Future Greenland Melt on Multi-Century and Multi-Millennial Time Scales assessed with the Community Ice Sheet Model version 2.1

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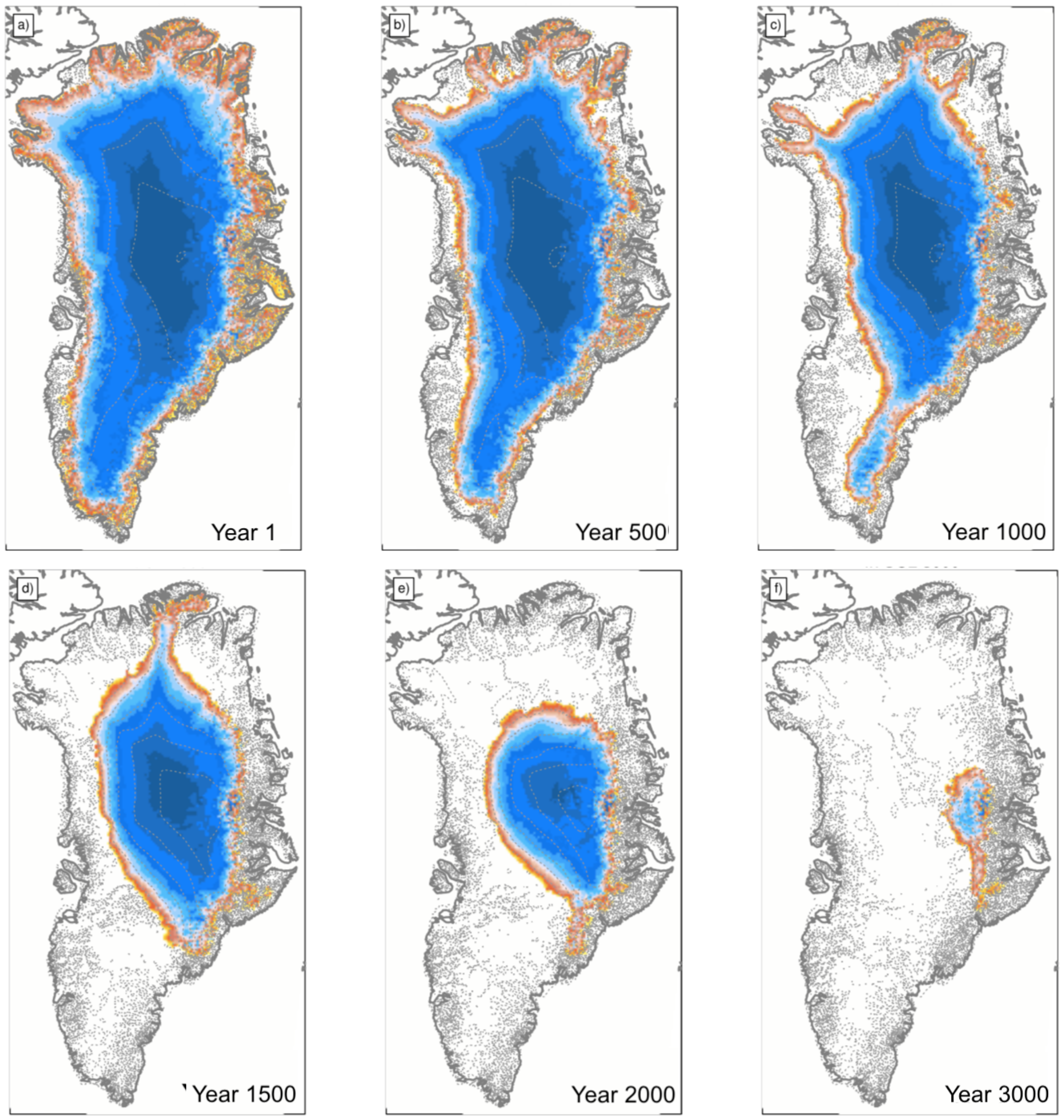

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Abstract

The Greenland Ice Sheet is the world's second largest ice sheet, storing an equivalent of 7.3 meters of sea level rise. Due to climate change, the Greenland ice sheet is currently losing mass at an accelerated rate. Ice sheet models are used to project long term melt of the ice sheet, which are often forced by output from climate models. Most of the multi-millennium time scale ice sheet simulations conducted in the past used SMB calculations based on empirical relationships between melt and temperature (Positive-Degree Day schemes).

In this thesis, I address the question of the future evolution of the Greenland ice sheet by means of an ice sheet model forced with an elevation dependent SMB field that accounts for the energy available for melt. This work focuses on key variables such as ice thickness, ice area, velocity and contribution to eustatic sea level rise, and assesses the reversibility of the mass loss. For this thesis, I performed uncoupled CISM2.1 simulations which were forced by the elevation-SMB field from a coupled CESM-CISM simulation. The coupled simulation used to force the ice sheet has a length of 160 years and a CO_2 concentration that is increased with 1% per year from pre-industrial levels and capped at 4 times CO_2. Time segments with 2x, 3x and 4x pre-industrial CO_2 concentrations of this CESM-CISM run were used to force the ice sheet on multi-millennium time-scales. In addition, a Recovery from 4x CO_2 was conducted in which the pre-industrial forcing from a coupled CESM-CISM simulation is re-introduced after 55% mass loss.

The 2x, 3x and 4x CO_2 scenarios resulted in a cumulative sea level rise of 0.49 m, 3.0 m, and 8.2 m by year 4,000. The 2x CO_2 scenario resulted in limited retreat and stability within 4,000 years. No stability of the ice sheet was attained by year 8,000 in the 3x CO_2 simulation, with a final Mass Balance of -108.8 Gt/yr (0.30 $\pm$ mm/yr). The 4x CO_2 simulation resulted in the complete deglaciation of the ice sheet within 3,000 years. Despite the lower initial topography compared to the pre-industrial ice sheet, the Recovery from 4x CO_2 simulation resulted into expansion of the ice sheet. Within 4,000 years, the mass increased from 46% to 67% relative to the pre-industrial ice sheet.

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Preface

This thesis is the product of months of work and is the conclusion of my Master Degree at the Delft University of Technology. I have always been interested in climate change and the cryosphere, so I am therefore glad I had the opportunity to work on the topic and to contribute towards the field.

I would like to thank everyone who have supported me during my thesis. First of all, I want to thank Miren Vizcaino and Laura Muntjewerf for supervising this thesis. I would furthermore like to thank the assessment committee, Riccardo Riva and Stef Lhermitte for their feedback on the thesis.

In addition, I would like to thank my fellow Geoscience and Remote Sensing students who worked in room 3.53, for their discussions, support as well as coffee breaks.

Finally, I would like to thank my friends and my family for always supporting me.

List of Abbreviations

Abbreviation	Full Name
AOGCM	Atmosphere Ocean General Circulation Model
CESM	Community Earth System Model
CIME	Common Infrastructure for Modelling the Earth
CISM	Community Ice Sheet Model
CLM	Community Land Model
DDF	Degree Day Factors
ESM	Earth System Model
ISM	Ice Sheet Model
NAMOC	North Atlantic Meridional Overturning Circulation
NEGIS	Northeastern Greenland Ice Stream
MB	Mass Balance
PDD	Positive Degree-Day: scheme to derive SMB with empirical relationships.
SEB	Surface Energy Balance: scheme to derive SMB with energy available for melt.
SLR	Sea Level Rise
SMB	Surface Mass Balance
SNICAR	Snow Ice and Aerosol Radiative Model
RCP	Representative Concentration Pathways

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Chapter 1

Introduction

The Greenland ice sheet is the second largest ice volume in the world, storing an equivalent of more than 7.3 meters of eustatic sea level rise (Bamber et al., 2013). Due to climate change resulting from anthropogenic greenhouse gas emissions, the Greenland ice sheet is loosing mass at an accelerating rate (see Rignot et al., 2011). It is likely that the Greenland ice sheet will continue to melt, not only on multi-century time-scales, but also on multi-millennium time-scales (e.g. Huybrechts & de Wolde, 1999, Ridley et al., 2005). The evolution of melt is shown to be dependent on the climate forcing scenario (Vizcaino et al., 2015), while the amount of CO_2 emissions is shown to affect the irreversible decline of the Greenland ice sheet (Charbit et al., 2008). As the melt of the ice sheet could result into more than 7 meters of sea level rise, it is important to understand and simulate the melt evolution of the Greenland ice sheet on multi-century and multi-millennium time scales.

In the literature, there are ample of examples of multi-century and multi-millennium Greenland ice sheet simulations (Huybrechts & de Wolde, 1999, Ridley et al., 2005, Vizcaino et al., 2015). Often, these multi-millennium time-scale simulations use temperature index model which parameterizes the Surface Mass Balance (SMB) by temperature. These Positive Degree-Day (PDD) schemes are often tuned towards the present day ice sheet and were shown to be more sensible to warming (Bougamont et al., 2007, Fitzgerald et al., 2012). A more sophisticated method to deriving the SMB is the Surface Energy Balance (SEB) scheme, which accounts for the available energy for melt. However, future Greenland projection that use SEB schemes are rare in literature.

In addition, multi-millennium simulations of the Greenland ice sheet that are fully coupled with the climate system are computationally expensive. As a result, two-way coupled simulations are less suitable to attempt a large variety of multi-millennium time-scale runs. Uncoupled ice sheet simulations do not incorporate the interactions between the ice sheet and the climate, but are computationally cheaper.

The Community Ice Sheet Model version 2.1 (CISM2.1) enables computationally cheap uncoupled ice sheet simulations, while accounting for the SMB-elevation feedback. CISM2.1 is the ice sheet component of the Community Earth System Model version 2.1 (CESM2.1). By using this ice sheet model in combination with CESM2.1, it is possible to force the ice sheet with an elevation dependent SMB field provided by a previously conducted CESM2.1 simulation. Due to the elevation dependency of the SMB field, changes in the surface elevation within CISM2.1 will results into alterations in the SMB even if the climatological forcing is constant (Lipscomb et al., 2018). In addition, the climate model used to derive the forcing, the Community Earth System Model version 2.1 (CESM2.1) calculates the SMB with a SEB scheme which is a more sophisticated method to derive the SMB compared to the widely used PDD schemes (Vizcaíno et al., 2013). As a result, the SEB scheme and the elevation dependent SMB forcing derived from CESM2.1 are suitable for uncoupled multi-millennium time-scale simulations.

1.1 Research Objectives and Approach

In this thesis, multi-millennium time-scale CISM2.1 simulations were forced by an elevation dependent SMB field. The CISM2.1 simulations were used to answer a main question and three sub questions. The main question is stated as following:

What is the response of the mass, area as well as the ice sheet velocity and equivalent sea level rise on multi-century and multi-millennium time-scales towards Greenhouse forcing scenarios when assessed by CISM2.1?

To answer this main research question, uncoupled CISM2.1 runs were conducted that were forced by an elevation dependent SMB field obtained from a fully coupled CESM2.1 simulation. Two coupled runs were used to base the SMB forcing; a pre-industrial simulation and a 1% to 4x CO_2 simulations. The latter starts at pre-industrial CO_2 concentrations and increases increases with 1% until 4 times pre-industrial levels are reaches. Based on the 1% increase to 4x CO_2 simulation, three simulations were conducted with a transient climate; 2x, 3x and 4x CO_2.

Additional sub-question will also be answered during this thesis:

1. **What are the effects of the greenhouse forcing scenarios on the ice sheet evolution?**
   The three transient forcing scenarios; 2x, 3x and 4x CO_2 are compared to determine the effects of the climate warming towards the evolution of melt of Greenland. The time-series as well as SMB, thickness and velocity maps of Greenland will be compared to asses the rate and extent of melt to determine the differences between the simulations.

2. **What is the response of the Humboldt, Jacobshavn and Hellheim glaciers to greenhouse forcing scenarios**
   The Humboldt, Jacobshavn and Hellheim glaciers are amongst the largest glaciers of Greenland and can be found in three different areas of Greenland: the North-West, West and South-East of Greenland. Transects of these three glaciers are compared in terms of Surface Mass Balance, Velocity and Elevation forced by transient 2x, 3x and 4x CO_2 climates.

3. **What is the response of a partially deglaciated Greenland towards re-introducing the pre-industrial climate**
   To answer this sub-question, a Recovery from 4x CO_2 simulation was conducted. This simulation re-introduces pre-industrial forcing to the ice sheet after 55% mass loss. The Recovery from 4x CO_2 simulation was conducted in an attempt to asses whether the ice sheet continues to deglaciate as a result of the SMB-elevation feedback or starts to gain mass.

1.2 Outline

First of all, in **chapter 2** I discuss relevant literature concerning the melt of the Greenland ice sheet. Important concepts such as the Surface Mass Balance and Mass Balance are introduced, as well as the schemes that are generally used to derive the Surface Mass Balance. The elevation feedback is introduced as well as literature on multi-century and multi-millennium time-scale simulations.

Chapter 3 discusses the methods used for this thesis, which includes the description of the relevant models. CISM2.1 is introduced as well as the climate model CESM2.1 and the land model component CLM (Community Land Model). The coupling between CISM2.1 and CLM is discussed and the simulations that were conducted are introduced.

The results of the simulations are introduced and analysed in **chapter 4**. The simulations are compared to existing literature and limitations are discussed in **chapter 5**. Final conclusions as well as recommendations for further research are reported in **chapter 6**.

Chapter 2

Literature Review

This chapter focuses on literature covering Greenland ice sheet melt on multi-century and multi-millennium time-scales. First of all, some concepts are introduced that are important to understanding Greenland melt. Secondly, melt feedbacks are introduced, with an emphasis on the SMB-elevation feedback. Thirdly, at the end of this chapter, literature concerning Greenland ice sheet melt with a focus on idealised forcing scenarios on multi-century and multi-millennium time-scales are discussed.

2.1 Background

This section introduces the concepts that are important for understanding Greenland melt. First of all, an introduction is given on greenhouse gasses and sea level rise. Secondly, two important terms: Surface Mass Balance and Mass Balance are explained in detail.

2.1.1 Greenhouse Gas Concentration and Emission Scenarios

Due to anthropogenic CO_2 emissions, the atmospheric CO_2 concentration has increased from pre-industrial concentrations at 280 ppm to 410 ppm at the time of writing. The CO_2 concentration will continue to rise in the future. However, the evolution of this increase, as well as the concentration reached are dependent factors such as population growth, economic development, as well as emission mitigation and carbon capture strategies. The evolution and amount of melt of the Greenland ice sheet is dependent on these climate forcing scenarios. Due to this uncertainty, there are several well-defined greenhouse gas scenarios which are commonly used in literature.

First of all, a commonly used forcing scenario are the RCP (Representative Concentration Pathways) scenarios (see Van Vuuren el al., 2011). These scenarios describe more realistic emission scenarios which are based on factors such as population growth and economic development. There are several RCP scenarios, which range from a low emission scenario (RCP 2.6), two intermediate scenarios (RCP 4.5 and RCP 6.0) to a business as usual scenario (RCP 8.5). While I discuss literature that used these scenarios for future Greenland ice sheet projections, none of RCP scenarios were used to force the ice sheet in any of the simulations conducted during this thesis. Instead, an idealised CO_2 scenario was used. In these idealised scenarios, the CO_2 concentration starts at pre-industrial levels (280 ppm) which is then increased by 1, or 2% per year. Eventually, the CO_2 concentration is capped at a specific threshold. This threshold is often 4 times pre-industrial CO_2 concentrations, but other thresholds such as 2 times pre-industrial CO_2 concentrations are used.

Later in this chapter, I discuss literature concerning both RCP, and more idealised climate scenarios on multi-century and multi-century time scales. In chapter 3, I discuss in detail which forcing scenarios were considered during this thesis.

2.1.2 The Surface Mass Balance and Mass Balance

This thesis, the melt rate and evolution of the Greenland ice sheet is assessed in terms of velocity, mass, area as well as the Surface Mass Balance (SMB), Mass Balance (MB) as well as the change in elevation, area, mass and equivalent sea level rise. At the surface of the ice sheet, snow results into mass increase and mass is lost as a result of melt and sublimation. Iceberg calving at the margins results into further mass loss which is presently comparable to the budget of accumulation and ablation. Furthermore, some mass is lost at the base of the ice sheet as a result of geothermal heating. To quantify a budget for these processes, two features are often used: the Surface Mass Balance (SMB) and the Mass Balance (MB).

The surface mass balance describes the net accumulation and ablation at the surface of the ice sheet. At the surface of the ice sheet, mass is added as a result of precipitation, while mass is removed due to run-off and sublimation. The SMB can therefore be described as following:

$$SMB = Precipitation - Runoff - Sublimation \tag{2.1}$$

Precipitation can be separated into rain and snow. Melt decreases the SMB, while some melt can refreeze. The SMB can therefore be written as:

$$SMB = Snowfall - Melt - Sublimation + Refreezing \tag{2.2}$$

If the SMB is positive there is net accumulation at the surface and if the SMB is negative, there is net ablation. Despite the SMB representing a local variable, the SMB is often integrated across the surface of Greenland to gain understanding of the full SMB budget. At the margins, the SMB is often negative as a result of higher temperature due to the lower elevation. The interior generally has more moderate temperatures. In South-West Greenland, there is more precipitation, and as a result, there is presently a large net positive SMB. The interior of Greenland is further removed from the coast, and at a higher elevation resulting in low SMB values. However, since this area is relatively cold the SMB is generally positive as accumulation exceeds ablation.

In the present day Greenland, mass is lost despite a positive net SMB. This is a result of a negative net Mass Balance (MB). The MB can be derived from the SMB using the following equation:

$$MB = SMB - D_{Ice\ Discharge} \tag{2.3}$$

The Mass Balance does not only incorporate surface processes, which are described by the SMB, but also includes the calving of ice at the ocean-terminating margins as well as basal melt, which takes place at the bottom of the ice sheet. Though, it is worth noting that the basalt melt is generally much smaller in magnitude compared to the calving rate, except if the ice sheet becomes fully land-terminating.

Schemes for Surface Mass Balance derivations

In Earth System Models, one of two schemes are often used to derive the SMB. First of all, the Positive Degree-Day or PDD scheme which is based on empirical relationships to calculate the SMB. For example, in a PDD scheme, snow, rainfall as well as run-off could be parameterized based on temperature. As a result, PDD schemes could becomes less accurate with time, since these parameters are based on empirical relationships. If the climate changes substantially, this relationship could become invalid. For example, Bougamont et al. (2007) showed that models using PDD schemes could be more sensitive to warming compared to Surface Energy Balance schemes. Therefore, PDD schemes could be biased for multi-millennium simulations. Most multi-millennium time-scale simulations of the Greenland ice sheet found in literature use PDD schemes to derive the SMB.

A second scheme is the Surface Energy Balance or SEB scheme. This scheme account for the amount of energy available for melt. As a result, SEB schemes are generally more realistic, but also more computationally expensive and, as stated before, are less sensitive to warming compared to the PDD scheme. This scheme is also used by the Community Land Model (CLM), which output is used to force the ice sheet model CISM2.1. In chapter 3, I discuss the calculations used by CLM to derive the SMB.

2.2 Interactions between the Climate System and the Greenland Ice Sheet

The climate affects the Greenland ice sheet which result in, for example, mass, elevation, area and albedo changes. However, these changes in the Greenland ice sheet can act as a feedback towards the climate system, therefore establishing a two-way, feedback mechanism. The Greenland melt simulations that are discussed during this thesis concern uncoupled runs of CISM2.1 with a forcing obtained from a CESM2.1. Since the CISM2.1 simulation is uncoupled, not all climate-ice sheet feedbacks are included. However, as stated before in chapter 1, CISM2.1 allows to be forced by an elevation dependent SMB, which allows the SMB-elevation feedback to be simulated.

This section, I first introduce the elevation feedback as well as some published research that derived this feedback. Secondly, other important climate feedbacks which are not incorporated in the uncoupled CISM2.1 simulations are discussed.

2.2.1 SMB-Elevation Feedback

The change in elevation acts as a positive or negative feedback to the Surface Mass Balance. This SMB-Elevation feedback is dependent on both the location as well as the geometry of Greenland. First of all, I introduce the processes that lead to the SMB-elevation feedback after which I discuss literature that quantified this feedback.

The temperature generally decreases with height, and this process is incorporated into climate models. For example, the climate model used for the simulations, CESM has a lapse rate of 6 degrees Celsius per kilometre with a constant selective humidity for Greenland (Lipscomb et al., 2013).Since the temperature is higher at lower elevations, a decrease in elevation will result into a decrease in SMB, as higher temperatures lead to more melt. The type of precipitation is also dependent on temperature. Snow is much more likely to fall under colder conditions, which results into a higher SMB compared to the same amount of rain. At higher elevations, topographic desertification can occur, reducing the amount of precipitation that is received by these areas. This desertification effects acts as a negative feedback to the SMB.

This separation between a positive and slightly negative elevation feedback was shown by Vizcaino et al. 2015. It was shown that a positive Elevation-SMB feedback can be found in the ablation areas and is most notably at low elevations. This positive Elevation-SMB feedback was found to occur at locations in which the melt increase as a result of elevation decrease is dominant. Furthermore, a negative SMB-feedback was found to occur at locations in which the topographic desertification becomes dominant, which occurs in most of the accumulation areas.

As a result of the elevation feedback, the SMB becomes more negative at the low-elevation margins, while the SMB becomes more positive in the interior when the thickness decreases. Vizcaino et al. 2015 have also shown that the elevation-SMB feedback acts as a positive feedback to the Greenland ice sheet melt. The relative total amount of mass loss due to the elevation-SMB feedback is 11% (31%) for RCP2.6, 10% (24%) for RCP4.5 and 8% (24%) for RCP8.5 at year 2100 (year 2300).

As the Greenland ice sheet melts, the elevation feedback can alter the amount of accumulation resulting from precipitation. According to Hakuba et al., 2012, which used the global atmospheric model ECHAM5-HAM with different Greenland Ice Sheet heights, the total precipitation and total accumulation increase as Greenland's topography decreases. The precipitation increases with 11% and the snow accumulation with 4% for every 25% of topography reduction. The same study also found that the precipitation distribution is altered resulting in most of Greenland receiving more precipitation, except West Greenland. Furthermore, the annual mean surface temperature was found to increase 2 degree Celsius with every 25% of elevation reduction.

A modelled feedback which could have a minor effect on the elevation and therefore SMB is the change in bedrock topography as a result of isostatic adjustment. This should pose as a minor negative feedback to ice sheet melt. As the ice sheet decreases in elevation, the mass on top of the bedrock decreases. Due to isostatic adjustment, the bedrock starts to rise.

The elevation can also affect other processes, such as the velocity of the ice sheet. The ice sheet velocity is dependent on the surface elevation. Furthermore, a significant topographic change can result into a change in the atmospheric circulation as the Greenland ice sheet acts as a barrier of flow (Toniazzo et al., 2004). For example, the melting of Greenland could result into an enhanced winter polar vortex, along with a north-eastward shift of storm tracks over the North Atlantic (Dethloff et al., 2004). However, this interaction between atmosphere and elevation is beyond the scope of this thesis, as it is not modelled in the uncoupled simulation.

Climate Feedbacks

As Greenland melts, there are a number of feedbacks that will occur besides the SMB-elevation feedback. Since the simulations that are conducted during this study are uncoupled ice sheet runs, these climate feedbacks are not modelled during the multi-millennium time-scale simulations.

First of all, the albedo could change as a result of ice sheet melt. Bare ground has a lower albedo compared to fresh snow, and snow-melt could result into the exposure of bare ice which has a lower albedo. As a result, the albedo feedback acts as a positive feedback to Greenland melt since a lower albedo would result into less reflection of Short-Wave radiation at the surface. For example, the albedo of snow was shown to dependent on the grain size (Wiscombe & Warren 1980). It was shown that an increase in the snow grain size of fresh snow from 41μm to 55μm in Greenland could result in a 10% increase of melt, as well as an earlier start of the melt season (Van Angelen et al., 2012). While this albedo-melt feedback is accounted for, as the SMB is derived with a Surface Energy Balance scheme, the effect of the albedo towards the climate was not modelled. The exposure of large areas of bare ground and tundra results additional climate warming.

