited number of relevant carbon removal techniques such as enhanced rock weathering and direct air carbon capture and storage (IPCC 2022). With ongoing anthropogenic $CO_2$ emissions, pursuing this option would become more and more challenging. Therefore, limiting anthropogenic carbon emissions remains a key factor to avoid irreversible melting of the GIS.

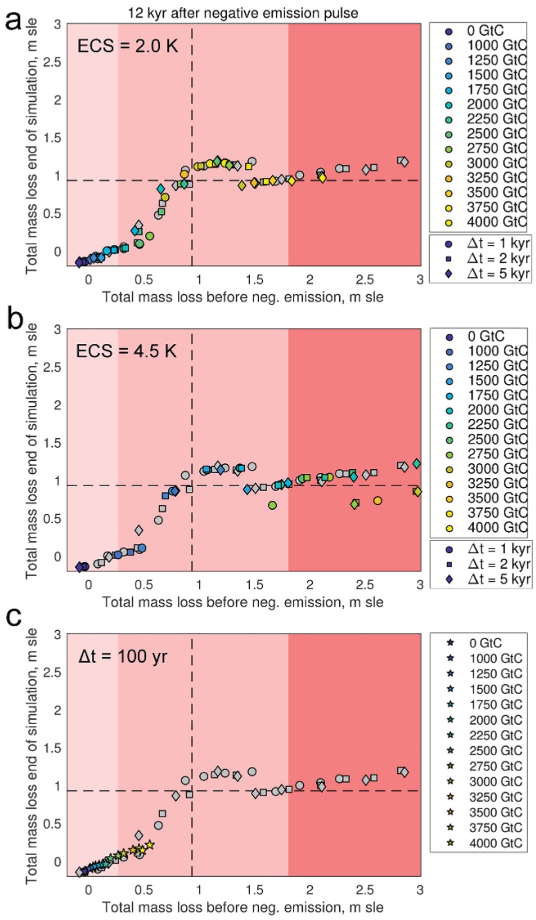


**Figure 5.** Total mass loss 12 kyr after the negative emission as a function of the total mass loss before the negative emission. (a) Climate sensitivity of 2 K, (b) climate sensitivity of 4.5 K, and (c) a scenario of rapid negative emissions with a time span before negative emissions are applied of 100 yr and a duration of negative emissions of 500 yr (compare figure 4). For comparison, the results from our reference model (figure 3) are plotted in grey colour.

## 5. Conclusions

Using the Earth system model of intermediate complexity CLIMBER-X, we explored whether future artificial $CO_2$ removal could lead to a regrowth of the GIS once it has partly melted. We found that once anthropogenic $CO_2$ emissions and associated global temperature rise cause the southern part of the GIS to partly melt with a decrease of the total GIS volume by more than ≈0.4 m sle, complete regrowth is inhibited even if the pre-industrial level of atmospheric $CO_2$ is restored. This finding is attributed to the hysteresis behaviour of the GIS (see also Robinson *et al* 2012, Höning *et al* 2023).

The critical cumulative carbon emission that causes a crossing of this threshold depends on the time before negative emissions are realised but also on model-specific parameters, above all the climate sensitivity. For example, for the currently best estimate of a climate sensitivity of 3 K, the threshold is crossed for cumulative emissions between 1250 and 1500 GtC if atmospheric $CO_2$ is artificially reduced 1 kyr after the emission pulse, but also for cumulative emissions between 1000 and 1250 GtC if $CO_2$ is artificially reduced 5 kyr after the emission pulse. Allowing for the whole possible range of values for the climate sensitivity between 2 and 4.5 K widens the critical cumulative carbon emission: for example, if $CO_2$ is artificially reduced 1 kyr after the emission pulse leaves a range between 1000 to 2250 GtC for the critical cumulative carbon emission. In our simulations, only immediate removal (that is, a few centuries after the emission) can avoid long-term mass loss of the GIS.

Despite these quantitative uncertainties, our results highlight the risk that relying on future artificial $CO_2$ removal techniques while $CO_2$ continues to accumulate in the atmosphere could cause the Earth system to cross critical thresholds if artificial $CO_2$ removal is utilized too late. $CO_2$ removal to restore the pre-industrial level could then avoid further mass loss but would not cause a re-build of the pre-industrial GIS. Keeping cumulative anthropogenic $CO_2$ emissions below the critical range of ≈1000–1500 GtC is therefore the only save way to avoid significant, irreversible mass loss of the GIS.

## Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.5281/zenodo.10357656.

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