The precipitation pattern of Greenland is highly influenced by the geometry and elevation of the ice sheet as it forms a barrier of flow. As Greenland retreats, the change in ice thickness can results in a change in the precipitation pattern. This feedback is not modelled in the CISM2.1 simulations.

2.3 State of Literature

While most research focuses on the Greenland melt prediction for the 21st century, some research also focuses on multi-century time scales and beyond. This section, I discuss some research that covered these multi-century and multi-millennium time scale simulations on the Greenland melt.

Letréguilly et al., 1991

Letréguilly et al., 1991 performed uncoupled multi-millennium Greenland simulations. The SMB was derived with a PDD scheme.

The Greenland ice sheet fully melted under a 6 decrease Celsius temperature increase by year 20,000. Furthermore, Letréguilly et al performed a recovery simulation, in which amongst others, the pre-industrial climate is re-introduced in an attempt to regrow the ice sheet. By year 30,000, the ice sheet has fully grown to the pre-industrial size.

Huybrechts & de Wolde, 1999

Huybrechts & de Wolde, (1999) is the first research that conducted simulations of the Greenland ice sheet on multi-millennium time scales with a coupled ice sheet - climate model. This research used a model which describes the solid earth, surface climate and ice sheet system. In addition, a Positive Degree-Day (PDD) scheme was used to derive the SMB. The resolution of the ice sheet model is 20 km x 20 km for the Greenland ice sheet.

The 4 times CO_2 forcing scenario show significant retreat of the Greenland ice sheet in Huybrechts & de Wolde (1999). The 4 times CO_2 forcing corresponded to 3.17 meter of sea level rise in roughly 1000 years. The 2 times CO_2 was shown to result into a sea level increase of 87.5 centimetres.

At calendar year 3000, the 4 times CO_2 forcing scenario contributes to the ice sheet size at an almost linear pattern. Therefore a mass equilibrium was not achieved in the 4x CO_2 simulation. This aforementioned research shows that the deglaciation of Greenland is a multi-millennial time scale process.

Ridley et al., 2005

Ridley et al., (2005) was the first research that used a complete two-way coupling between an ice sheet model and a complex climate model on a multi-millennium time scale. The ice sheet model used is two-way coupled to an atmosphere-oceanic general circulation model (AOGCM). This complex climate model, HadCM3: (the third Hadley Centre Coupled Ocean-Atmosphere Global General Circulation Model) and a three dimensional ice sheet model, GISM (Greenland Ice Sheet Model) were used to simulate Greenland melt up to a time scale of 3000 simulation years. To derive the SMB, a PDD scheme was used which parameterized the surface melt on surface air temperature.

Furthermore, the coupling between the ice sheet and climate model is applied once every model year. The runs Ridley et al. conducted are several two-way coupling simulations as well as one, one-way coupling simulation up to a timescale of 3000 years. The two-way coupled simulations, beside two controls, also concerned a 2% increase per year until 4 times CO_2 scenario. The 4 times CO_2 scenario indicated that the Greenland ice sheet will melt within the 3000 year time period until only a small ice sheet in the eastern mountains remains.

Ridley et al., (2005) furthermore showed that there are potentially 4 phases of Greenland melt under 4 times CO_2 forcing:

1. Volume and area decrease relatively to each other, but the height remains similar. Most melt takes place in areas that are less constrained by mountains.
2. The volume to area decreases due to increased flow as a result of steeper surface slopes.
3. The ice margin is lower in the west, which increases ablation. The ice sheet retreats towards the mountains in the east.
4. A new quasi-equilibrium is reached as the ice sheet has retreated into the mountains in the East.

While Ridley et al. (2005) does provide useful information on the melt pattern of Greenland as well as the timing. However, the resolution is relatively course by contemporary standards. The resolution of the models used by Ridley et al. is 20 km for the ice sheet model. The CISM model runs that are used for this thesis has a horizontal resolution of 4 x 4 km. Therefore, the CISM runs should be more sophisticated at representing the margins of Greenland compared to the GISM runs. Furthermore, while Ridley et al., (2005) does have full coupling between the ice sheet model and climate model, the resolution of the AOGCM is relatively poor with an atmospheric resolution of 2.5 degree latitude and 3.75 degree longitude and 19 vertical levels, while the ocean has a resolution of 1.25 degree latitude and longitude, with 20 vertical levels.

Vizcaíno et al., 2008

Vizcaíno et al., 2008, used the ice sheet model SICOPOLIS coupled with a more complex Earth System Model; an Atmosphere-Ocean General Circulation model, the MPI-model ECHAM5-MPIOM-LPJ. The surface mass balance is calculated using a PDD scheme. The ice sheet model has a relatively coarse resolution; 80 kilometres horizontal resolution with 21 elevation classes in the ice sheet. While this research focuses on the climate interactions, such as NAMOC and the atmosphere, a comparison was made between 2-way and 1-way coupling for a number of forcing scenarios.

The pattern of the ice sheet volume and area decrease is very similar between the 1-way and 2-way coupling. However, at calendar year 3600, the 1-way coupling runs shows a decrease in volume and area change while the 2-way coupling continues a relatively similar decay rate. Furthermore, at the end of the simulation, the mean summer temperature is 10 K warmer in the 2-way coupling run compared to the 1-way coupling run.

Huybrechts et al., 2011

A research by Huybrechts et al. (2011) focused on the response of both the Antarctic as well as the Greenland ice sheet, while using a Earth System Model of intermediate complexity.

This research concerns simulations of the Greenland ice sheet up to a timescale of 3000 years using 2 times and 4 times pre-industrial CO_2 forcing. The ice sheet model that was used for this multi-millennial time scale research is the "Antarctic and Greenland Ice Sheet Model" (AGISM), with two way coupling using the climate model LOVECLIM. The simulations conducted by Huybrechts et al. (2011) have a high resolution of 10 x 10 km with 31 vertical layers in the ice sheet, and 9 vertical layers in the bedrock. In contrast, the aforementioned research by Ridley et al., (2005) concerned a resolution of 20 x 20 kilometre. A PDD scheme was furthermore used to derive the SMB. Huybrecht et al parameterized the accumulation due to snow, rainfall, as well as meltwater run-off on temperature.

Huybrechts et al. showed that under a 4 times CO_2 forcing the Greenland Ice Sheet will have almost disappeared within 3,000 years, except for a few small ice sheets in the eastern mountains. The simulation furthermore shows a smaller final ice sheet extent compared to Ridley et al., (2005). Huybrechts et al. also showed that there are significant differences between the 2 times and 4 times pre-industrial CO_2 forcing. By year 3000, the 2x CO_2 forcing has reached similar levels to the 4x CO_2 scenario by year 1000.

Huybrechts et al. shows that 3000 years should be sufficient to describe the complete melt of Greenland under 4 times CO_2 forcing. However, 3000 years was shown to not be sufficient to 2 times CO_2 forcing.

Aschwanden et al., 2019

Aschwanden et al., 2019, conducted ice sheet simulations on a 1000 year time-scale when forced by the RCP2.6, RCP4.5 or RCP8.5 scenario. The ice sheet model used was the Parallel Ice Sheet Model (PISM) and the regional climate model used is HIRHAM5. Similar to most models discussed, a PDD scheme is used to derive the SMB. Furthermore, Aschwanden et al., 2019 concerns an uncoupled PISM simulation in which a linear interpolated trend was used to derive the temperature change between years 2300-2500. After year 2500, the temperature was kept constant.

Aschwanden et al., 2019 showed a fast melt rate of the Greenland ice sheet. The RCP2.6, RCP4.5 and RCP8.5 resulted in 0.59 to 1.88 meters, 1.86 to 4.17 meters, and 5.23 to 7.28 meters of sea level rise. In the RCP 8.5 scenario, full deglaciation of the Greenland ice sheet occurred within 1000 years.

Greve, 2000

Greve, (2000) used the ice sheet model SICOPOLIS (SImulation COde for POlythermal Ice Sheets) and applied it to the Greenland ice sheet on a time-scale up to 1,000 years. The horizontal resolution of this ice sheet model is 20 x 20 kilometres with 51 vertical levels in the cold-ice region, 11 in the temperate ice region and 11 levels in the lithosphere. The simulations that were conducted increased the surface temperature with 1 to 12 degree Celsius. After 1,000 years, the 10 degree surface temperature increase showed substantial retreat to the central east. The simulation that considered 12 degree temperature increased showed almost complete retreat after 1,000 years.

Charbit et al., 2008

While the aforementioned literature focuses on the final stable condition of the Greenland Ice Sheet, a research by Charbit et al., (2008), is focused on which CO_2 scenario leads to the irreversible melt of the Greenland ice sheet. Charbit et al. used the CLIMBER model, which is an atmosphere, ocean, vegetation model of intermediate complexity, which is coupled to an ice sheet component. Furthermore, Charbit et al. also accounted for the natural sink in CO_2. Similar to most studies discussed, Charbit el al., calculates the SMB based on a PDD scheme.

Charbit et al. found that the CO_2 emission should not exceed 2500 GtC in order to prevent complete melting of the Greenland ice sheet. However, lower CO_2 emission values already lead to substantial melt. The highest CO_2 emission scenario of 3500 GtC lead to complete melting after 8,000 simulation years. Furthermore, this run was continued until the CO_2 scenario recovered to present-day values. However, the ice sheet did not regrow according to this simulation, since the ice sheet feedback lead to higher temperatures in Greenland.

Ridley et al., 2010

A follow up study on Ridley et al., (2005) concerns a study which focused on the thresholds for the irreversible decline of the Greenland ice sheet: Ridley et al., (2010). This research used eleven initial Greenland Ice Sheet states which are intermediate results derived from the 4 times CO_2 forcing simulations by Ridley et al., (2005). These initial states were forced using pre-industrial conditions and ran on time-scales of tens of millenniums. While Ridley et al., (2010) used a similar climate model as Ridley et al., (2005), this Ridley et al., (2010) coupled this AOGCM asynchronously to the ice sheet model, as the regrowth of the ice sheet is generally a magnitude slower compared to the melt.

First of all, Ridley et al., (2010) showed that the ice sheet does not revert back to original size after substantial deglaciation. The simulations show that there is a tendency towards one of three different equilibriums: at 100%, 80% and 20% of the initial volume. The 100% state was only reached when the initial condition is either 90% or 100% of the present-day extent.

Toniazzo et al., 2004

A research which also used HadCM3, (Toniazzo et al., 2004) focused on the possible regrowth after the entire ice sheet has deglaciated. However, Toniazzo et al., 2004 did not use a dynamical ice sheet model as the research considered conditions without an ice sheet. Due to several feedbacks such as the albedo and topographic feedback, which will be discussed in more detail later on, the ice sheet will not regrow after complete melt, even if pre-industrial

CO_2 conditions are retained. Furthermore, this research concerns an SMB scheme which is similar to a Surface Energy Balance scheme.

Driesschaert et al., 2007

Driesschaert et al., (2007) focused on the effects that Greenland has on the Atlantic Meridional Overturn Circulation (AMOC). LOVECLIM-1.0 was used to simulate the melt of Greenland with ice sheet model AGISM, which has a resolution of 10 km x 10 km. Different CO_2 scenario such as 2 times and 4 times pre-industrial CO_2 concentrations were considered. They found that a forcing exceeding $7.5W/m^2$, which is reached at 4 times CO_2, will result in the complete melting within 3000 years.

Vizcaino et al., 2015

Vizcaino et al., 2015 considered three aforementioned RCP scenarios on a time-scale up to 2300. The model used is the European Center/Hamburg 5.2 (ECHAM5.2)/Mark Planck Institute Ocean Model: ECHAM5/MPI-OM. This an Atmosphere Ocean General Circulation Model (AOGCM) and was used in combination with the ice sheet model SICOPOLIS 3.0, which has a horizontal resolution of 10 kilometres. The surface melt is calculated with a mix between the Surface Energy Balance Scheme and the Positive Degree-Day scheme.

The RCP scenarios that were considered are RCP2.6, 4.5 and 8.5 which reach atmospheric CO_2 concentrations of 421, 538 and 936 ppmv respectively at year 2100. In the simulations that were conducted by Vizcaino et al., 2015, the atmospheric CO_2 concentration decreases at year 2040 for the RCP2.6 run. The RCP4.5 atmospheric CO_2 concentration reaches equilibrium soon after 2100. However, the RCP8.5 atmospheric CO_2 concentration are capped at 4 times pre-industrial CO_2 concentrations, which is reached before 2150. The final temperature anomalies, averaged over the final 20 years are: 1.2, 3.2 and 9.4 degrees Celsius for RCP2.6, RCP4.5 and RCP8.5 respectively. The sea level rise that resulted from these scenarios were simulated to be 68 mm, 135 mm and 539 mm.

Conclusions on the State of Literature

This section, I have discussed literature concerning multi-century and multi-millennium time scale simulations on Greenland melt. Table 2.1 shows the papers discussed as well as their corresponding models, SMB scheme and ice sheet model resolution. Furthermore, the model used in this thesis, CISM2.1 was added. In chapter 3, CISM2.1 will be discussed in more detail.

As can be seen in the table, the literature that was discussed mostly concerns PDD schemes, which as previously discussed, could be more biased to climate warming compared to SEB schemes (Bougamont et al. 2007).

CESM, or more specifically the land model CLM, which is one of the components of CESM, uses a Surface Energy Balance (SEB) scheme to derive the SMB. Furthermore, CISM2.1 has

Table 2.1: Literature on Long Term Melt Projections

Literature	Ice Sheet Model	Earth System Model	SMB scheme	H. ISM Res.
Vizcaino et al., (2015)	SICOPOLIS	ECHAM5-MPIOM	SEB	10 x 10 km
Huybrechts & de Wolde, (1999)	*	*	PDD	20 x 20 km
Ridley et al., (2005)	GISM	HadCM3	PDD	20 x 20 km
Vizcaíno et al., (2008)	SICOPOLIS	ECHAM5-MPIOM	PDD	80 x 80 km
Huybrechts et al. (2011)	AGISM	LOVECLIM	PDD	10 x 10 km
Models used in this Thesis	CISM	CESM (uncoupled)	SEB	4 x 4 km

* In Huybrechts & de Wolde, (1999) neither the Ice Sheet Model nor the Earth System Model have been given specific names.

a 4 x 4 km resolution, which is higher compared to the studies discussed.

Chapter 3

Method and Data Sets

In this chapter, the models used for the ice sheet simulations are discussed as well as the simulations conducted.

3.1 Model Description

The multi-millennium time-scale simulations were conducted with the Community Ice Sheet Model version 2.1 (CISM2.1), which is the land ice component of the Community Earth System Model version 2.1 (CESM2.1). In this section, the Ice Sheet Model and Earth System models are introduced and their coupling is discussed. Furthermore, the land model component of CESM, which is the Community Land Model (CLM), is discussed in detail: CLM is integral to forcing the ice sheet as it derives the SMB.

3.1.1 The Earth System Model: CESM

CISM2.1 is a component of the Community Earth System Model (CESM2.1). While CISM2.1 can be forced with the output from several climate models, the simulations conducted for this thesis were forced by SMB-elevation field derived from CESM2.1 output. The CISM2.1 simulations are run using the CESM infrastructure. While I only performed CISM2.1 simulations, the boundary conditions for these simulations were provided by previously conducted CESM2.1 simulations.

CESM contains five physical components including CISM2.1 (Hurrell et al., 2013). Table 3.1 summarises these five physical components; each describe a component of the climate.

During this thesis, CISM was ran uncoupled with an elevation-dependent SMB forcing. Therefore, only CISM was active, but was forced by output derived from the Community Land Model: CLM. CLM provides the temperature of the uppermost-ice layer as well as the SMB forcing , which is send through the coupler to CISM. This coupler between CLM and CISM is CIME (Common Infrastructure for Modeling the Earth) (see Foucar et al.,

Table 3.1: **List of CESM2.1 components**. CESM2.1 consists of five physical components. CISM2.1 is the ice sheet components of CESM2.1. In a fully coupled (BG) simulation, all five components are active. In an uncoupled simulation (TG), only CISM2.1 is active and is forced by the output from a previously coupled simulation.

Component	Model Name	Full Name
Atmosphere	CAM	Community Atmosphere Model
Land Surface	CLM	Community Land Surface Model
Oceanic	POP	Parallel Ocean Program
Surface Ice	CISM	Community Ice Sheet Model
Sea Ice	CICE	Community Ice Code

2017). As a result, CLM forces CISM resulting in a change of the ice sheet in, amongst other variables, the area as well as topography (Lipscomb et al., 2018).

Since in the simulation conducted during this thesis CISM was ran uncoupled, CLM was inactive during each simulation. Instead, an already existing output of CLM from a previously conducted coupled simulation was used to force the ice sheet. While some of the interactions between the climate and CISM as well as multi-century time scale climate responses were not simulated, the topographic feedback is still modelled due to the elevation classes that were used to force CISM. (Lipscomb et al., 2018). This interaction between CISM and CLM is explained in detail in section 3.1.3.

Configurations of CESM

There are several types of CESM configurations which involve an active CISM, two of which were used for the simulations used in this thesis. These configurations determine which of the aforementioned CESM components were active during the simulations. There are four configurations with an active ice sheet model; BG, FG, IG and TG (see Lipscomb el a. 2013). The BG and TG configurations were used for the coupled and uncoupled simulations.

BG is the fully coupled configuration that has all five climate components active. Therefore, the atmosphere, ocean, sea ice, land surface and ice sheet components are active. This configuration was used to derive the forcing that was used for the uncoupled CISM2.1 simulations.

TG is the uncoupled configuration. This configuration was used for the multi-millennium simulations for this thesis. Only the ice sheet model, CISM2.1, is active in a TG run. To force the output, the coupler files used were originally derived from CLM output of a previously conducted, BG, FG or IG simulation. For this thesis, I used CLM output that resulted from a previous BG run.

Each of these configurations have different benefits and weaknesses. BG-runs, while fully coupled and should therefore result in more realistic simulations, is computationally expensive. TG runs on the other hand are computationally cheap: The TG simulations which were run during this thesis took close to 1 hour to simulate 1,000 years on NCAR's Cheyenne super computer, while the BG runs simulated roughly 10 years per day. Therefore, TG simulations are substantially computationally cheaper. However, since the climate was never updated with the new ice sheet topography in the TG runs, the results should be worse at representing reality. Since the ice sheet is forced by an elevation dependent SMB, a topographic feedback is still in place, despite the absence of two-way coupling. Since forcing needs to provided in a TG simulation, it is not possible to conduct a TG simulation with an original climate.

3.1.2 Ice Sheet Model: CISM2.1

The Ice Sheet component of CESM is the Community Ice Sheet Model version 2.1. CISM2.1 is a parallel, three dimensional thermomechanical model. Within CISM2.1 equations for mass, internal energy as well as momentum equations are solved resulting in the thickness, velocity and temperature evolution of the ice sheet (Lipscomb et al., 2019),(Rutt et al., 2009). The Surface Mass Balance as well as the surface temperature are not derived within CISM2.1, but in the land model CLM. CISM2.1 converts the SMB and temperature forcing and maps them onto the topography within CISM. CISM2.1 furthermore runs most efficiently at a squared grid-resolution of 4 x 4 kilometres. The 4 x 4 kilometre grid-resolution is therefore the resolution used during each simulation.

Calving and Sea Level in CISM2.1

Calving of ice takes place at the contacts between the ice sheet and water surfaces. During the CISM2.1 runs conducted during this thesis, calving was derived simplistically: The simulations did not allow for any ice shelves, and any ice that is floating is immediately calved. Therefore, once ice is floating according to Archimedes law, the thickness is immediately reduced to 0 meters (see Lipscomb et al., 2013, which had a similar approach to calving). Furthermore, if ice flows towards an ocean point, this ice will also be immediately calved. This limitation can be applied for Greenland, as limited ice shelves can be found in present-day Greenland and most are concentrated above 76 degree North.

A further simplification in the simulations conducted during this thesis is that the sea level is not allowed to evolve. Therefore, during the simulation, as Greenland melts, no change in sea level occurs. The borders of the sea can change as ice that is grounded melts: The bedrock topography is below sea level in the centre of the ice sheet. If melt is sufficiently fast enough, the ice sheet can form calving fronts in the centre of the ice sheet before the bedrock topography is lifted above sea level due to isostatic adjustment.

3.1.3 The land model: CLM

The land model CLM is used to force the ice sheet model CISM. Within this land model, the surface mass balance as well as the surface temperature are calculated and used to force CISM. SNICAR (Snow, Ice and Aerosol Radiative Model) is used to derive the radiative balance of snow, including the albedo dependencies on soot concentration and snow ageing as well as the amount of radiation absorbed (Lawrence et al., 2011).

If the climate was coupled, CLM would also provide data to the other components within CESM. Since CISM is ran uncoupled, the CLM component is inactive and the CLM data provided to CISM is from a previously conducted coupled run. This section, I will discuss how CLM output forces CISM and how this forcing changes as the topography within CISM changes. Secondly, I will discuss the method in which SMB is derived within CLM.

Coupling between CLM and CISM

CLM has a 1 degree horizontal resolution, while in contrast, CISM has a resolution of 4 by 4 kilometres. Generally, CLM has only 1 elevation class, but above glaciated surfaces, the land model has 10 elevation classes. The boundaries for these 10 elevation classes in CLM are: 0, 200, 400, 700, 1.000, 1.300, 1.600, 2.000, 2.500, 3.000 and 10.000 meters. As a result of these elevation classes, variables within CLM such as radiative budget, temperature, humidity as well as snow and rain partitioning, are dependent on height above glaciated areas.

The data from CLM is send to CISM. The 1 degree resolution, 10 elevation classes of CLM are applied to the 4 x 4 kilometre topography field of CISM using bi-linear interpolation. To derive the SMB in a grid-cell based on height, linear interpolation of the elevation classes takes place. As a result of this interpolation, a grid-cell at 300 meters will receive the average SMB and surface temperature of both 200 meters and 400 meters in the CLM elevation classes. If the topography within CISM2.1 changes, the results of the linear interpolation change as well. For example, if the aforementioned grid-cell's elevation reduces from 300 meters to 200 meters, the SMB and surface temperature are equal to the 200 meter class in the CLM forcing output. (Lipscomb et al. 2013). As a result, despite providing the same forcing data, the SMB forcing can change as the topography changes.

The main benefit of this method is that it ensures CISM and CLM have a similar amount of mass change resulting from freezing and melting (Lipscomb et al. 2013). In addition, this elevation dependent SMB field also enables modelling of the SMB-elevation feedback without the need of providing new forcing files for each simulation year. Therefore, even if an elevation dependent SMB-field is repeated and provided to CISM2.1, the SMB-elevation feedback is still modelled.

Surface Mass Balance Calculation

The Surface Mass Balance is calculated within CLM for the 10 elevation classes. Along with the surface temperature, the SMB is send from CLM to CISM, which is converted to a 4 x 4 kilometre resolution using the elevation classes. There are two schemes which are generally used to calculate the SMB evolution of the Greenland ice sheet; a positive degree day (PDD) scheme or a Surface Energy Balance (SEB) scheme, which is used by CESM.

I previously discussed these two SMB schemes in chapter 2. PDD schemes are based on empirical relationships to derive the SMB. PDD schemes could be less useful for multi-century or millennium simulation as empirical relationships that are valid today could become invalid in a different climate. For example, Bougamont et al., 2007 have shown that PDD schemes could have a large response to simulated warming compared to SEB schemes.

A Surface Energy Balance (SEB) scheme is used by CESM, more specifically CLM, which is within the architecture of CESM. It allows for different processes to contribute to the melt, and is not based an empirical relations. The calculation of the SMB within CLM is as following:

$$SMB(ice + snow) = Snow + Rain - Runoff - Sublimation \tag{3.1}$$

This computation is conducted under a snow surface type and bare ice. However, calculating the run-off does require additional computations. First of all, run-off can be computed using the following equation:

$$Run - off = AvailableLiquidWater - Refreezing \tag{3.2}$$

The Available Liquid Water is equal to the sum of melt and rain. Therefore, Run-off can also be written as:

$$Run - off = Melt + Rain - Refreezing \tag{3.3}$$

The amount of melt however, is dependent on several factors: the radiative, turbulent as well as the sub-surface flux.

$$Melt = RadiativeFlux + TurbulentFlux + Sub - surfaceFlux \tag{3.4}$$

The radiative flux is the budget of both short-wave and long-wave radiation and the turbulent flux is the budget of latent and sensible heat flux (Lipscomb et al., 2013). The sub-surface flux simply concerns the ground flux. These three fluxes contribute to the melt, which can be expressed as following:

$$Melt = SW_{down}(1 - \alpha) + LW_{down} - \epsilon\sigma T^4_{surface} + SHF + LHF + GF \tag{3.5}$$

SW and LW are abbreviations for short-wave and long-wave radiation. Long-wave radiation is emitted by the surface, which is why the term $\epsilon\sigma T^4_s$ is subtracted. Due to the albedo (α), a fraction of the SW radiation is reflected. The emission of long-wave radiation is equal to the emissivity (ϵ) multiplied by the Stefan-Boltzmann constant (σ) and $T^4_{surface}$. The turbulent fluxes are represented by the Sensible Heat Flux (SHF) and the Latent Heat Flux (LHF). Finally, the sub-surface flux is represented by the ground flux (GF). This final flux is positive towards the surface (Vizcaíno et al., 2013).

3.2 Climate and Ice Sheet Simulations

In this thesis, uncoupled ice sheet model simulations with forcing derived from two fully coupled climate were conducted. This section, I introduce the two coupled simulations, as well as the uncoupled simulations. A flow chart that summarises the simulations is shown in figure 3.1.

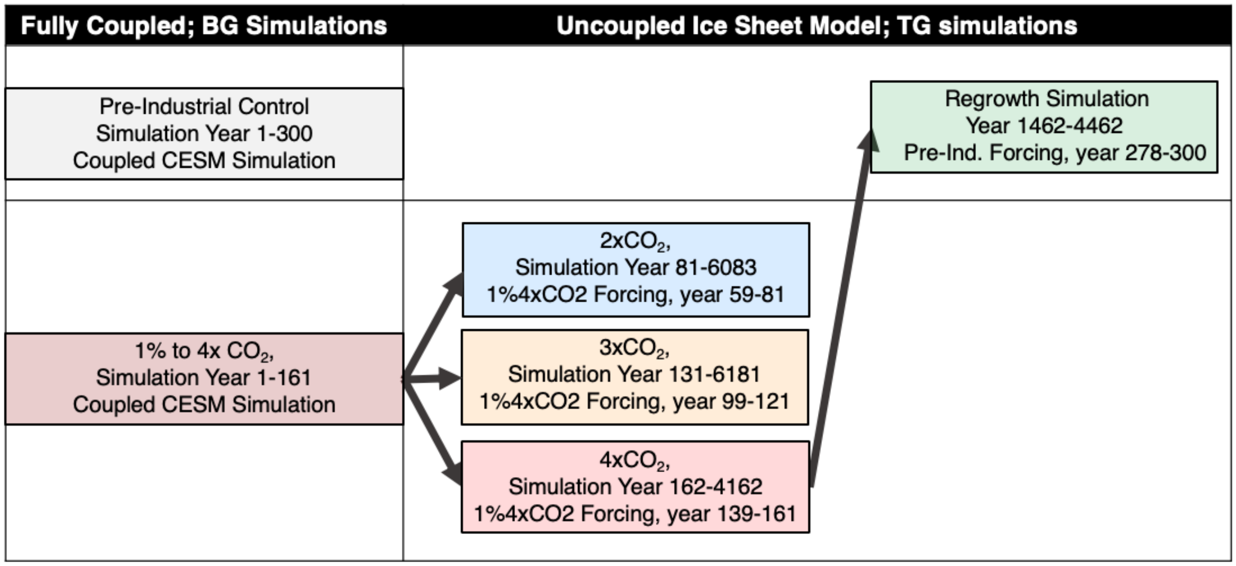


Figure 3.1: **Flow map and forcing of the coupled and uncoupled simulations.** This flow-map shows the simulations that were used for this thesis. There are two fully coupled climate simulation, which form the basis of the uncoupled simulations that I conducted.

3.2.1 Coupled Simulations

The output from two fully coupled CESM simulations were used to derive the forcing for the uncoupled CISM simulations. First of all, a pre-industrial control simulation was used. This simulations concerns a constant CO_2 concentration equal to pre-industrial conditions at 280 ppm. As a result, during the control simulation, the ice sheet should be in a quasi equilibrium. This simulation is continued for 300 years.

The second climate simulation that was used for the simulations of this thesis concerns a 4x CO_2 simulation. At the start of this simulation, the CO_2 concentrations are representing pre-industrial levels, which is increased by 1% per year. The atmospheric CO_2 concentration is capped at 4x pre-industrial CO_2 concentrations, which is reached after roughly 150 years (see figure 3.6). However, there is inertia in the response of the climate system towards the increase in temperature. Therefore, it takes decades to centuries for the components of the climate system, such as the ocean, to respond to the warming of the climate. However, the BG simulation is available until year 162, therefore, in the 2x, 3x and 4x CO_2 simulation, the climate is transient.

These two CESM simulation form the basis of the simulations conducted for this thesis. Since the ice sheet model is active during these simulations, the CESM output of the climate simulations can be used as the first 300 years of the ice sheet model. Furthermore, as CLM is ran during these coupled simulations, SMB as well as surface temperature forcing for CISM is produced. This forcing is used to extend these CESM simulations with an uncoupled CISM simulation.

L2P1 Correction in the Coupled Simulations

An issue that was found in the coupled simulations was a substantial retreat in the Humboldt region as well as the western margins during the pre-industrial simulations. To solve the retreat in these regions, two corrections were applied:

The L2 correction concerns Long-Wave radiation with height. During the coupled simulation, down pointing long-wave radiation is considered to be constant with height.

The P1 correction concerns rain partitioning based on temperature. Warm rain can be either converted in run-off or snow-fall. This partitioning is based on temperature. However, with the P1 correction, all warm-rain is converted into run-off.

3.2.2 Applying the Forcing to the Uncoupled Simulations

An uncoupled CISM2.1 simulation cannot simulate the climate. Therefore, it requires information that describes the climate. This climate data can be derived from a coupled (I, F or B) simulation. Only if this data is available, can the ice sheet be forced with a certain climate. During this simulation, 4 uncoupled simulations were conducted: a 2x, 3x and 4x CO2 simulation and a Recovery from 4x CO_2 simulation .The 2x, 3x and 4x CO2 simulations each used the *same* coupled warming simulation as forcing. The recovery simulation was forced by the coupled pre-industrial simulation.

The forcing applied for the CISM2.1 simulations

The 4x CO_2 simulation is the warmest forcing scenario and was forced with the 1% to 4x CO_2 coupled simulation. The CISM2.1 output of a BG simulation, when using the same forcing, CISM2.1 settings, and initial ice sheet, should give the exact same output as the TG simulation. Therefore, for the first 161 years, the output of the coupled simulation can be used.

Figure 3.2 shows this schematically. The first 161 years of the coupled simulation directly represents simulation years 1-161. Since forcing is only available until year 161, the forcing was repeated to force the ice sheet on multi-century and multi-millennium time-scales.

As shown in the schematic in figure 3.2, to simulate years 162-184 in the uncoupled simulation, forcing years 139-161 were used. For years 185-207, years 139-161 of the forcing are used as well. The forcing is repeated every 23 years until the end of the simulation is reached. As a result, only *one* coupled simulation is used to force the ice sheet on multi-millennium time-scales. Therefore, the same 23 years of forcing are repeated to simulate years 139 until the end of the simulation at year 4162.

The same coupled simulation used for the 4x CO_2 scenario, is also used for the 3x and 2x CO_2 simulation. Schematics of the 2x CO_2 and 3x CO_2 forcing are depicted in figures 3.3 and 3.4.

The first 81 years and 121 of the 2x and 3x CO_2 scenarios have the same output as the coupled simulation. After these initial 81 and 121 years, 23 years of forcing is repeated throughout the entire simulation. For the 2x CO_2 simulation, forcing years 59-81 were repeated and for the 3x CO_2 simulation, years 99-121 were repeated every 23 simulation years.

This method for the forcing of the ice sheet on multi-millennium time-scales is similar in the Recovery from 4x CO_2 simulation. This simulation branches off the 4x CO_2 simulation at year 1462. The forcing used for the Recovery from 4x CO_2 simulation was derived from the pre-industrial climate. Similar to the 2x, 3x and 4x CO_2 simulation, 23 years of the forcing is repeated every 23 years of the simulation. While there is forcing data for 300 years of pre-industrial climate, only 23 years of forcing are used.

23 year length of the forcing

As stated before, the forcing is looped every 23 years. This number was chosen deliberately, as it reduces bias from the mean and avoids large shifts in SMB in the outputted data.

First of all, there is inter-annually variability in the climate. Therefore, it is not recommended to use only a limited number of years for the SMB, as it is possible that only relatively warm or cold years are considered. However, since the climate is transient and not equilibrated, the length of the forcing should not be too long. Therefore, the forcing should not be smaller or larger than 20 to 30 years.

The output frequency for the simulation is 10 years, which was chosen over a 1 year output frequency to reduce the amount of data. Since the climate for the warming scenarios is in a transient climate, the SMB can shift substantially (e.g. 800 Gt/yr) during the 23 years of forcing. As a result, it is important that the output of the uncoupled simulation represents every year used for the forcing. However, at the same time, the years used for the forcing should be evenly spread in the outputted data. The bias that is created by these two situations is shown in figure 3.5.

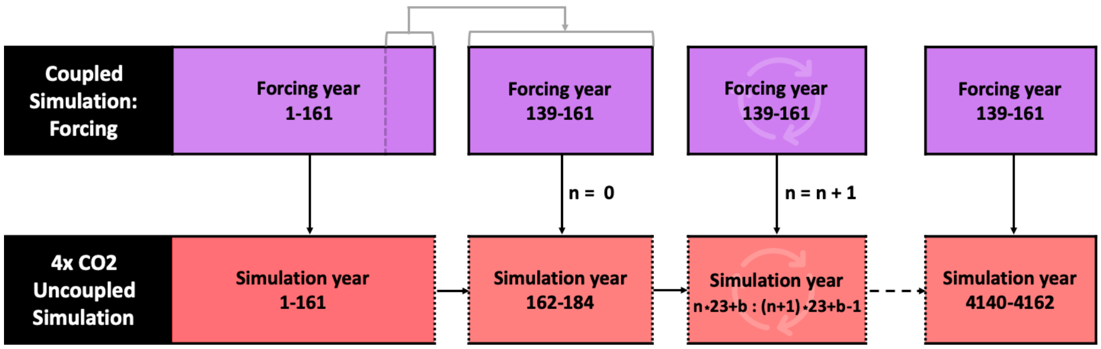


Figure 3.2: **The schematic for the forcing of the 4x CO2 scenario**. The BG warming simulation increases the CO_2 concentrations by 1% per year. The CO_2 concentration is capped at 4x CO_2 pre-industrial concentrations. This coupled simulation represents the first 161 years of the simulation. To force the ice sheet on multi-millennium scales, the last 23 years (139-161) of this coupled simulation are repeated to force the uncoupled simulation. (b = 162)

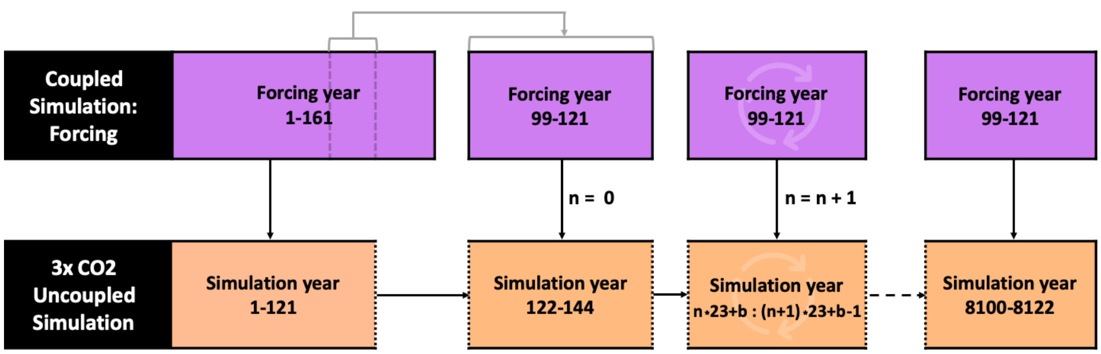


Figure 3.3: **A schematic of the forcing used for the 3x CO_2 simulation**. For the first 121 years, the output of the BG simulation can be used for the ice sheet simulation. After year 121, years 99-121, representing 3x CO_2 concentrations, of the forcing are repeated every 23 years until the end of the simulation. (b = 122)

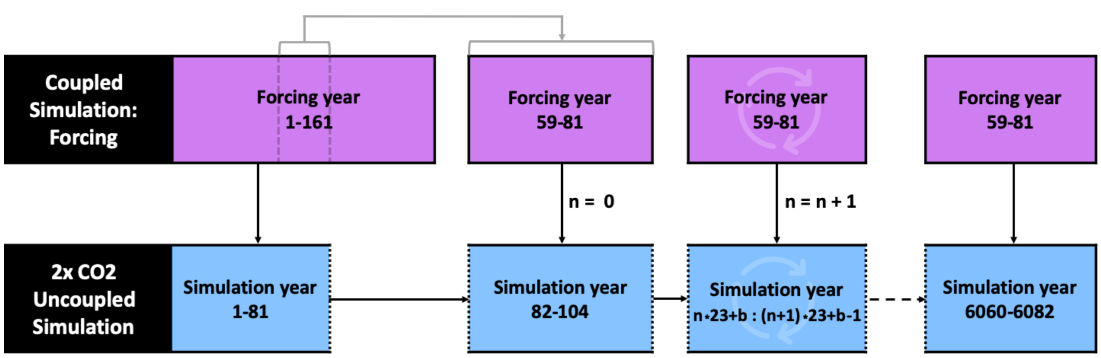
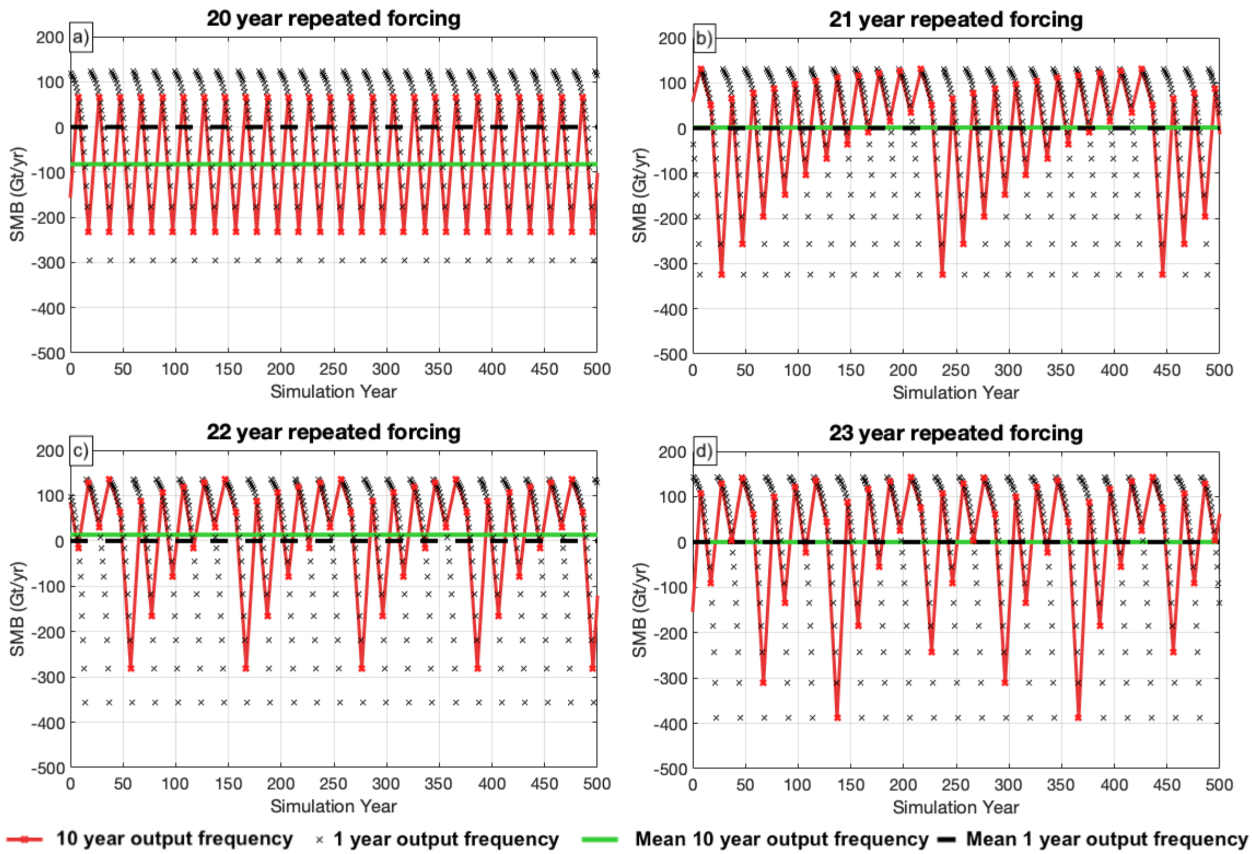


Figure 3.4: **A schematic of forcing applied during the 2x CO_2 simulation**. The first 81 years of the simulation have the same output as the coupled simulation. Years 59-81 of the forcing are repeated to force the ice sheet on multi-millennium time-scales. (b = 82)



Length of Forcing (years)	20	21	22	23	24	25	26	27	28	29	30
Mean Bias (Gt/yr)	-82.4	0.00	12.1	0.00	13.0	-24.4	14.0	0.00	15.1	0.00	119

Figure 3.5: **The effect of the length of the repeated forcing when applying a 10 year output frequency on an idealised SMB.** The 20 year (a) and 22 year (c) lengths of the forcing have a bias of the mean between the sampled and true data, since not every forcing year is sampled. Years 21, 23, 27 and 29 have the same mean for the 10 year and 1 year output frequency. The 21 year forcing length (b) has an uneven distribution of the warmer and colder year, resulting in large shifts in the forcing every 210 years. The mean of the 23 year forcing length (d) is equal to the true output and samples the forcing more evenly. Therefore, a 23 year length of the forcing was chosen. While the are still large shifts in the forcing, these are more spread out across 230 years. It should furthermore be noted that the *non-zero* biases in the table are highly dependent on which years are outputted.

For the forcing length of 20 and 22 years (figure 3.5a+c), there is a bias from the mean as not every year in the forcing was outputted. Only 2 and 11 years of the SMB forcing are represented in the time-series. As a result, some years in the forcing are not outputted as the output frequency and length of forcing are in sync. Since a forcing length of 22 years outputs 11 years of the forcing, compared to 2 years with a 20 year length of the forcing, the bias from the mean in the 22 year forcing length is less substantial.

The 21 and 23 year length of the forcing both showed a mean similar to the true mean. However, with a 21 year length of the repeated forcing, the years with low or high SMB were unevenly sampled (figure 3.5). Therefore, every 10 outputted years (210 years), a large shift in the outputted SMB occurred. The 23 year length of the forcing has a more evenly distributed sampling of the SMB, with several smaller shifts occurring every 230 years (see figure 3.5b). Since the forcing data is outputted more evenly and each year in the forcing is outputted, the final length of the forcing was chosen to be 23 years.

It should furthermore be noted that both the 17 and 27 year lengths of the forcing are also suitable to be used combined with a 10 year output frequency. However, a 23 year length of the forcing was preferential, as the forcing length is short while inter-annual variability are still well represented.

3.2.3 Forcing Scenarios

Four different forcing scenarios were considered for this thesis. Figure 3.6 shows the CO_2 concentration during the 1% to 4x CO_2 simulation that is used to force the ice sheet. The 2x, 3x and 4x CO_2 forcing, shown by the blue, orange and red bands, have a CO_2 concentration that is on average 2, 3 and 4 times larger compared to pre-industrial.

The SMB of the years outputted by the coupled simulation are shown in figure 3.7. The SMB for 2x CO_2 (blue), 3x CO_2 (orange) and 4x CO_2 (red) are repeated every 23 years. The SMB changes during the simulation due to changes in the ice sheet elevation.

The Recovery from 4x CO_2 simulation is forced by the climate derived from the pre-industrial coupled simulation. This forcing is repeated every 23 years. The main difference between the Recovery from 4x CO_2 simulation and pre-industrial simulation is that the ice sheet starts with 45% of the initial ice sheet mass. A more detailed summary of these forcing scenarios can be found in table 3.2.

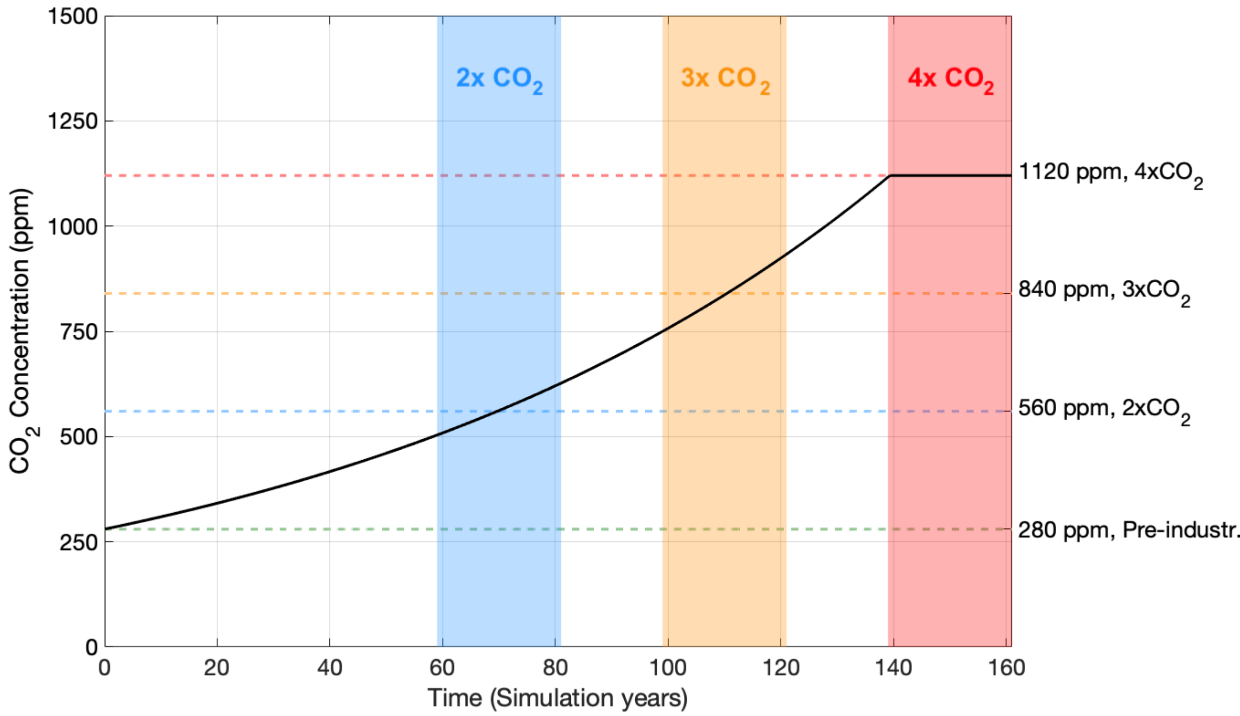
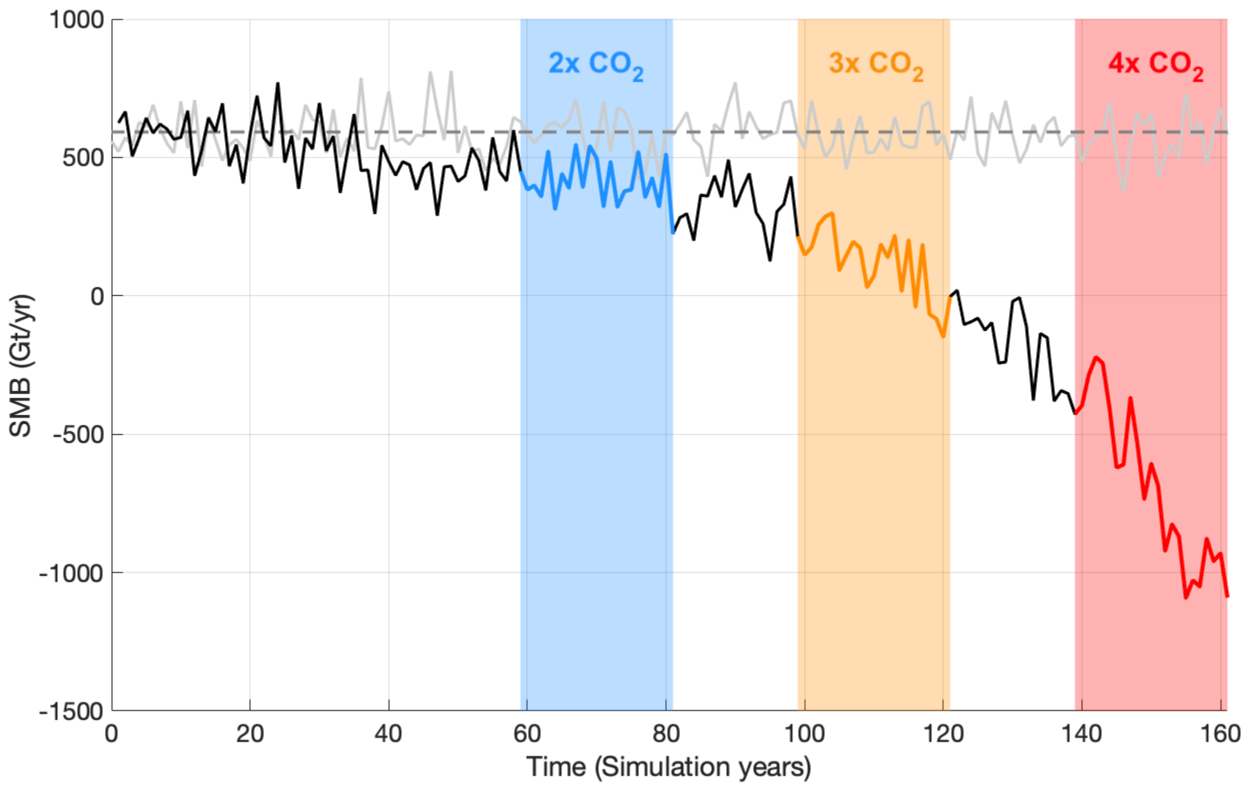


Figure 3.6: **The CO_2 concentrations in the coupled and uncoupled warming scenarios**. The CO_2 concentration in the coupled simulation that is used for the forcing of the 2x, 3x and 4x CO_2 scenario is depicted by the black line. The CO_2 concentration starts at 280 ppm, increases with 1% per year and is capped at 4x CO_2. The 23 years of forcing that is repeated has a mean of 2x, 3x and 4x CO_2. These forcings are represented by the blue (2x CO_2), orange (3x CO_2) and red (4x CO_2) bands.

High Forcing Scenario: 4x CO_2

The high CO_2 scenario concerns 4x CO_2. However, this simulation is different from the true 4x CO_2 simulation as the climate is not in quasi equilibrium. The first 162 years of the simulation shows a 1% increase in CO_2 concentration per year. At year 139, 4x CO_2 concentrations are reached. Since the climate system has inertia towards CO_2 increase, the SMB continues to drop. Therefore, the SMB in the 1% increase to 4x CO_2 simulation, continues to decrease. Years 139-161, amounting to 23 years, are used to force the ice sheet on multi-millennium time-scales.



SMB	Pre-industrial	2x CO_2	3x CO_2	4x CO_2
Forcing Years	1-300	59-81	99-121	139-161
Mean SMB (Gt/yr)	592	412	117	-686
Max SMB (Gt/yr)	813	546	299	-221
Min SMB (Gt/yr)	372	224	-148	-1092
σ SMB	82	86	123	286
Trend (Gt/yr^2)	-	-2.3	-13	-38

Figure 3.7: **The SMB during the coupled 1% to 4x CO_2 and pre-industrial simulation**. The SMB of the pre-industrial simulation is depicted in grey with the mean represented with a dashed line. The coupled warming simulation is depicted in black, with blue, orange and red representing the SMB forcing used for the 2x CO_2 (59-81), 3x CO_2 (99-121) and 4x CO_2 (139-161) forcing scenarios.

Intermediate Forcing Scenario: 3x CO_2

A cold 3x CO_2 uncoupled simulation was conducted. This run uses CLM output of the coupled run for year 99 - 122. Similar to the 4x CO_2 run, the climate used for the 3x CO_2 simulation is transient. However, the 3x CO_2 represents an intermediate climate between the 2x CO_2 and 4x CO_2 simulation, with an integrated SMB that is close to 0 Gt/yr at the start of the simulation. As a result, the drop in integrated SMB from the start of the simulation is close to the total calving flux at simulation year 0. This simulation is ran on a time-scale of 8,000 years.

Low Forcing Scenario: 2x CO_2

A 2x CO_2 simulation was run during this thesis. The first 82 years are similar to the 4x CO_2 run, with an increase in CO_2 of 1 percent per year from pre-industrial conditions. Forcing from years 59 to 82 are looped to force the ice sheet on a time-scale of 6,000 years. However, similar to the 3x CO_2 and 4x CO_2 simulation, this 2x CO_2 is not a "true" 2x CO_2 scenario due to inertia in the climate system: it takes longer for the entire climate system to respond to the change in climate. Instead, this simulation is an attempt to introduce a slightly warmer climate to Greenland, which should not be enough to destabilise the ice sheet. This should therefore indicate which areas are more susceptible to the warming in Greenland and furthermore show which processes could lead to the final stabilisation of the ice sheet.

Recovery Simulation: Re-introducing Pre-Industrial Conditions

As is discussed in chapter 4 in detail, by year 1,500 in the 4x CO_2 scenario, the ice sheet has retreated towards the interior of Greenland. This results in an ice sheet with strong negative SMB under 4x CO_2 forcing. To determine if the SMB-Elevation feedback causes the ice sheet to eventual collapse after substantial melting, the pre-industrial climate used for the control simulation was re-introduced to the ice sheet. 23 years of the pre-industrial forcing are repeated to simulate 4,000 years.

This forcing however was never coupled with the ice sheet after the ice sheet started melting. Therefore, the regrowth or deglaciation of the ice sheet is an effect of elevation change that took place during the 4x CO_2 simulation.

Table 3.2: **Summary of the CISM2.1 simulations**

	2x CO_2	3x CO_2	4x CO_2	Recovery
Starting Year	82	122	162	1462
Simulated Years	6,000	8,000	4,000	4,000
Forcing	1% to 4x CO_2	1% to 4x CO_2	1% to 4x CO_2	Pre-industrial
Forcing Years	59-82	99-122	139-162	277-300

3.3 Post-processing of the CISM2.1 output

The final results are represented as time-series and maps of Greenland.

Time-series were made of ice sheet scales that concern general descriptions of the ice sheet. These scalars are ice area, mass as well as the mass balance components. Maps were created of the ice thickness and velocity. These maps were made using the NCL mapping software. For the surface mass balance maps, python was used. Average of 230 years were taken to remove climate variability.

3.3.1 Transects of the Greenland Ice Sheet

Transects of the SMB, surface velocity and elevation were produced for this thesis to gain information on the evolution of the ice sheet within a chosen glaciers. The glaciers of focus are Jacobshavn, Humboldt and Hellheim, which are shown in figure 3.8.

To gain information on the amount of retreat during the TG simulation, the initial topography at the start of the TG simulation was chosen as the initial topography. Therefore, for the 2x, 3x and 4x CO_2 simulations, the initial years are 82, 122 and 162 respectively. A distance of 0 kilometres was chosen to be the initial ice sheet extent of the start of the TG simulation.

As was discussed before, the SMB is highly dependent on the climate. Each year in a forcing cycle has a slightly different SMB even if the elevation is constant. Therefore, a 230 year running mean was applied to the SMB.

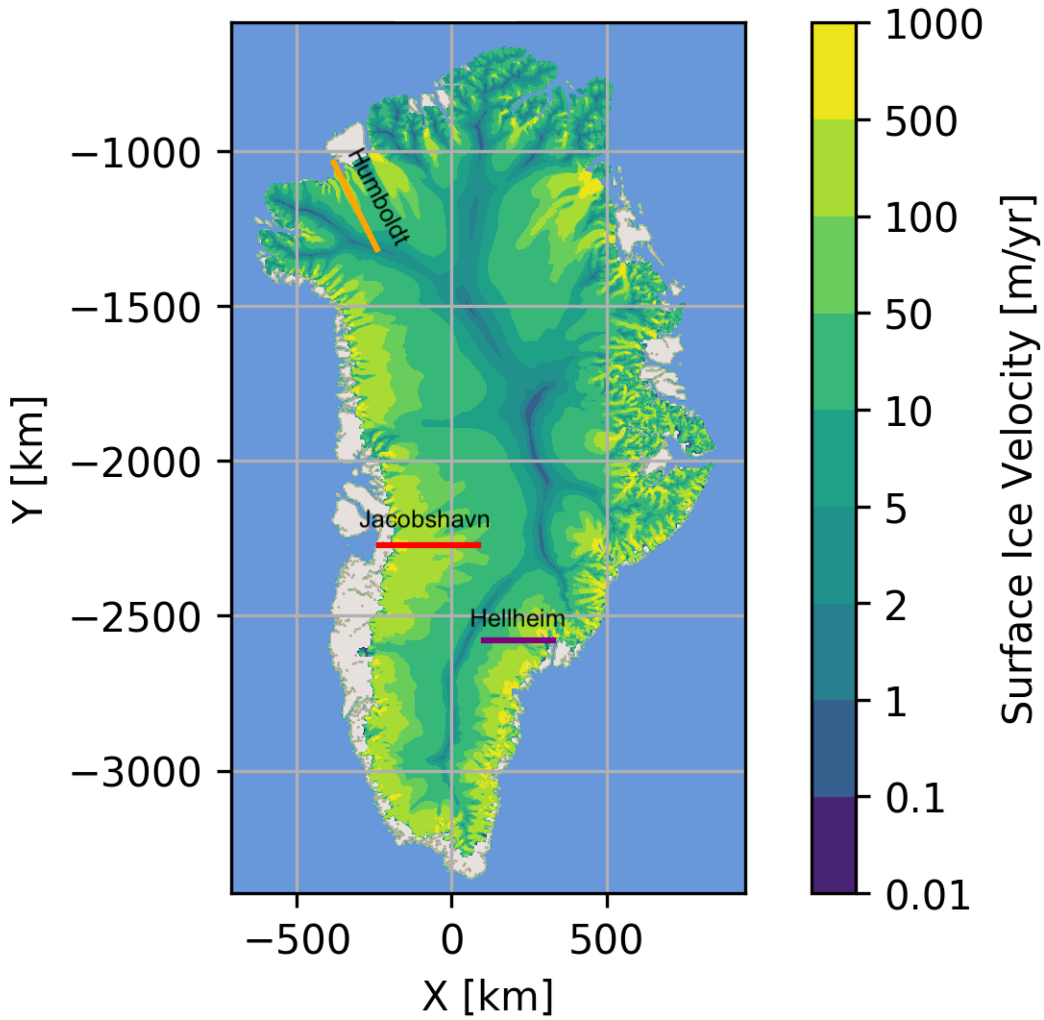


Figure 3.8: **The location of the transects for Hellheim, Humboldt and Jacobshavn glaciers**

3.3.2 Classification for the Ice Discharge Maps

To gain an understanding of the change in calving rate in a 2D space throughout the time-series, maps of the calving rate were made. However, CISM2.1 outputs the calving rate per 4 x 4 kilo meter grid-cell, and therefore larger ice-flow are represented by several grid-points. This can be seen in figure 3.9, which shows a velocity map of Western Greenland with non-zero calving gird-points depicted as blue and red grid-cells. In order to depict the calving rate per ice-flow, a classification scheme was built.

In larger ice flows, the grid-points with non-zero calving rates are connected. Therefore, a classification scheme that identifies all directly and diagonally connected grid-points is a first step towards classification. However, many of the non-zero calving grid-points can be found outside the larger ice-flows. These grid-points have, in general, low values, several magnitudes smaller than 1 Gt/yr. Therefore, if only a connected elements classification scheme is used, large patches of low calving-rates or larger ice flows will be grouped as one class. To solve this issue, the search radius of the classification scheme is adapted based on the magnitude of the calving rate. This is represented by the different coloured pixels in figure 3.9. The threshold for the change of search radius was established at 0.02 Gt/yr. This value was determined by visually assessing the classification for the glaciers in Greenland. To remove redundant ice discharge flows, as each margins that borders will often have ice discharge, a threshold of 0.02 Gt/yr was used for plotting.

Figure 3.9 shows the classification of the outlet flows. The red grid-cells have a calving rate that exceeds 0.02 Gt/yr and the blue pixels have a calving rate that is below this threshold. The high-calving rate grid-cells check for each surrounding pixel if it has a non-zero calving rate. If a non-zero calving rate is found (blue or red grid-cells), this grid-cell will receive the same class as the red-grid-cell. Therefore, if there are many grid-cells with high calving rates in an area, they will all receive the same class, as well as the surrounding low calving rates. The low calving rate grid-cells, which are depicted by a blue colour, receive their own class, except if they are connected by a red-pixels. As a result, the smaller ice-flows each receive their own class, while several grid-points that constitute one ice flow are classified as one class. These smaller ice flows will later be filtered out by using the threshold for plotting.

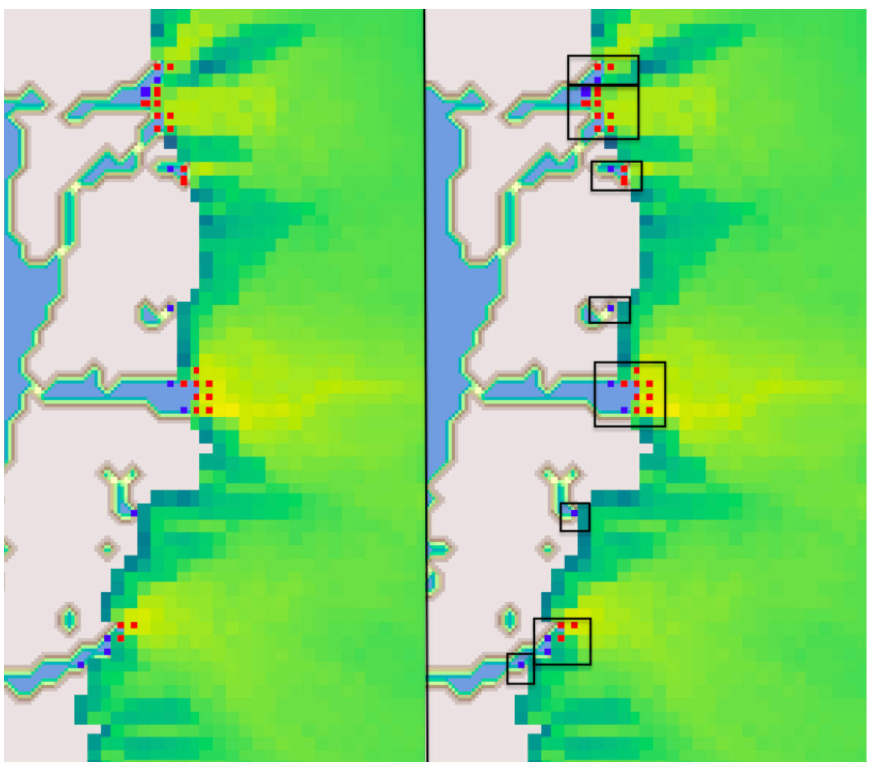


Figure 3.9: **An example for the classification of the ice discharge per ice flow**. Each black square represents a class and each blue or red coloured scare shows a grid-cell with a non-zero calving rate. A grid-cell with an ice discharge larger than 0.02 Gt/yr is depicted as red and groups each neighbouring grid-cell as the same class. A blue grid-cell has a low calving rate and will receive its own class unless it is connected to a red-pixel.

Chapter 4

Results and Analysis

The results from the uncoupled CISM2.1 runs that were performed in this thesis are introduced. First of all, I discuss and compare the evolution of melt of the 2x, 3x and 4x CO_2 simulations in detail. Secondly, I introduce the results from the Recovery from 4x CO_2 simulation. As stated before, a general overview of the simulations is shown in table 3.2.

4.1 Pre-industrial and Spin-Up Simulations

A pre-industrial coupled and uncoupled simulation were conducted. The coupled simulation was ran for 300 years, while the uncoupled simulation was ran on a time-scale of 9,000 years.

Figure 4.1 shows the cumulative sea level rise of each scenario, including the uncoupled pre-industrial scenario. The trend in sea level rise for the pre-industrial simulation is 0.018 mm/yr.

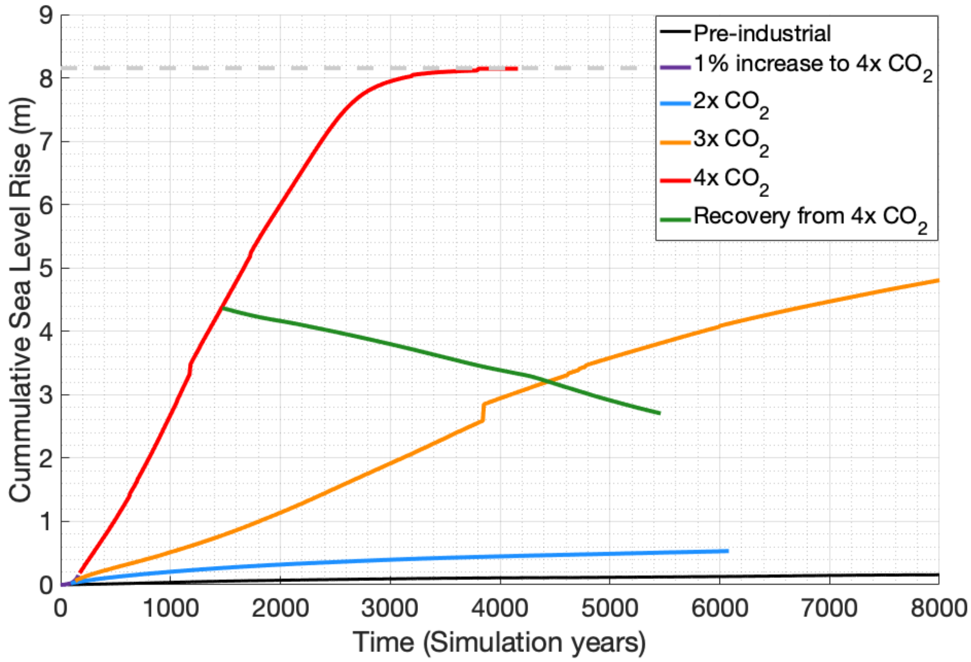


Figure 4.1: **The cumulative sea level rise during the 2x, 3x and 4x CO_2 simulation, as well as the uncoupled pre-industrial simulation**. The total sea level equivalent mass that is stored in the Greenland ice sheet is shown with a dashed grey line.

4.2 Greenland Melt Evolution of the Warming Scenarios

Three warming scenarios were considered in this thesis; a 2x, 3x and 4x CO_2 simulation. This section, the results for each of these simulations are introduced and analysed. First of all, the initial responses to climate warming by year 500 are introduced. Secondly, the deglaciation of Greenland on multi-millennium time-scale is assesses. Thirdly, the maximum sea level rate and minimum ice discharge for each simulation are introduced. Fourthly, the responses of the Hellheim, Humboldt and Jacobshavn are analysed. Lastly, the equilibrium of the ice sheet in each warming scenario is discussed.

4.2.1 Response of the Ice Sheet by year 500

The most substantial response to climate warming took place within the first 500 years (see figure 4.6a+c. The first 500 years for the 2x, 3x and 4x CO_2 climates shows similarities, even though the SMB decrease varies substantially between the different scenarios. The pre-industrial integrated SMB of 592 $\pm$ 82 Gt/yr decreases to 428 $\pm$ 84 Gt/yr (year 59-81), 136 $\pm$ 137 Gt/yr (year 99-121) to -654 $\pm$ 280 Gt/yr (year 139-161) for the 2x, 3x and 4x CO_2 scenarios respectively (see table 3.7).

As shown in figure 4.4a,b,c the SMB is low at the margins in each scenario and has decreased compared to the initial ice sheet (4.14a). As a result, these regions are the first areas to

show substantial deglaciation. The timing and extent of this retreat was different for each warming scenario. By year 500 of the 2x CO_2 scenario, the ice sheet thickness and extent show little change. The thinning within the first 500 years was furthermore limited to the West and North-West of the ice sheet.
By year 500 in the 3x CO_2 simulation, the ice sheet thinned and retreated in the West, South and East. The warmest scenario considered here, 4x CO_2, had substantial retreat in all margins of Greenland. In each scenario, the thickness decrease in the interior is limited and some areas in the interior accumulate mass (see figure 4.4a+b+c).

This vulnerability of the margins of the ice sheet compared to the interior can be explained by the low ice sheet topography of the margins. At margins with low topography, the SMB is dominated by melt rather than precipitation as temperatures are higher. Increasing the temperature both decreases the SMB at the margins and expands the ablation area, since the equilibrium line increases in altitude. Due to the 2-3 kilometre thickness of the ice sheet in the interior, temperatures are lower and the melt rate is substantially decreased. As a result, the SMB is mostly dominated by changes in precipitation. Therefore, increasing the temperature in the interior will not lead to a substantial decrease in SMB in the high elevation interiors. Instead, the warming of the climate can lead to a larger increase in precipitation compared to melt, resulting in a more positive SMB. These processes can be seen in figure 4.4. The ablation areas have expanded further into the interior with increasing warming. This is partly due to the warming of the climate, and thinning and retreat of the margins by year 500. In the 3x and 4x CO_2 scenarios (figure 4.4), the climate warming has resulted into an increase in SMB in the interior. As shown in the figure, the 4x CO_2 scenario has larger ablation areas compared to the 2x and 3x CO_2 scenarios. By year 500, the ablation areas contribute 7%, 13% and 35% of the ice sheet area in the 2x, 3x and 4x CO_2 scenarios.

The substantial retreat at the margins combined with thickening in the interior can also be seen by the mean thickness (see figure 4.1). The mean thickness increases during the first 500 years of the 4x CO_2 simulation, as a result of retreat of the low-elevation margins and thinning in the interior.

The thinning and retreat at the margins also lead to a decrease in ice discharge. As shown in figure 4.6, the ice discharge decreases substantially for each warming scenario and table 4.2. The decrease in the total calving rate is also visible in spatial maps per outlet glaciers, as shown in figure 4.2. The 2x CO_2 scenario (figure 4.2b) showed reduced calving outflow in the West and North-West of the ice sheet compared to the pre-industrial ice discharge map (figure 4.2 d). The 3x CO_2 scenario had a more substantial decrease in oceanic terminating glaciers in the West and East. The South-East and North however, still retain most of the larger glaciers. In the 4x CO_2 scenario, at year 500, most glaciers became land terminating. The number of outlet glaciers have decreased substantially. Some larger glaciers, such as Kangerdlugssusaq, Jacobshavn and NEGIS remained ocean-terminating by year 500, but the ice discharge rate of these glaciers has reduced substantially.

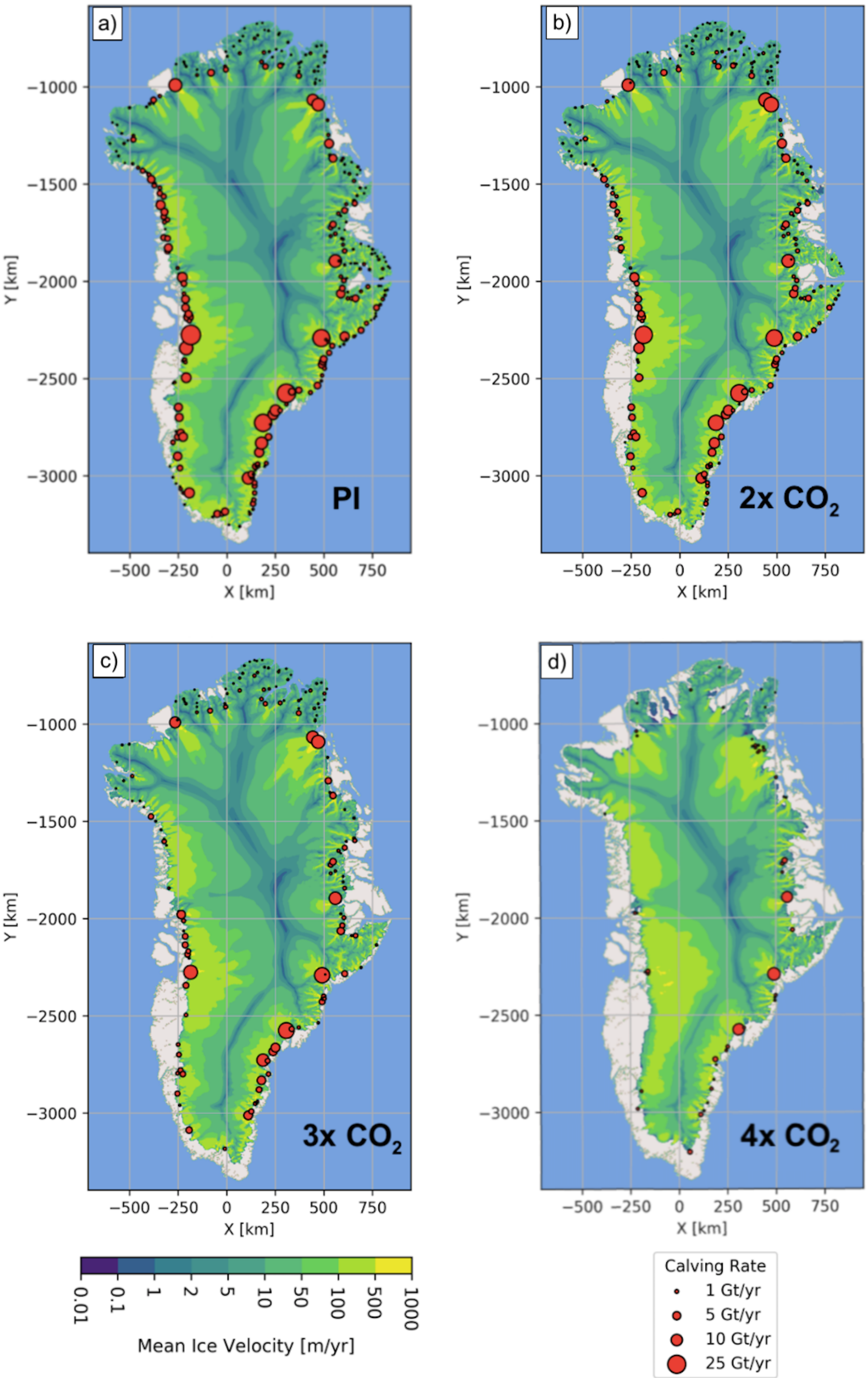


Figure 4.2: **Mean ice discharge for the warming scenarios by year 500**. These maps show the total ice discharge per classified ice flow outlet for the 2x CO_2 (b), 3x CO_2 (c) and 4x CO_2 (d) scenarios averaged over years 390-610 and the pre-industrial (a) scenario. More climate warming led to enhanced retreat and thinning at the margins resulting into a reduction in ice discharge.

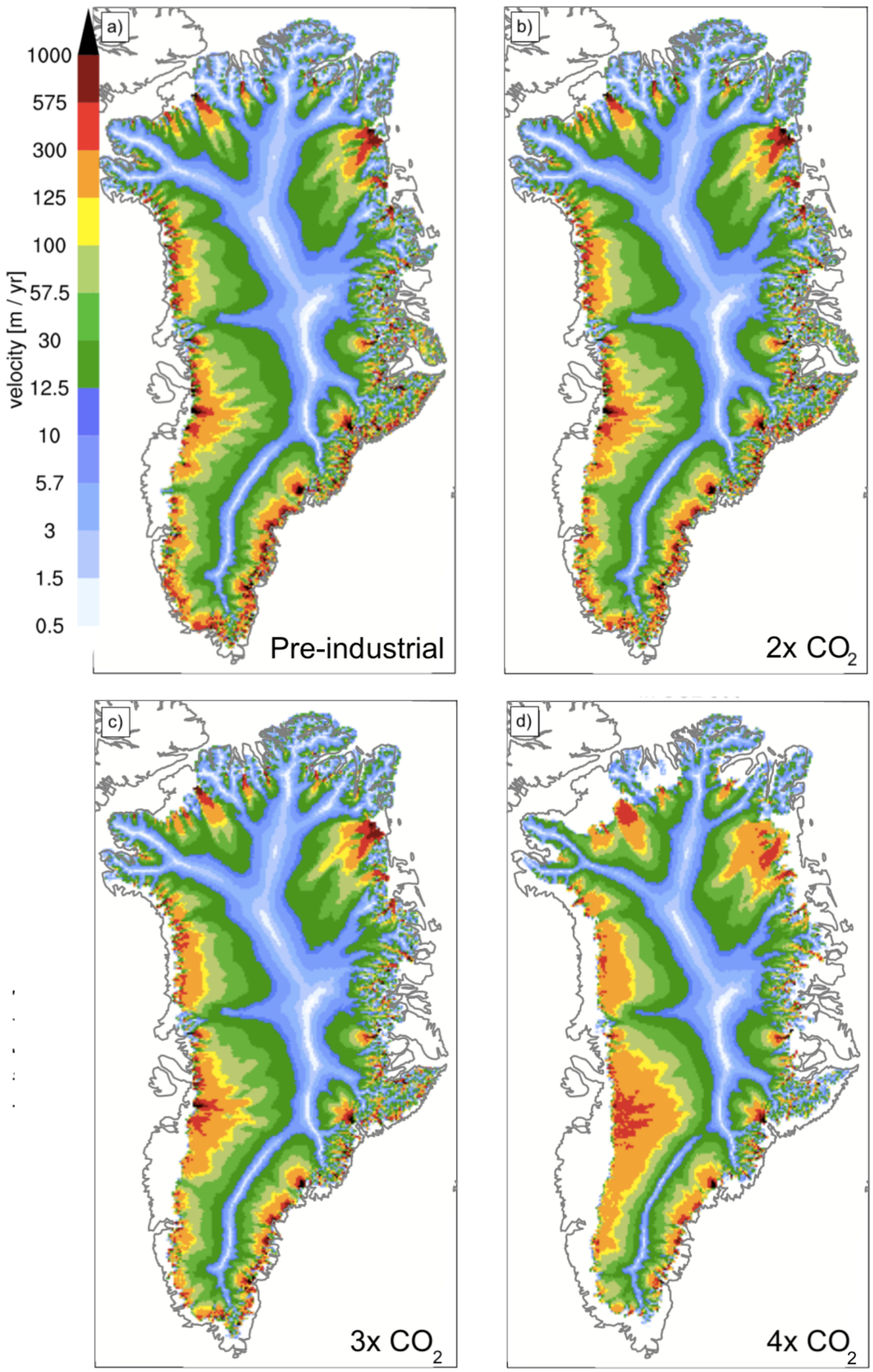


Figure 4.3: **The velocity by year 500 in the 2x, 3x and 4x CO_2 simulations**.

Table 4.1: Mean and Maximum Thickness

Thickness (m)	2x CO_2		3x CO_2		4x CO_2	
Simulation Year	Mean	Max	Mean	Max	Mean	Max
1	1643	3701	1643	3701	1643	3701
500	1646	3704	1695	3714	1691	3722
1000	1637	3701	1678	3720	1691	3722
1500	1627	3695	1648	3711	1652	3620
2000	1619	3688	1612	3639	1482	3310
4000	1598	3676	1548	3645	253*	2653*
6000	1586	3670	1507	3496	-	-

Table 4.2: **The change in SMB, MB and Ice Discharge by year 500 for the 2x, 3x and 4x CO_2 compared to the mean of the pre-industrial simulation.**. The SMB drop by year 500 is partly compensated by a decrease in ice discharge and basal melt in each scenario.

MB components (Gt/yr)	Mean PI	2x CO_2	3x CO_2	4x CO_2
SMB	592 $\pm$ 82	430 $\pm$ 85	150 $\pm$ 111	-876 $\pm$ 289
Calving Rate	579 $\pm$ 4	447 $\pm$ 4	287 $\pm$ 9	83 $\pm$ 15
MB	-11 $\pm$ 82	-61.0 $\pm$ 83	-157 $\pm$ 113	-978 $\pm$ 289

By year 500, the previously discussed reduction in ice discharge has partly compensated the drop in SMB in the 2x and 3x CO_2 simulation. The drop in SMB in the 4x CO_2 simulation is also partly compensated by a drop in ice discharge. However, due to a strong negative SMB, the MB is negative as well. These changes in SMB, MB and calving rate by year 500 are summarised in table 4.2. The drop in SMB is compensated by a decrease in calving rate and basal melt by 67%, 65% and 33% for the 2x, 3x and 4x CO_2 scenarios. In the 2x CO_2 and 3x CO_2 scenario, this compensation of ice discharge leads to a small sea level rise of 0.17 $\pm$ 0.23 mm/yr and 0.43 $\pm$ 0.31 mm/yr. However, in the 4x CO_2 scenario, the drop in SMB is almost 3 times higher compared to the pre-industrial ice discharge rate. As a result, even though the ice discharge has reduced by 86% the sea level rise in the 4x CO_2 simulation is 2.7 $\pm$ 0.8 mm/yr by year 500.

4.2.2 Multi-Millennium Time-Scale Melt of the Greenland Ice Sheet

The Greenland ice sheet showed melt on multi-millenium time-scale in each scenario. However, the 2x, 3x and 4x CO_2 scenarios have a substantially different response in stability as well as timing of deglaciation.

The 2x CO_2 simulation shows limited retreat and attains stability by year 4,000 (4.6). As shown in figure 4.10, the total retreat in Greenland by year 4,000 is limited to the South-West and North-West.

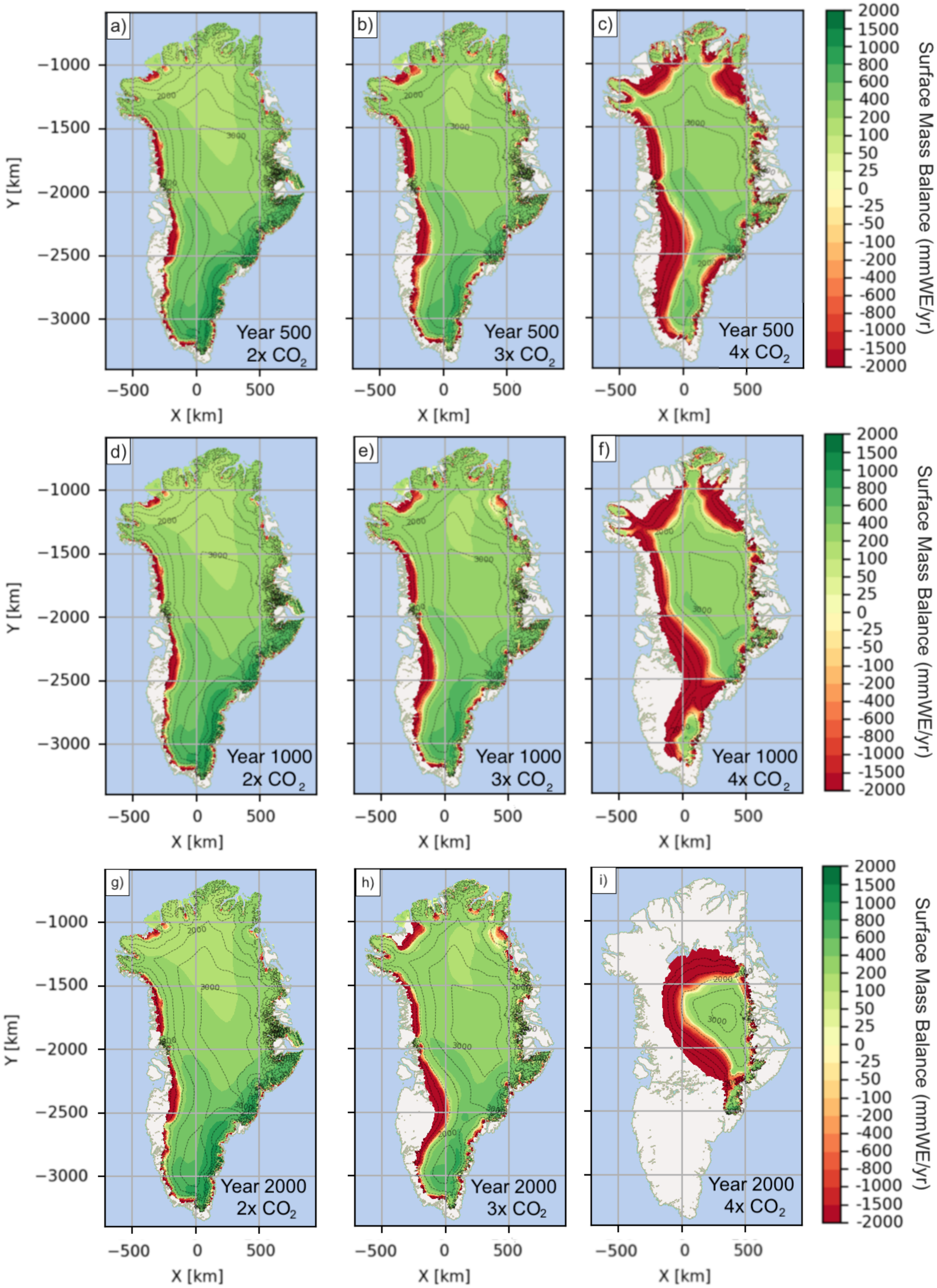


Figure 4.4: **The SMB during the 2x, 3x and 4x CO_2 scenarios**. To remove the climate variability, the SMB was averaged over 230 years. The SMB is shown for year 500 (a,b,c), year 1,000 (d,e,f) and year 2,000 (g,h,i)

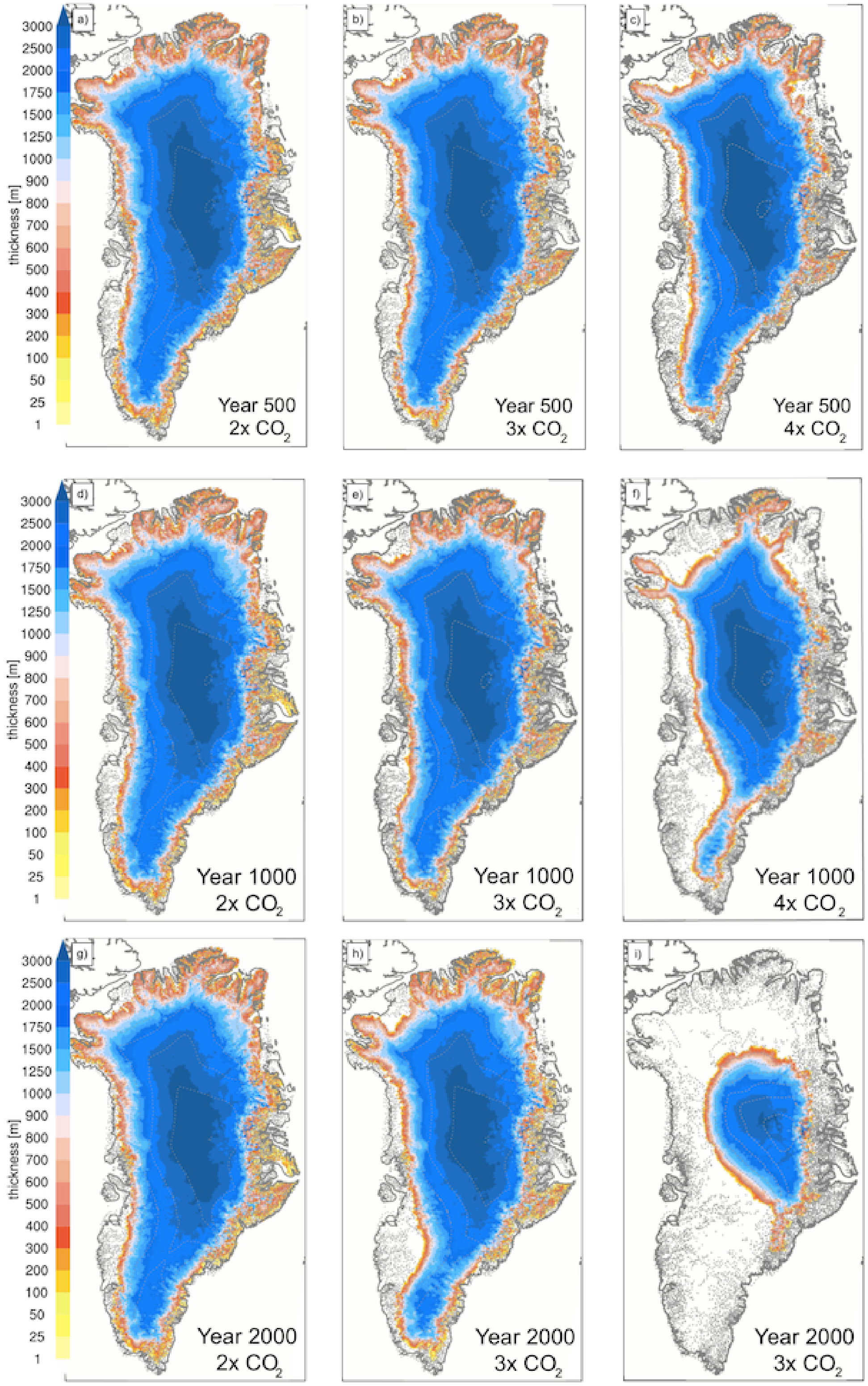


Figure 4.5: **The evolution of the thickness and ice sheet extent in the 2x, 3x and 4x CO_2 simulations**. Year 500 (a,b,c), year 1000 (d,e,f) and year 2000 (g,h,i) are shown for each warming scenario.

The 3x and 4x CO_2 scenarios however, showed a very different ice sheet response. In both the 3x and 4x CO_2 simulation, the interiors melt on multi-millennium time-scales. By year 2,000, deglaciation is confined to the margins in the 3x CO_2 simulation (see figure 4.5h). By year 1,000, the interiors show substantial melt in the 4x CO_2 scenario as can be seen in figure 4.4f. During both the 3x and 4x CO_2 simulations, the deglacation is not uniform across Greenland: By year 1,000 in the 4x CO_2 simulation, melt is less substantial in the East, South-East as well as some small patches in the North (see figure 4.5f). The areas with faster melt tend to be the areas with larger surface velocities, as shown in figure 4.3. As a result, melt is asymmetrically across Greenland leading to the formation of often elongated ice cap peninsulas that are attached to the main ice sheet (see figure 4.5f). This processes is also present in the 3x CO_2 simulation (figure 4.5h). In the ice sheet model, these ice caps are immediately removed within 1 internal time step (0.1 years) if they are detached and the maximum thickness does not exceed 2 kilometres. As a result, sharp decreases in ice area are present in the time series as these ice cap peninsulas are removed (see figure 4.6b). This feature has recently been resolved due to, amongst others, the results of this thesis.

The timing and extent of the retreat are different for the 3x and 4x CO_2 simulations, as can be seen in figure 4.5, 4.10 and in table 4.4. The decrease in ice area and ice mass is faster in the 4x CO_2 scenario compared to the 3x CO_2 scenario. As a result, the 3x CO_2 simulation takes substantially longer to deglaciate compared to the 4x CO_2 scenario.

4.2.3 Maximum Sea Level Rise Contributions

The minimum of the mass balance fluxes is substantially different for each warming scenario considered. The 2x CO_2 simulation has a positive SMB throughout the simulated 6,000 years, as can be seen in figure 4.6d. The minimum 230 year average Mass Balance -93.4 $\pm$ 83 Gt/yr corresponding to a sea level rise of 0.26 mm/yr. This minimum in Mass Balance is reached during the first 230 years (year 82-302) of the uncoupled 2x CO_2 simulation. By year 4,000 the 230 year the mass balance is close to 0 mm/yr. While the SMB is positive throughout the simulation, the SMB drops from 592 $\pm$ 82 Gt/yr to 385 $\pm$ 86 Gt/yr by year 4000. This drop in SMB is fully compensated by a decrease in ice discharge from 579 $\pm$ 4 Gt/yr to 377 $\pm$ 16 Gt/yr. This small SMB results in only 0.57 meters of sea level rise.

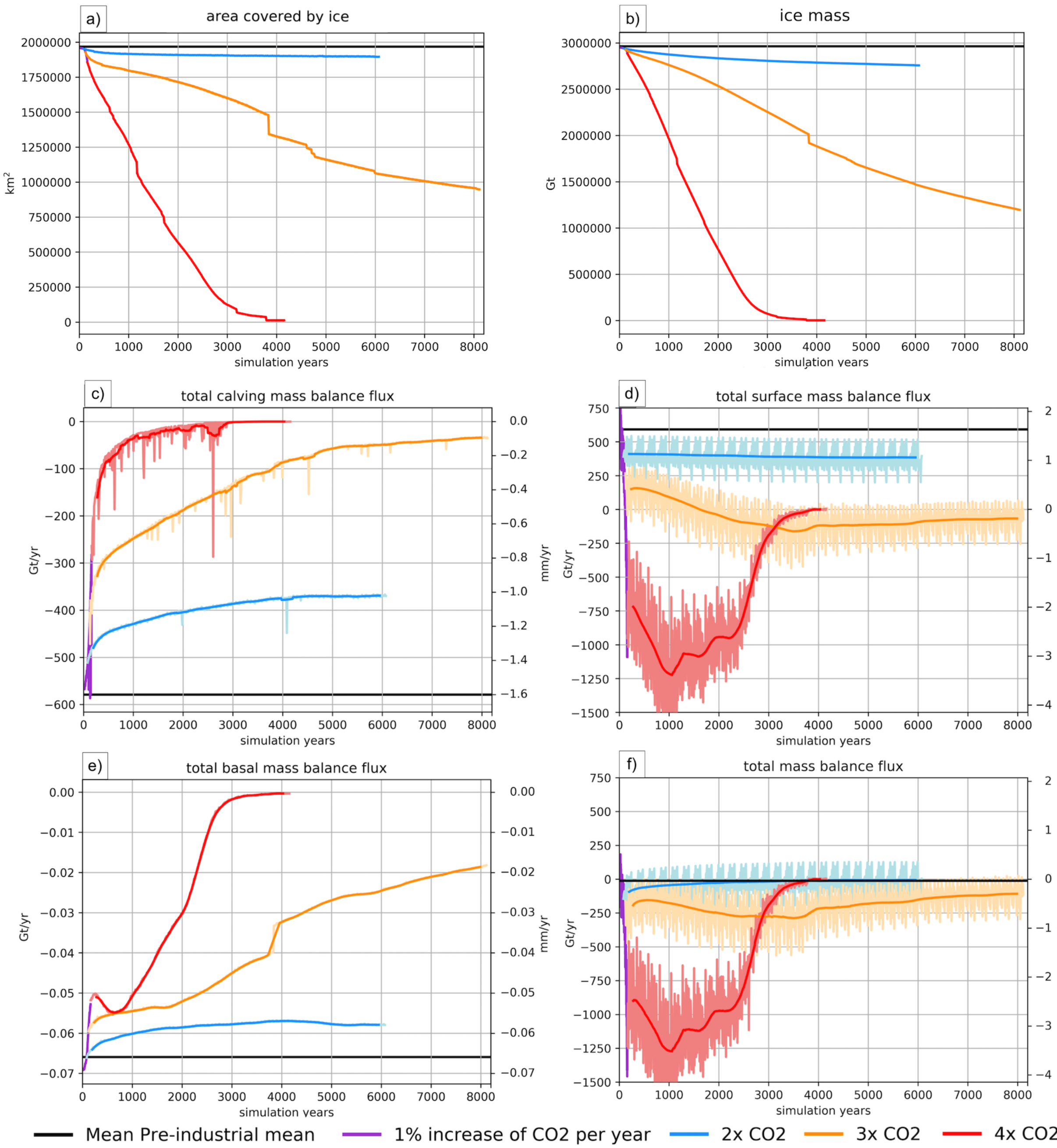


Figure 4.6: **The ice area, mass and mass balance component evolution of the Greenland ice sheet in the 2x, 3x and 4x CO_2 scenario**. Figure a and b show the ice area and ice mass of the ice sheet. Figures c,d,e and f show the mass balance components. In the mass balance component plots, the darker colours show the 230 year running mean of the data.

The minimum Mass Balance for the 3x and 4x CO_2 simulations are not reached at the start of the simulation. By year 1,060, the SMB is minimum at -1,224 ± 309 Gt/yr, with a MB of -1,273 ± 310 Gt/yr corresponding to a sea level increase 3.52 ± 0.86 mm/yr. The ice area at year 1,060 has reduced to 62.3% of the original ice sheet extent. A map showing the minimum SMB, averaged over year 890-1110 is shown in figure 4.4f. By year 1,000 the ablation areas contribute 45.6% of the ice sheet. In contrast, at the start of the uncoupled simulation (year 162-382), 34.5% of the ice sheet is ablation areas.

The 230 year mean SMB increases after year 1,060 as the increase in SMB due to thinning is fully compensated by the loss of area. Therefore, if substantial area is lost, the SMB increases towards 0 Gt/yr as areas with low SMB are removed. By year 1,060, the increase in the 230 year mean SMB is most likely predominantly caused by the removal of the ice sheet in the South by year 1,170 (see figure 4.5h+j).

The 3x CO_2 simulation has a substantially higher SMB compared to the 4x CO_2 simulation. The SMB during the 3x CO_2 simulation is positive until simulation year 1,500. The SMB continued to decrease until it reached a minimum by year 3,400 with -162 $\pm$ 124 Gt/yr. This minimum SMB corresponds to a Mass Balance at -288 $\pm$ 124 Gt/yr which is equivalent to a sea level rate of 0.80 $\pm$ 0.34 mm/yr. These minimum MB and SMB are reached with an ice sheet extent of 78% compared to the pre-industrial ice sheet. As shown in figure 4.5h, an area with low thickness can be found between the Southern and Main ice sheet. It is very likely that the loss of this bridge between the Main and Southern ice sheet led to the increase in SMB after year 3,400.

Minimum Ice Discharge

A striking difference between the 3x and 4x CO_2 simulations was the evolution of the ice discharge. In the 4x CO_2 scenario, each margin except the Eastern margin substantially retreated. In the 3x CO_2 scenario, retreat was limited in the North, East and North West (see figure 4.5b,e,h). The reduction of ice discharge shown by year 500 in the 4x CO_2 scenario takes 4600 years for the 3x CO_2 scenario. By year 4900 (3x CO_2) and 650 (4x CO_2) the ice discharge has reduced by 90% from the pre-industrial mean and the ice sheet can be considered to be land terminating. By year 1,000, during the 4x CO_2 scenario, calving in the ocean is limited to the North. As the ice sheet retreated towards the interior, new calving fronts form in areas with a bedrock topography below 0 meters. Therefore, during the 4x CO_2 scenario, the ice discharge will only reach 0 Gt/yr by year 3650, as the ice has retreated towards the mountains in the East. The calving rate steadily declined with roughly 63 Gt/yr per 1000 years between year 500 and 3000 in the 3x CO_2 simulation. By the end of the simulation, year 8122, the ice discharge had reduced by 94% compared to the pre-industrial ice sheet.

4.2.4 Response of the Jacobshavn, Hellheim and Humboldt Glaciers

Transects of the Humboldt, Jacobshavn and Hellheim glaciers were made to asses the response of these glaciers under the 2x, 3x and 4x CO_2 forcing. Figures 4.7, 4.8, 4.9 show the evolution of Jacobshavn, Hellheim and Humboldt glaciers in the 2x, 3x and 4x CO_2 scenarios respectively. The locations of the transects is shown in figure 3.8.

Hellheim shows virtually no change during the 2x CO_2 simulation, while the glacier sub-

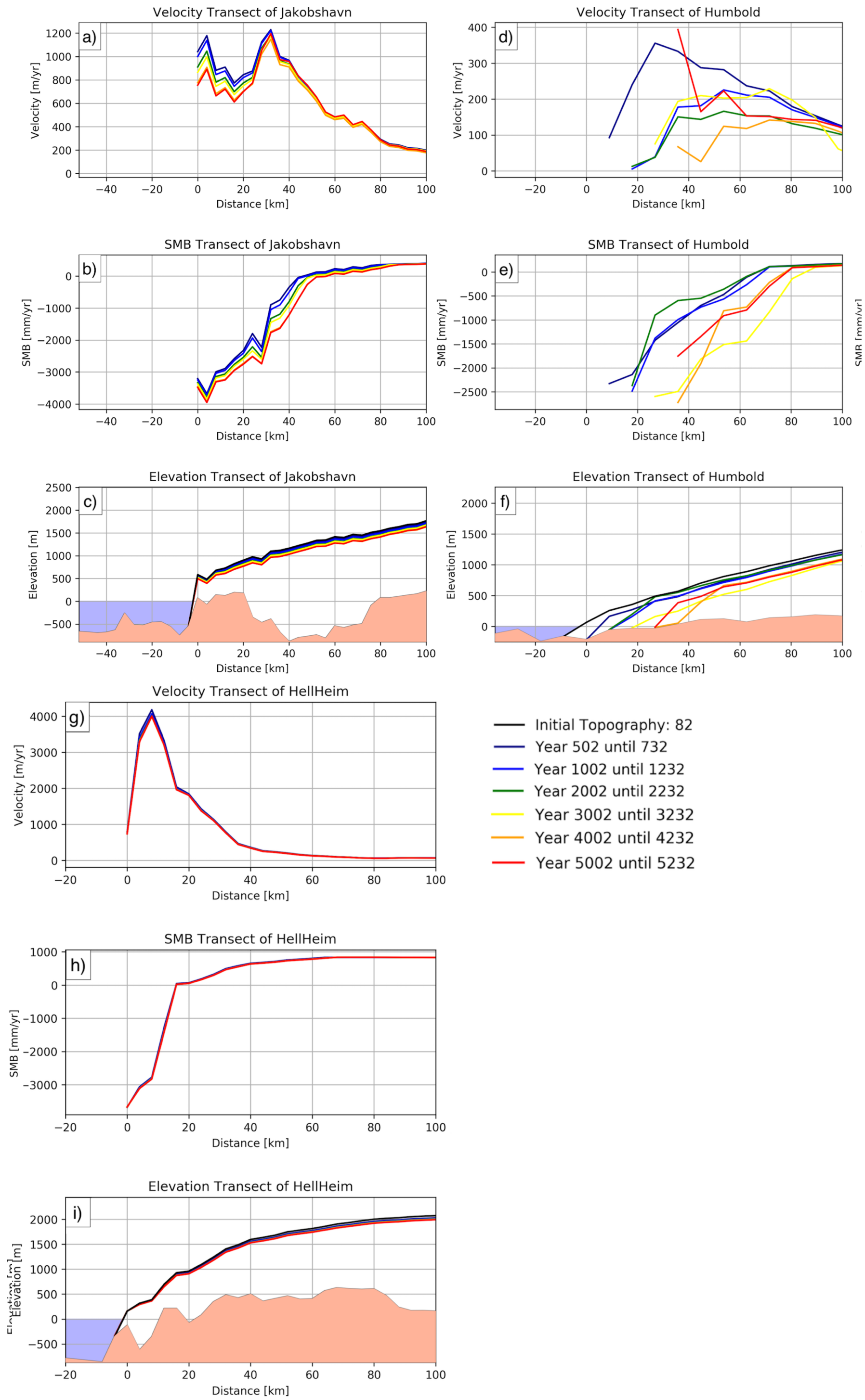


Figure 4.7: **Transects of surface velocity, SMB and elevation of three major glaciers in Greenland during the 2x CO_2 scenario.** This figure shows the velocity, SMB and elevation transects for Jacobshavn (a,b,c), Humboldt (d,e,f) and Hellheim (g,h,i).

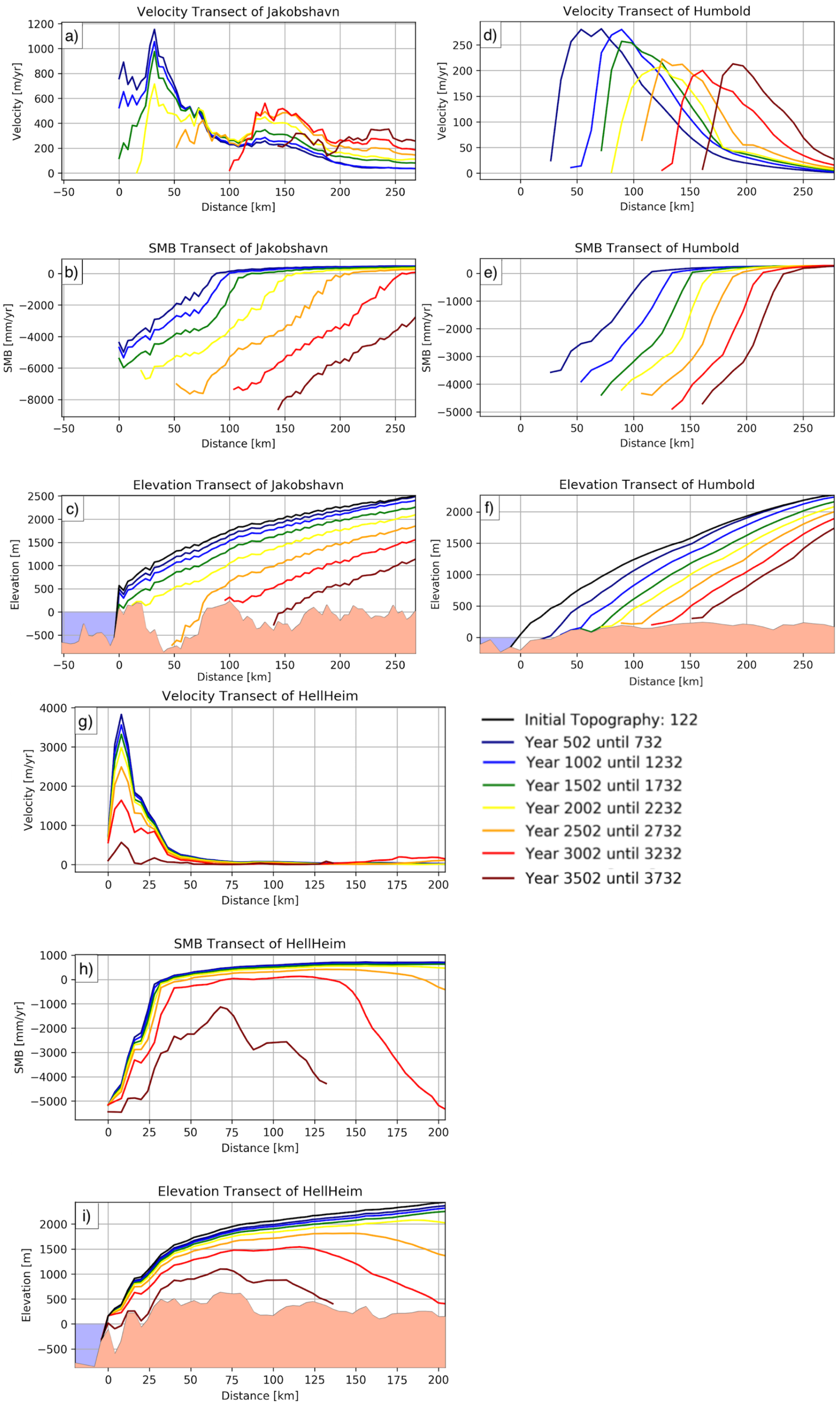


Figure 4.8: **Transects of surface velocity, SMB and elevation of three major glaciers in Greenland during the 3x CO_2 scenario.** This figure shows the velocity, SMB and elevation transects for Jacobshavn (a,b,c), Humboldt (d,e,f) and Hellheim (g,h,i).

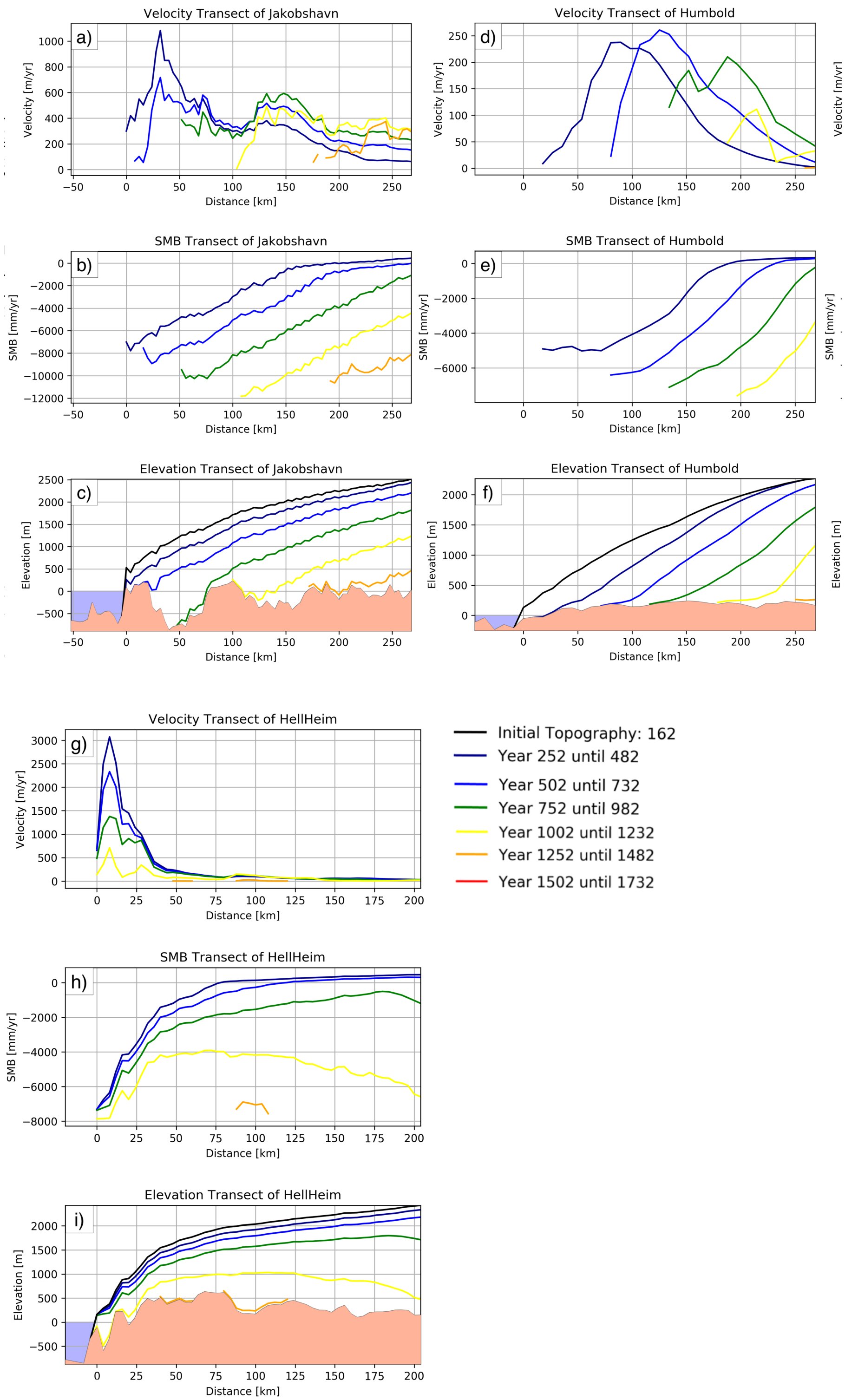


Figure 4.9: **Transects of surface velocity, SMB and elevation of three major glaciers in Greenland during the 4x CO_2 scenario.** This figure shows the velocity, SMB and elevation transects for Jacobshavn (a,b,c), Humboldt (d,e,f) and Hellheim (g,h,i).

stantially melts in the 3x and 4x CO_2 scenario. In the 3x CO_2 scenario, Hellheim is still ocean terminating by year 3,500, while in the 4x CO_2, Hellheim becomes land-terminating by year 1,000. This deglaciation is in both scenarios accompanied with a decrease in SMB and velocity. The ice sheet retreat is substantial in the South and West. Therefore, the ice sheet retreats towards Hellheim from the South-West: By year 3,500 in the 3x CO_2 scenario, Hellheim is ocean-terminating, but in the West, the ice sheet has retreated towards Hellheim. Once the retreat in the West is close to Western margin, the SMB decreases and the glacier rapidly melt.

Jacobshavn in the 2x CO_2 scenario shows little change. The glacier loses some mass resulting in a small decrease of velocity and SMB. In the 3x CO_2 and 4x CO_2 scenario, the margin of Jacobshavn retreats, however, the timing is substantially different: By year 1,500 and year 500 in the 3x and 4x CO_2 scenarios the margin of Jacobshavn starts to migrate towards the interior. After 1,000 years, Jacobshavn has retreated by 100 kilometres in the 4x CO_2 scenario, while it takes 3,000 years to retreat to the same distance in the 3x CO_2 scenario.

The Humboldt glacier shows substantial retreat in the 2x, 3x and 4x CO_2 scenarios. In the 2x CO_2 scenario, Humboldt becomes land terminating after 3,000 years and stabilises after a total retreat of roughly 30 kilometres. After 3,000 years the 3x CO_2 simulation however, shows a retreat of roughly 120 kilometres. The 4x CO_2 in comparison takes 750 years to retreat 120 kilometers.

Due to the SMB-elevation feedback, the SMB drops as the ice thins. With increased warming, the SMB lowers. For example, in Jacobshavn, with only limited thinning at the margins, the SMB is -3,200 mm/yr in the 2x CO_2, -4,000 mm/yr in the 3x CO_2 scenario and -6,500 mm/yr in the 4x CO_2 scenario.

The surface velocity changes substantially during the simulation. As the ice sheet retreats, the location of maximum velocity migrates as well, as can be seen by the transects of Humboldt and Jacobshavn. However, as the ice sheet retreats and thins, the maximum velocity decreases as well. For Hellheim, thinning of the ice sheet is limited in the margins, but thinning increases further inland. As a result, the surface slope decreases resulting in a substantial decrease in velocity. Acceleration of glaciers would be expected as the retreat is generally faster at the margins compared to the interior. However, substantial acceleration of the ice flow was not found on multi-century time-scales.

4.2.5 Equilibrium of the Ice Sheet

The 2x, 3x and 4x CO_2 scenarios have lead to substantially different ice sheet extents. The 2x and 4x CO_2 scenario have reached a final steady state by year 4,000, while the ice sheet in the 3x CO_2 scenario continues to evolve by year 8,000. The final ice sheet mass, area, SMB and MB can be found in table 4.4.

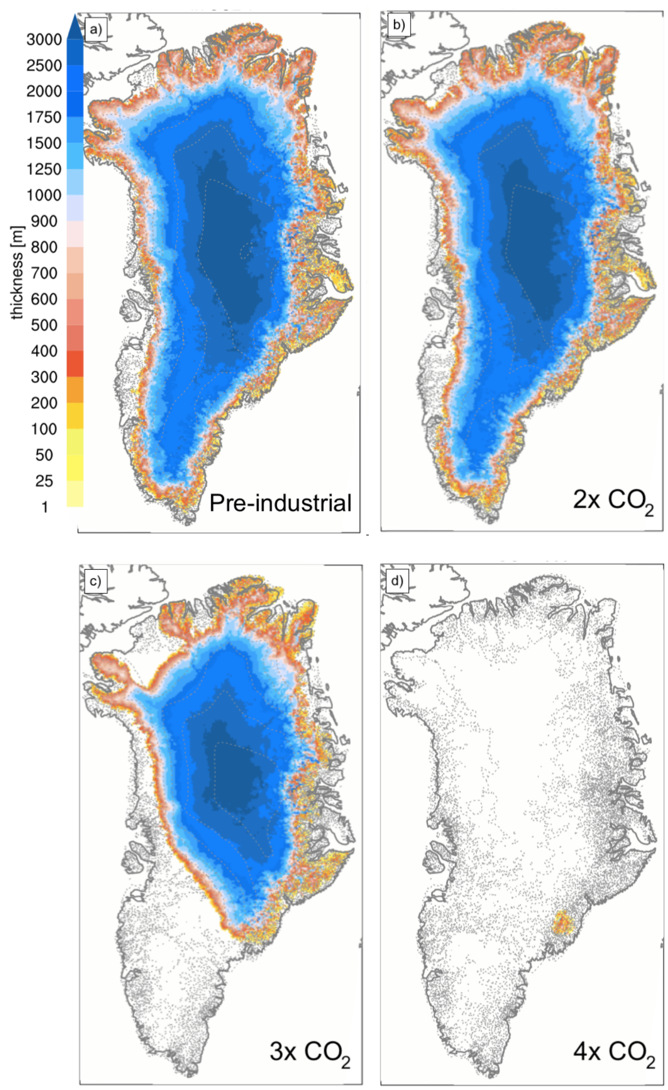


Figure 4.10: **The ice sheet thickness and extent by year 4,000 in the 2x (b), 3x (c) and 4x CO_2 (d) scenarios**. The pre-industrial ice sheet is shown in figure a.

The 2x CO_2 scenario was simulated for 6,000 years, though a steady-state was reached by year 4,000. The final ice sheet during the 2x CO_2 scenario has reduced 7.0% in mass resulting in 0.57 meters of sea level rise. Compared to the pre-industrial ice sheet, the SMB and calving rate have reduced by 35.2% and 36.2%. Since the reduction in SMB and ice discharge is similar, the ice sheet establishes a new steady-state with retreat and thinning of the ice sheet in the West and North-West. The 2x CO_2 simulation also shows some isostatic adjustments (see figure 4.11), which could have acted as a negative feedback towards ice melt.

The 4x CO_2 scenario is in stark contrast to the 2x CO_2 scenario. The ice sheet showed full deglaciation within 3,000 simulation years in the 4x CO_2 scenario. By year 3,600, the ice sheet shows a very small ice sheet extent, limited to the South-East of Greenland. By the end of the simulation (year 4162) the total sea level rise is 8.2 meters, with a total of 99% of ice mass and area.

The 3x CO_2 simulation was conducted for 8,000 simulation years. However, the ice sheet never reaches a quasi-equilibrium during the simulation. By year 8,000 the ice sheet has reduced 52% and 60% in area and mass, amounting to a total sea level rise of 4.9 meters. The Mass Balance by year 8,000 is negative with -108 $\pm$ 84 Gt/yr, which is equivalent to a sea level rate of 0.30 $\pm$ 0.23 mm/yr. The total SMB flux is negative at -67.3 $\pm$ 84.6 Gt/yr with an ice discharge of 34.3 $\pm$ 0.7 Gt/yr. Furthermore, the ice sheet extent is mostly locate in the centre of Greenland. The negative SMB and MB shows that the ice sheet will likely continue to retreat towards the East of Greenland in a time-scale exceeding 8,000 years.

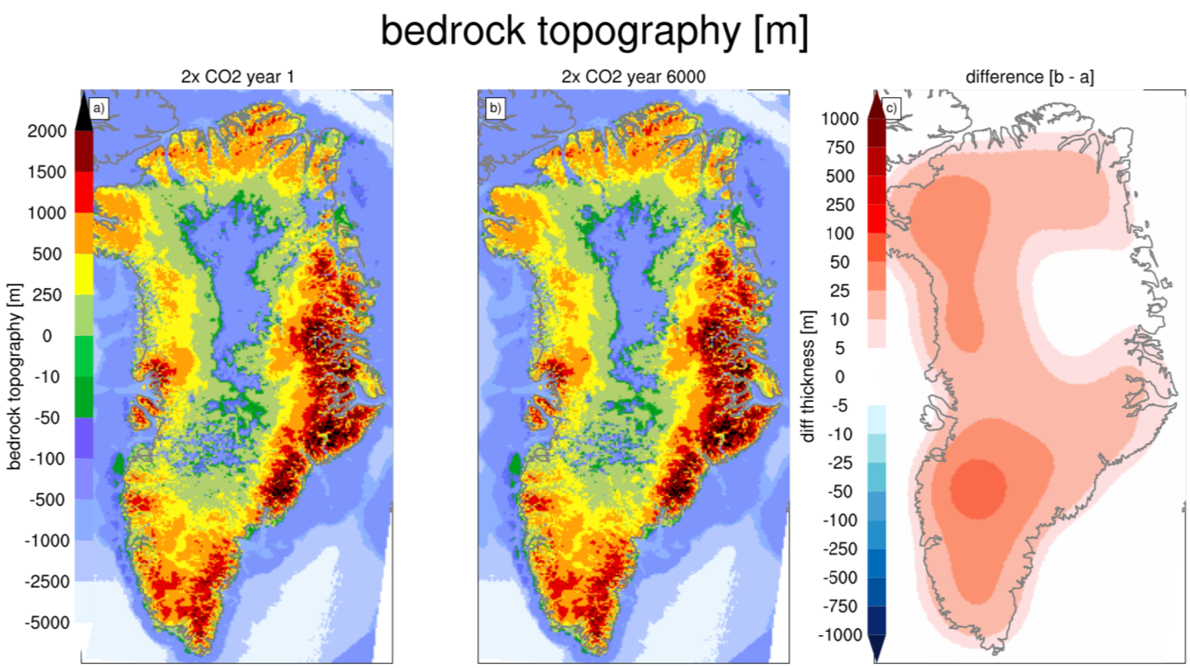


Figure 4.11: **The bedrock topography changes in the 2x CO_2 scenario**

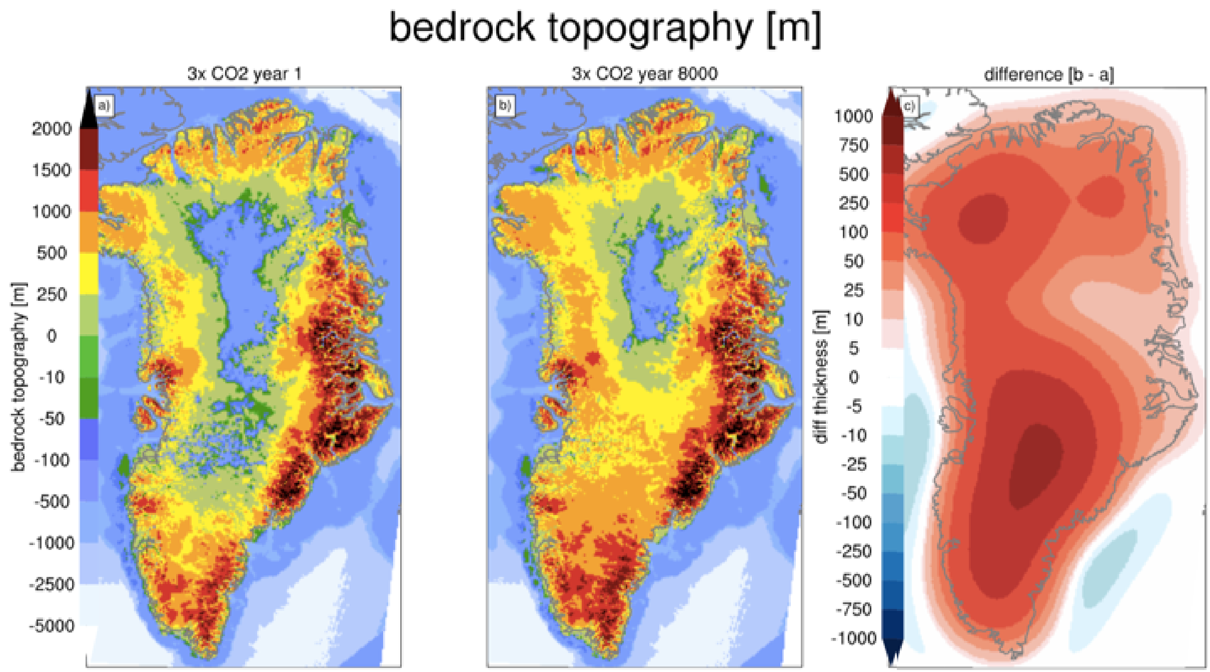


Figure 4.12: **The bedrock topography changes in the 3x CO_2 scenario**

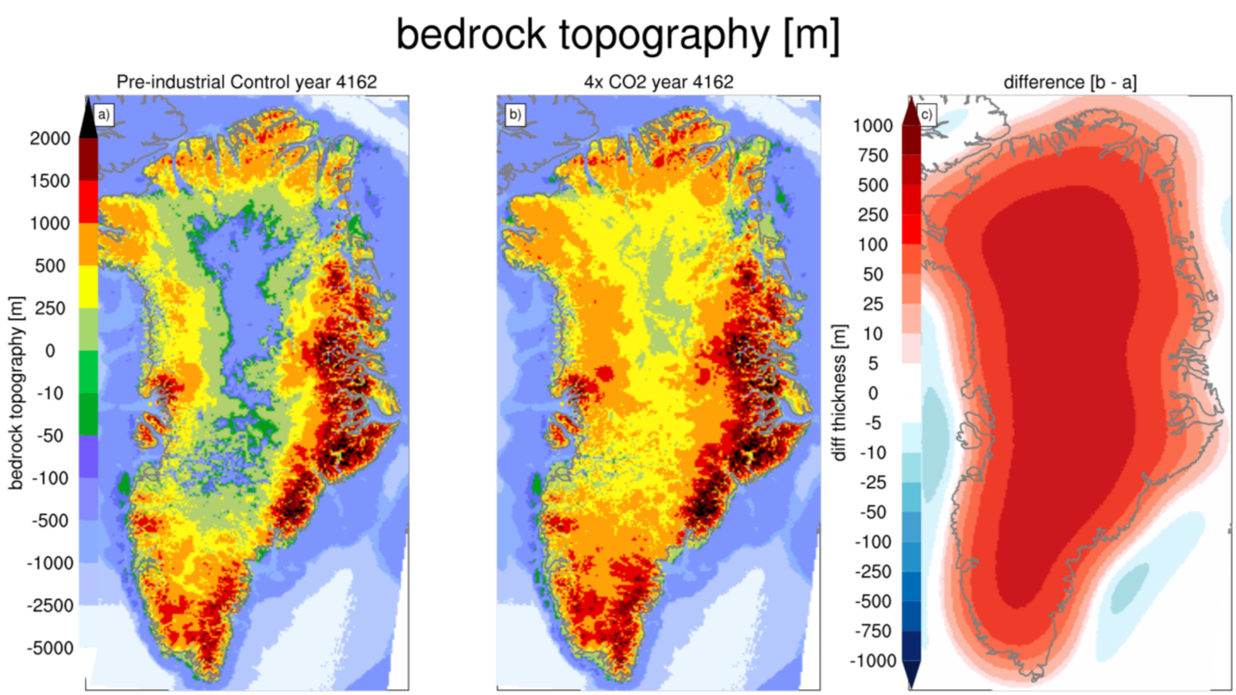


Figure 4.13: **The bedrock topography changes in the 4x CO_2 scenario**

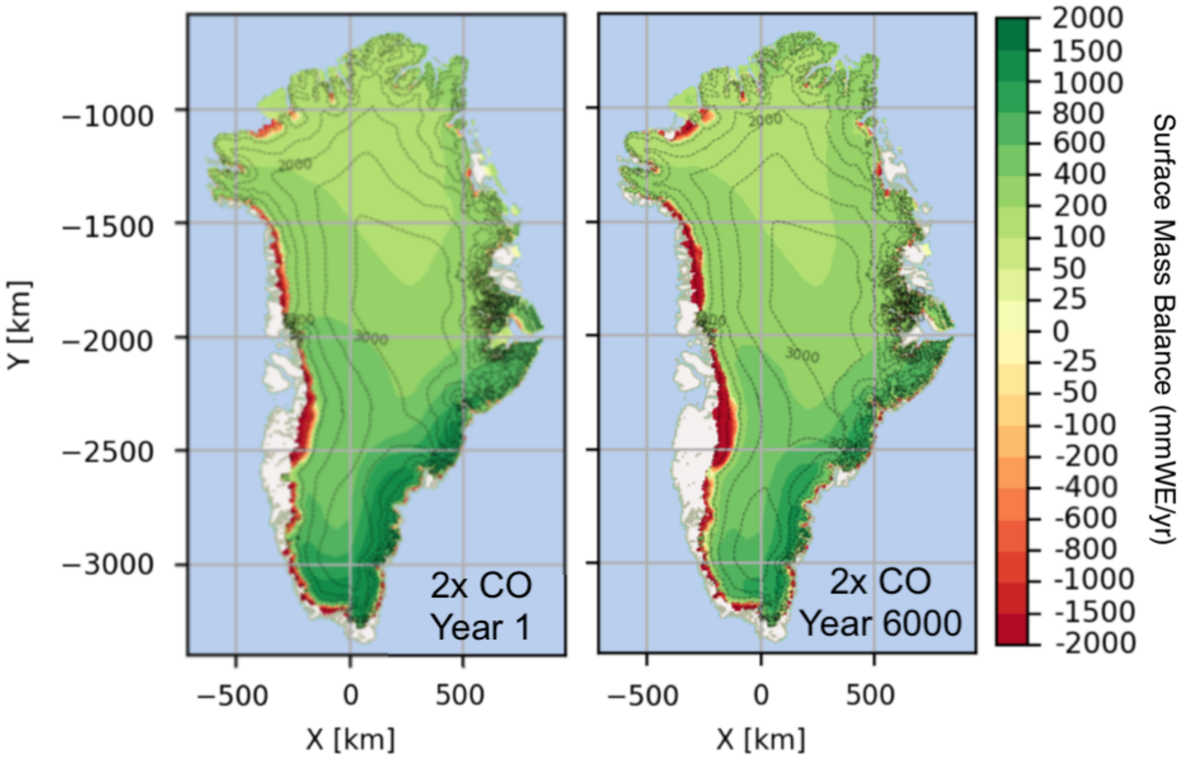


Figure 4.14: **The SMB of the ice sheet by year 1 and 6,000 in the 2x CO_2 simulation**

4.3 Recovery from 4x CO_2

Pre-industrial forcing was re-introduced to the ice sheet after the ice sheet had lost 55% of the intial mass. This simulation was run for 4,000 years to asses whether the ice sheet starts to recover, or if the elevation feedback would result into an irreversible decline of the ice sheet.

The pre-industrial forcing used was derived with a pre-industrial ice sheet: The climate was never updated during the 4x CO_2. The SMB-elevation field provided by the climate are therefore exactly the same for the pre-industrial and the recovery simulation. In addition, new ice caps do not form outside of the existing ice sheet. Therefore, if there are positive SMB values outside the main ice sheet, mass only accumulates if the grid-cell borders an ice sheet with ice thickness.

First,the initial ice sheet for the Recovery from 4x CO_2 simulation is introduced. Secondly, the response of the ice sheet within the first 500 years is discussed. Thirdly, the continuation of the melt on multi-millennium time scales is assessed. Lastly, the state of the ice sheet after 4 millennia of pre-industrial forcing is discussed.

4.3.1 The Recovery from 4x CO_2 simulation

By year 1,500 in the 4x CO_2 simulation, the ice sheet has more than halved in volume and extent. The SMB is strongly negative, at -1073 ± 240 Gt/yr. Figure 4.16a shows the SMB by year 1500. Most of the margins have shown substantial retreat. Furthermore, due to the low elevation of the bedrock combined with the SMB-elevation feedback, should result into a change in SMB.

The initial year for the Recovery from 4x CO_2 simulation was chosen to be 1462. This year was chosen as the ice sheet has reduced by 55% in volume. Furthermore, the ice sheet a small ice sheet extent (4.18a) and low SMB values (4.16b). The exact year 1462 was chosen as files suitable for performing a branching simulation were made every 100 years, starting from year 162.

4.3.2 Initial response to Re-Introducing the Pre-industrial Forcing

The re-introduction of pre-industrial forcing towards a ice sheet that has halved in mass had a substantial response in terms of SMB, ice sheet dynamics as well as area and mass. First, the SMB is compared between 4x CO_2 forcing and pre-industrial forcing. Secondly, the response of the ice sheet area, mass and ice discharge within the first 500 year of the pre-industrial forcing are discussed. Thirdly, the dynamical response as well as the consequences of the shift in dynamics are introduced and analysed.

Decrease in Surface Mass Balance

The change in forcing has a direct impact on the SMB, as can be seen in figure 4.15d. The SMB shifts from -1073 ± 240 Gt/yr to 243 ± 61 Gt/y. This decrease in SMB is immediately, as the SMB is directly dependent on forcing as well as the elevation. Since the elevation and extent of the ice sheet have changed substantially by year 1,500, the SMB has decreased by 60%: The SMB of the 23 years used for the forcing is 598 ± 94 Gt/yr with a pre-industrial ice sheet topography.

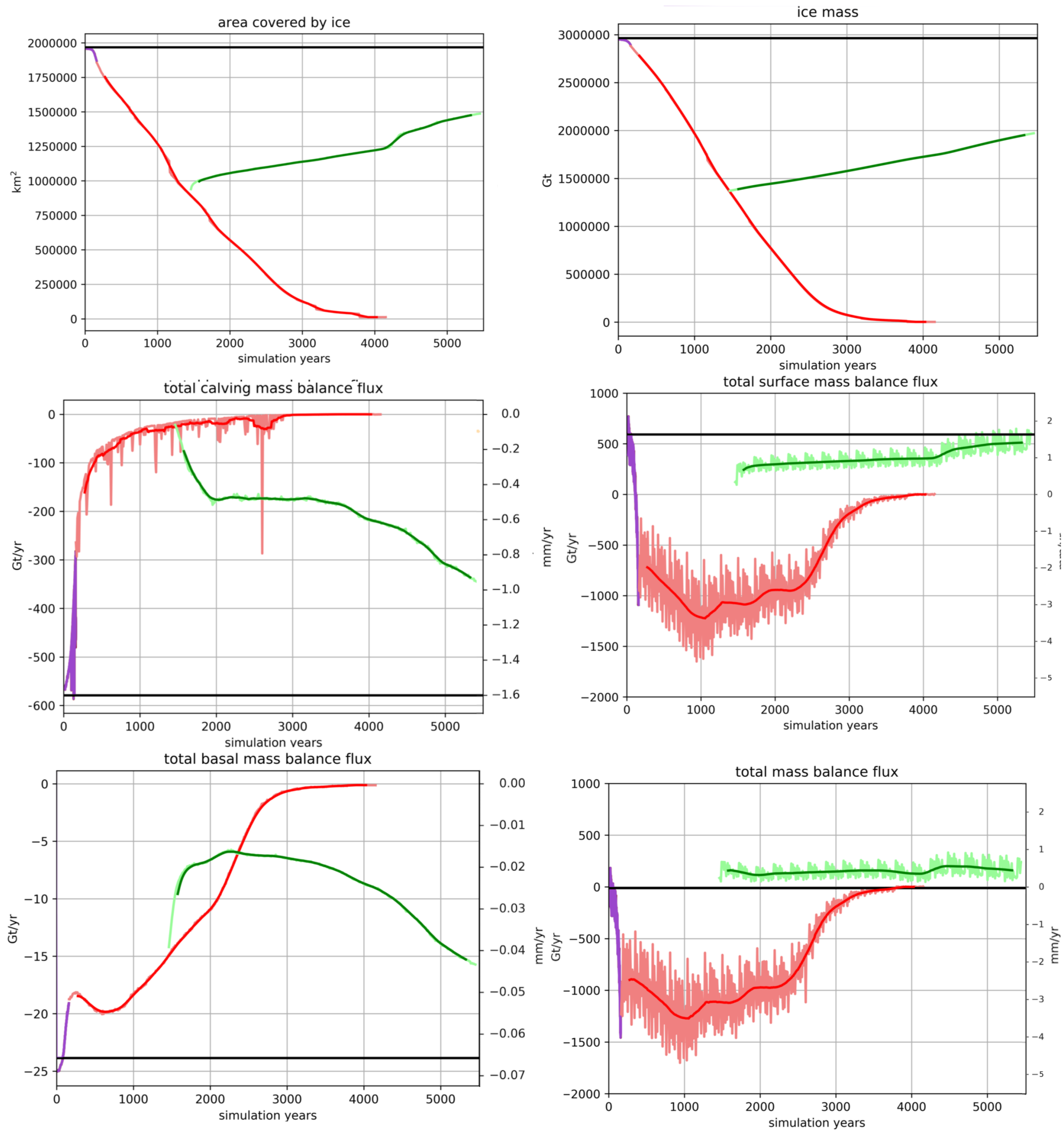


Figure 4.15: **The ice area, mass and mass balance component evolution of the Greenland ice sheet in Recovery from 4x CO_2 simulation**. Figure a and b show the ice area and ice mass of the ice sheet. Figures c,d,e and f show the mass balance components with 230 year running mean.

The shift in SMB due to the forcing can also be seen in figure 4.16. With 4x CO_2 forcing, 49% of the ice sheet is in the ablation zone by year 1,500. Once the pre-industrial forcing is introduced, this value shifts to only 7.6%. The ablation zones under pre-industrial forcing are substantially smaller compared to 4x CO_2. The ablation areas are only present close to the margins. Furthermore, the ablation zone with pre-industrial forcing is absent in the North and South-East. Since the pre-industrial climate is dryer in the interior compared to the 4x CO_2 simulation, the SMB is decreased slightly in the interior of Greenland when pre-industrial forcing is introduced.

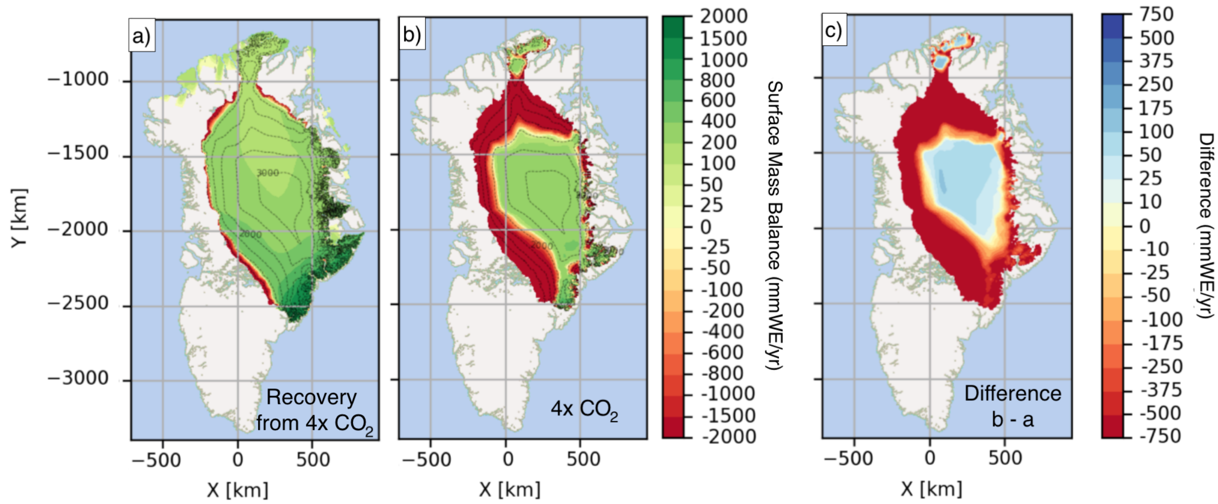


Figure 4.16: **The Surface Mass Balance of the 4x CO_2 simulation (a) and Recovery from 4x CO_2 (b) and the difference (c)** The two plots have a similar elevation, but a different forcing resulting in a different SMB values

Ice Sheet Area, Mass and Ice Discharge

The MB becomes positive immediately as pre-industrial are introduced due to the shift in SMB. As a result, there is a large response of area and mass within the first 500 years (see figure 4.6e). The ice sheet expands most substantially in the South-East, but all margins in Greenland migrate outwards. Within the first 10 years after introducing pre-industrial conditions, the ice area increased by 2% ($4.50*10^3$ km^2/yr) and the mass only increased with 0.1% (106 Gt/yr). Within 100 years after the introduction of the pre-industrial climate, the rate of area increase reduces towards an increase of roughly 0.1% every 10 years. As can be seen in table 4.4, by year 2,000, 500 years after re-introducing pre-industrial conditions, the area and mass of the ice sheet have increased by 12% and 5%.

The expansion of the ice sheet towards the South-East (figure 4.18b) is accompanied with a substantial increase in ice discharge, as shown in figure 4.15c. The ice sheet evolves most substantially during the first 500 years, the total calving rate increases from 25 ± 18 Gt/yr (year 1,500) to 187 ± 5 G/yr (year 2,000).

Dynamical Response

The shift in forcing has a substantial dynamical response (see figure 4.17). In the 4x CO_2 simulation, large ablation zones resulted into the establishment of high glacial velocities: Due to substantial retreat and strong negative SMB, a steep slope can be maintained resulting in large velocities. However, once pre-industrial forcing were re-introduced, the large surface slope and therefore the large velocities cannot be maintained and the flow velocity start to decrease. However, while the SMB shift is immediately, the ice sheet dynamics take multiple centuries to adjust.

It is likely that this shift in flow velocity had two major impacts on the ice sheet. First of all, the high flow velocities may have aided the rapid area expansion of the ice sheet without the need of major mass increase. Large quantities of ice mass were transported to the margins. In the 4x CO_2 simulation, more ice melted compared to mass brought in due to ice dynamics, therefore resulting into ice retreat. However, with pre-industrial forcing, most ice that is transported to the margins due to ice flow is not melted and the ice sheet starts to expand. Secondly, a combination of a decrease in SMB (see figure 4.16c) and high ice velocities could have resulted into the thinning in the interior (figure 4.18a). The maximum thickness decreases by almost 100 meters within the first 200 years after pre-industrial forcing are introduced. Large quantities of ice are transported towards the margins due to the high flow velocities. In the 4x CO_2 simulation, this was partly compensated by a high SMB in the interior. Less ice accumulates in the interior immediately after the re-introduction of pre-industrial forcing, while the ice dynamics are still similar to the 4x CO_2 forcing. After 4,000 years, this thinning in the interior has mostly recovered.

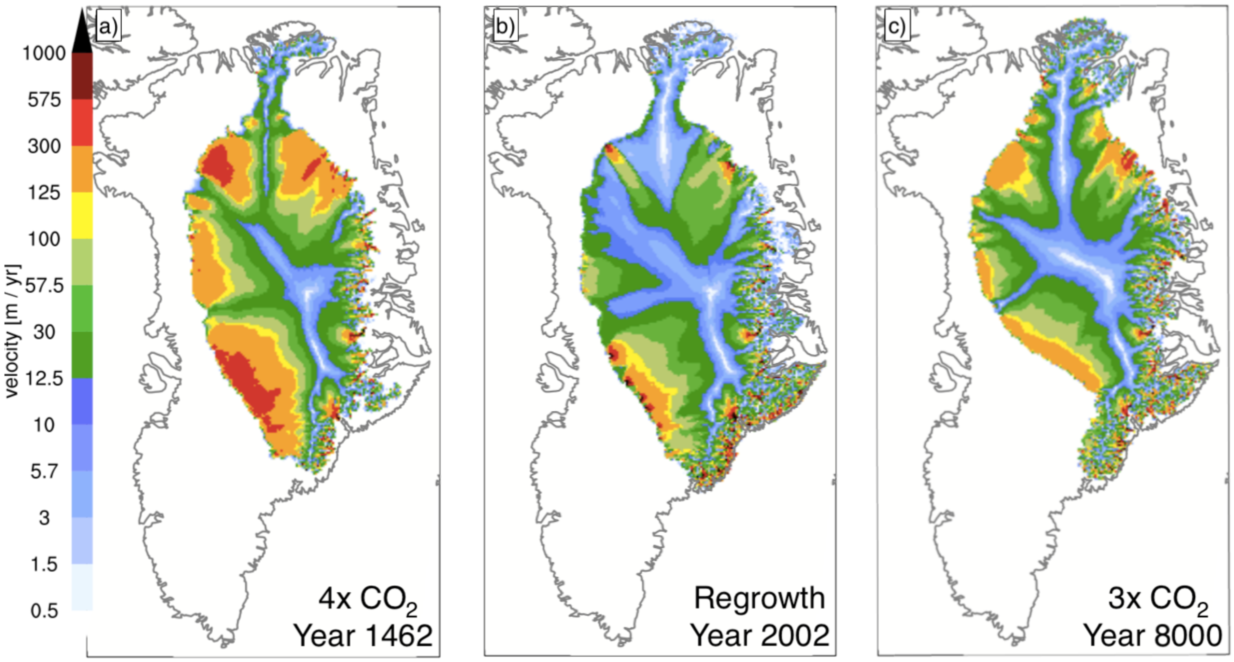


Figure 4.17: **The surface velocity of the ice sheet during the start of the Recovery from 4x CO_2 simulation compared to the final velocity in the 3x CO_2 scenario**. The flow velocity shifts substantially within the first 500 years of the recovery simulation. During the 4x CO_2 scenario, large ablation areas have resulted into large ice flow velocities. Once pre-industrial conditions are introduced, the glacial velocity reduced within 500 years. The 3x CO_2 scenario at year 8,000 has a relatively comparable ice sheet extent compared to the 4x CO_2 at year 1,500. The area with large glacial velocities of the 3x CO_2 scenario is smaller compared to the 4x CO_2 scenario, but large compared to the recovery simulation at year 2000.

4.3.3 Multi-Millennium Time Scale Recovery of the Ice Sheet

After the first 500 years, the ice sheet increases more gradually in ice area and calving. Furthermore, glacial velocities have decreased substantially as a result of the increase in SMB and the expansion of the ice sheet.

The millennia after this initial response, the ice sheet continues to gain substantial mass and area, as can be seen in the thickness evolution in figure 4.18 and the time-series in figure 4.15a+b. During the 4,000 years of pre-industrial forcing, the ice sheet expands towards the South West and North. The rate of area and SMB increase shifts by year 4,000: Between 4180 to 4380, the ice sheet increases by 502 km^2/yr. After this sudden increase in ice area, the ice area increase stabilises at 139 km^2/yr in the time-period between 4400-5400.

An explanation for this sudden increase can be found in the SMB. The South-East has more precipitation, resulting in a high SMB (figure 4.14a shows the pre-industrial SMB). Since during the simulation, snow can only accumulate in a grid-cell that is connected to the ice sheet, a new ice cap could not form until the main ice sheet migrated towards the South. Eventually, the ice sheet migrated towards the South-East, which initiates rapid expansion of ice.

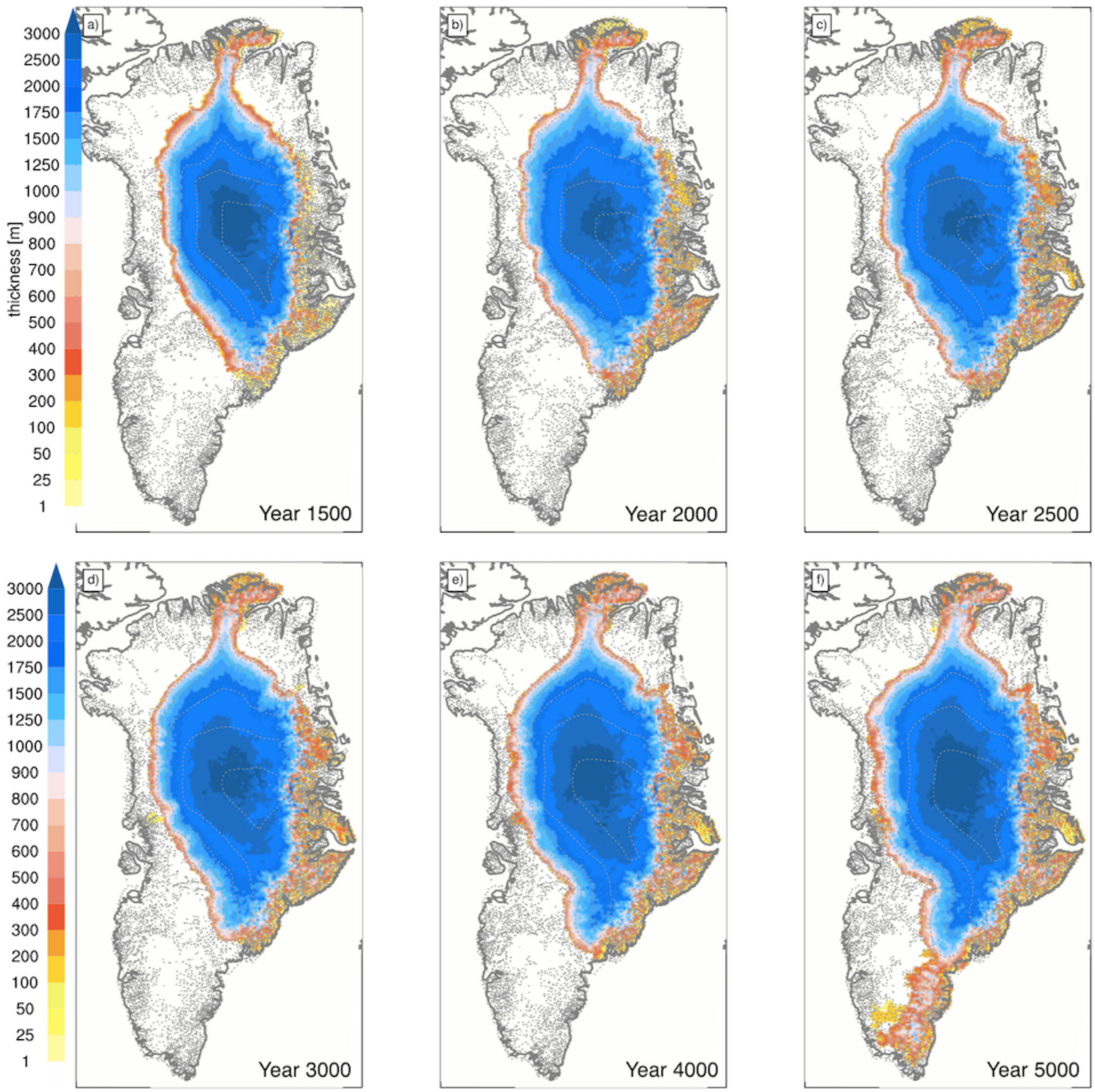


Figure 4.18: **The evolution of thickness of the Recovery from 4x CO_2 simulation**. The recovery simulation starts at year 1462 and was ended at year 5462. Within these 4000 years, the ice sheet shows a substantial increase in thickness and ice area extent. Within the first 500 years, the ice sheet shows thinning in the interior, but expansion at the margins. The ice sheet gradually expands. By year 5000, the ice sheet has almost reached the West coasts.

4.3.4 Assessment of the Recovery of the Ice Sheet

The ice sheet after 4,000 years of pre-industrial climates is still transient, but has grown substantially. The ice sheet has grown in volume from 46% to 67% of the pre-industrial ice sheet, which amounts to an increase from 8.95*10^5 km^2 (year 1462) to 1.49*10^6 km^2 (year 5462) resulting in a sea level drop of 1.7 meters (see table 4.4). By year 4,000 the SMB has increased to 511 Gt/yr, which close to the SMB of the pre-industrial control simulation at 592 Gt/yr. The calving rate however has not fully recovered with 346 Gt/yr, resulting in a positive MB of 159 Gt/yr.

Table 4.3: Mean and Maximum Thickness of the 4x CO_2 simulation

Simulation Year	Mean Thickness (m)	Maximum Thickness (m)
1462	1670	3633
1662	1507	3545
1962	1492	3446
2362	1495	3397

Total Greenland Ice Sheet Surface Area				
Simulation Year	2x CO_2 (km^2)	3x CO_2 (km^2)	4x CO_2 (km^2)	Recovery (km^2)
500	$1.92 * 10^6$	$1.83 * 10^6$	$1.60 * 10^6$	-
1000	$1.95 * 10^6$	$1.80 * 10^6$	$1.27 * 10^6$	-
2000	$1.91 * 10^6$	$1.72 * 10^6$	$5.73 * 10^5$	$1.055 * 10^6$
3000	$1.90 * 10^6$	$1.60 * 10^6$	$1.24 * 10^5$	$1.138 * 10^6$
4000	$1.90 * 10^6$	$1.33 * 10^6$	$1.26 * 10^4$	$1.220 * 10^6$
6000	$1.90 * 10^6$	$1.07 * 10^6$	-	-
8000	-	$9.59 * 10^5$	-	-

Greenland Ice Sheet Cumulative Sea Level Rise					
Simulation Year	PI	2x CO_2 (m)	3x CO_2 (m)	4x CO_2 (m)	Recovery (m)
500	0.01	0.16	0.31	1.08	-
1000	0.03	0.24	0.56	2.73	-
2000	0.07	0.36	1.2	6.0	4.2
3000	0.09	0.43	2.0	8.0	3.84
4000	0.11	0.49	3.0	8.2	3.4
6000	0.13	0.57	4.1	-	-
8000	0.16	-	4.8	-	-

Integrated Surface Mass Balance				
Simulation Year	2x CO_2 (Gt/yr)	3x CO_2 (Gt/yr)	4x CO_2 (Gt/yr)	Recovery (Gt/yr)
500	408 ± 85	154 ± 111	-876 ± 289	-
1000	407 ± 85	91 ± 119	-1,213 ± 317	-
2000	399 ± 85	-43 ± 118	-944 ± 200	297 ± 50
3000	390 ± 86	-120 ± 124	-190 ± 58	330 ± 51
4000	386 ± 86	-119 ± 97	0 ± 3	355 ± 58
6000	384* ± 86	-94 ± 87	-	-
8000	-	-67.3 ±85	-	-

Table 4.4: **The Greenland Ice Sheet area, cumulative SLR and SMB for the 2x, 3x and 4x CO_2, and the Recovery from 4x CO_2 simulation**. Some years are left blank as they were not simulated. The final years are 6082, 8122, 4162 and 5462 for the 2x, 3x and 4x CO_2, and recovery simulations respectively. To derive the SMB, a 230 year mean was taken to negate the effects of climate variability. For example, year 1,000 was derived with the mean of year 890-1,110, with a 10 year output frequency, this amounts to 23 outputted years. For the final year, the mean of the last 230 year was used. Year 6,000 in the 2x CO_2 simulation shows the mean of the final 230 years, as this simulation ends at year 6082.

Chapter 5

Discussion

In this chapter, the simulation conducted for this thesis are compared to existing literature on multi-century and multi-millennium time-scales. Secondly, an assessment is made on PDD and SEB schemes. Thirdly, effect of interactions between processes that were not modelled are discussed. Finally, general limitations and strengths of CISM2.1 are discussed.

5.1 CISM2.1 Simulations in context to the Literature

5.1.1 The 2x, 3x and 4x CO_2 simulations

Three warming simulations with transient climates were performed during this thesis: the 2x CO_2 simulation with limited warming resulting into only 7% loss of volume. A 3x CO_2 simulation, which shows a small SLR that persists during the 8,000 simulation years. Finally, the warmest scenario considered is the 4x CO_2 simulation, resulting in the full deglaciation of the ice sheet within 3,000 years.

The 4x CO_2 scenario is in good agreement in terms of ice sheet extend and evolution with several coupled simulations, while the 2x CO_2 scenario has a substantially slower melt. The sea level rose by 87.5 cm, 316.7 cm by simulation year 1,000 in coupled 2x and 4x CO_2 simulations in Huybrechts & de Wolde, 1999. Compared to 24.4 cm and 273 centimetres in the 2x and 4x CO_2 scenarios performed during this thesis. The ice sheet extent in the 4x CO_2 scenario is also similar to Huybrechts & de Wolde. However, the CISM2.1 ice sheet extent is slightly larger in the North as the initial ice sheet has a larger ice sheet extent. Furthermore, the evolution of melt is also similar to Ridley et al., 2005 (see table 5.1). Both the CISM2.1 simulation and Ridley et al., showed substantial retreat at the margins with limited thinning in the interior. Furthermore, in both Huybrechts et al., 2011, Ridley et al., 2005 and the CISM2.1 4x CO_2 simulations, the ice sheet melted within 3,000 years.

However, there are two main differences between these simulations. First of all, Huybrechts & de Wolde, Huybrechts et al. and Ridley et al, each performed ice sheet model simulations that are fully coupled with the climate. The climates used for the simulation are more equilibrated compared to the CISM2.1 4x CO_2 simulation. As a result, the climate used for the CISM2.1 simulation should be colder compared to the pre-industrial climate. Since the timing in the 4x CO_2 simulation is similar to the coupled simulations despite a colder climate this might suggest that the ice sheet is more sensitive in the uncoupled CISM2.1 simulations. Since the total SMB decreased had a trend of 38 Gt/yr^2 in the 4x CO_2 forcing an equilibrated climate may have substantailly warmer forcing. An equilibrated 4x CO_2 simulation could therefore result in full deglaciation of the ice sheet taking substantially less than 3,000 years.

Secondly, Huybrechts & de Wolde, Huybrechts et al. and Ridley et al used PDD schemes to perform the multi-millennium time-scale simulations. While it has been shown that these PDD schemes are more sensitive towards warming (Bougamont et al., 2007, Fitzgerald et al., 2012), the bias resulting from the PDD method might heavily depend on the tuning and choice of Degree-Day Factors.

Similar to the simulations conducted during this thesis, Aschwanden et al., 2019 performed uncoupled ice sheet model simulations. RCP4.5, RCP4.6 and RCP8.5 simulations were considered. To extend these simulations on millennium time scales, the trend in the climate was continued until year 2500 and then stabilised.

The RCP scenarios used in Aschanden et al., had a stabilised CO_2 concentrations of 650ppm, 850 ppm for the RCP2.6 and RCP4.5 as well as a CO_2 concentration of 1370 ppm by year 2100 in RCP8.5 (Van Vuuren et al., 2011). For the 2x, 3x and 4x CO_2 simulations of this thesis, the mean CO_2 concentrations are roughly 560, 840 and 1120 ppm. Based on CO_2 concentrations, it would be expected that the RCP8.5 is more similar to the 4x CO_2 simulation. However, the timing of melt is substantially longer in the CISM2.1 simulations compared to Aschwanden et al., 2019: The RCP8.5 showed full deglaciation within 1,000, which takes 3,000 years in the 4x CO_2 simulation. The RCP4.5 showed a mass loss of 27-57% by year 1,000. In the 3x CO_2 scenario, a mass loss of of 27% is reached by year 3,300 and 58% is reached by year 7,500. RCP2.6 simulation shows a minimum of 8% of mass loss by year 1,000, which is reached by year 1,250 in the 3x CO_2 simulation. The 2x CO_2 simulation shows a mass loss of 7% by year 6,000.

Table 5.1: 4x CO_2 timing; the volume in CISM2.1 compared to Ridley et al., 2005

Simulation Year	CISM2.1 Simulations	Ridley et al., 2005
1	100%	100%
600	83%	61%
1200	56%	35%
1800	33%	17%
2400	13%	7%
3000	3%	3%

5.1.2 Recovery from 4x CO_2

The Recovery from 4x CO_2 simulation re-introduced the pre-industrial climate towards the ice sheet after 55% mass loss during the 4x CO_2 simulation. The recovery simulation showed substantial regrowth of the ice sheet resulting in a sea level drop of 42 centimetres per millennium. This fast recovery of the ice sheet was also shown in a control simulation by Langen et al., 2012. By introducing present day temperatures and precipitation fields towards an ice free Greenland without re-coupling, the ice sheet fully recovered. Similar results are shown in Letréguilly et al., 1991: When forced by pre-industrial conditions, an ice free Greenland showed full recovery by 30,000 years. Furthermore, within 4,000 years, the ice sheet in Letréguilly et al., 1991 recovered from roughly 45% volume to 65% volume, while the recovery simulation showed a recovery of 46% to 67% volume. It should be noted however that both Langen et al and Letréguilly et al used PDD schemes to derive SMB. Despite this difference, Langen et al. Letréguilly and the Recovery from 4x CO_2 show that by re-introducing pre-industrial climates uncoupled, a semi or completely melted ice sheet results into a substantial recovery of the ice sheet.

If coupling takes place between the ice sheet and climate after substantial ice sheet loss, the recovery of the ice sheet is limited. Toniazzo et al., 2004 showed that when implementing full coupling, the ice sheet does not regrow from an ice free Greenland.

Ridley et al., 2010, considered several initial ice sheet volumes, ranging from 0 to 100%. Pre-industrial CO_2 concentrations were re-introduced to the smaller ice extents. During the regrowth of the ice sheet in Ridley et al., the ice sheet was coupled asynchronously to the climate. The initial ice sheet volume of 40 and 50% were shown to lead to a final ice sheet equilibrium at roughly 20% of the initial ice sheet extent. The volume furthermore never exceeded 55% of the original ice sheet when starting the ice sheet at 40% of the initial volume. During the Recovery from 4x CO_2 simulation, however, by year 5,000 the mass has reached 65% of the original volume. In addition, the final ice sheet extent in Ridley et al., 2010, has several smaller ice caps in the North and West and larger ice caps in the South and East. The ice sheet after 4,000 years of the Recovery from 4x CO_2 in comparison shows recovery of most of central Greenland and some of South Greenland (see figure 4.18f).

These results show that coupling with the climate has a large influence on the ability of the ice sheet to recover after substantial melt. The SMB-elevation feedback alone is not strong enough to allow continued deglaciation of the Greenland ice sheet. It is likely that the climate-albedo feedback is important towards reducing the ice sheet recovery. As glaciated areas are replaced by tundra, the albedo decreases which results into additional climate warming.

In addition, the atmospheric circulation is similar to the pre-industrial ice sheet extent in the recovery simulation. The pre-industrial forcing was made using a pre-industrial ice sheet volume and geometry. The deglaciation of the margins should result in a migrate of the precipitation induced by orographic lifting. This should result into an increase in precipitation in the interior, which was not modelled by the uncoupled simulation. Despite the absence of this negative feedback, the ice sheet continued to recover.

In conclusion, the absence of the albedo feedback coupled with a present day atmospheric circulation may have had a large influence into aiding the recovery of the ice sheet.

5.2 Surface Energy Balance and Positive Degree-day Schemes

To calculate the SMB in CESM2.1, a Surface Energy Balance (SEB) scheme was used. This scheme accounts for the available energy to melt. In many climate models however, a Positive Degree Day (PDD) scheme is used in which the SMB is parameterized based on temperature.

A major benefit of the PDD schemes compared to the SEB schemes is that PDD schemes are computationally cheaper. SEB schemes require additional parameters such as wind speed, radiative components and surface roughness, making SEB scheme computationally more expensive and more difficult to implement. PDD schemes make physical sense, as the melt is furthermore dominantly controlled by the temperature. Ohmura (2001) showed that the dominant heat source for melt is the long-wave atmospheric radiation. Other important contributors to determining melt, such as the sensible heat flux, short wave radiation and emission of radiation are also highly correlated to the temperature. As a result, PDD schemes are widely used in literature.

However, while temperature is the dominant factor towards melt, there are additional factors to be considered. Bougamont et al., 2007 showed that PDD schemes could show a biased response to climate change as PDD schemes do not account for changes in cloud cover, specific humidity, wind and lapse rate. Additionally, the albedo feedback as fresh snow is removed and the decreased ability of melt water to refreeze as snow becomes saturated, could also amount to this larger response.

PDD schemes use Degree-Day Factors (DDF) to tune the melt towards temperature. These DDF (DDF_{ice} and DDF_{snow}), are determined experimentally. However, DDF values tend to vary substantially depending on the location and time. Hock (2003) showed that DDF in mountainous regions can vary substantially between locations as it is dependent on weather and surface types. In addition, van den Broeke et al., 2010 showed that the DDF can vary with time, as an upwards trend for the DDF was found in South-West Greenland from 2003 to 2007. Large temporal variability in the PDD were also shown by Huss & Bauder, (2009) and the DDF was found to decrease as climatic forcing increases. Since the DDF are highly tuned towards the present day climate and can change substantially with location and time, multi-millennium time-scale projections could be affected by implementing PDD schemes.

As stated before, the SMB for the simulations conducted during this thesis used a Surface Energy Balance scheme. Since the climate was ran uncoupled after year 161 for the 4x CO_2 simulation, the SMB was modelled using an ice sheet extent and geometry that is similar to the present-day ice sheet. Changes in the SMB therefore resulted from changes in the topography. However, despite the constant forcing, the SMB was shown to evolve throughout the simulation, as could be seen in figure 4.6.

Bougamont et al., 2007 used a very similar approach as the CISM2.1 simulations, with an uncoupled simulation forced with a transient 4x CO_2 climate. In Bougamont et al., 2007, the climate was increased with 1% per year until 4x pre-industrial concentration were used. The last 10 years of the forcing were repeated on multi-century time-scales. This last 10 year representative forcing is comparable to forcing years 129-139 in the CESM2.1 simulation. In addition, Bougamont compared both a PDD as well as a SEB scheme. The PDD and SEB scheme showed substantial differences in SMB. The SEB showed an SMB up to 900 Gt/yr higher compared to the PDD scheme. Furthermore, once implementing the constant forcing and an unchanged ice sheet geometry and dynamics, Bougamont et al, showed that the PDD has a constant net SMB and SMB components. The SEB scheme however, evolved throughout the simulation as surface snow is removed, increasing the surface albedo. The latter was not present in the CISM2.1 simulation. Since the forcing files in the uncoupled CISM2.1 are repeated, without topography changes, the SMB does not evolve.

5.3 Interactions between the Climate and Ice Sheet that were not Simulated

The uncoupled CISM2.1 simulations in this thesis were forced by an elevation dependent SMB field. The SMB was furthermore derived with an Surface Energy Balance scheme which accounts for the available energy for melt. During this thesis, the SMB-elevation feedback was shown to lead to a continued melt in the 3x CO_2 simulation and eventual deglaciation in the 4x CO_2 scenario. However, the elevation-feedback did not lead to complete melt in the 2x CO_2 scenario.

Besides the SMB-elevation feedback, there are several feedback of the ice sheet that influence the climate and therefore also affects the melt. Two feedbacks could have lead to a different ice sheet are introduced in this section: First of all, the potential influence of the absence of the albedo feedback is introduced. Secondly, the effects of a constant Greenland geometry on precipitation is discussed.

Albedo induced Climate Feedback

The change in albedo of Greenland can have a substantial impact on the climate. Ice sheets have high albedo values, in general ranging from fresh snow (0.9) to bare ice (0.6 in SNICAR). As deglaciation continues, regions with ice and snow are replaced with tundra, large lakes and eventually forested regions with lower albedo values. As a result of this decrease in albedo, less Short-Wave radiation is reflected at the surface which leads to climate warming. As a result, this albedo feedback should enhance melt in a coupled simulation.

The albedo feedback could have had a substantial influence on the mass and area increase during the Recovery from 4x CO_2 simulation. Despite a total mass loss of 55% by year

1462 in the 4x CO_2 simulation, the ice sheet recovered at all margins once the pre-industrial climate was introduced. In the North and South-East, positive SMB was found at the margins and the ablation percentage has decreased from 49% during 4x CO_2 forcing to 7.6% due to the re-introduction of pre-industrial conditions. In contrast however, literature that used synchronously or asynchronously coupled simulations (e.g. Ridley et al., 2010) show limited recovery of the ice sheet after substantial ice loss.

An explanation for this discrepancy between the coupled and the CISM2.1 simulation could be related to this climate-albedo feedback. The pre-industrial climate that was re-introduced was made with a pre-industrial ice sheet extent. Therefore, the climate never included changes of the albedo. The climate is therefore substantially colder at the margins. As a result, the ice sheet can show substantial recovery of the ice sheet within the 4,000 simulation years.

While the albedo-climate interaction was not modelled, it should be noted that the albedo feedback of melt towards the radiative balance in the ice sheet is incorporated in the SMB calculations in CLM.

Precipitation with the Geometry of the Greenland Ice Sheet

As the ice sheet melts, the pattern of precipitation changes. The high topography of the surface of the ice sheet can act similarity to precipitation as mountain regions. The thickness of the ice sheet acts as a barrier of flow, resulting into enhanced precipitation. As the ice sheet retreats, this barrier of flow migrates, which should lead to a migration of the regions with high precipitation, increasing precipitation in the interior. In an uncoupled simulation however, the areas with high precipitation do not evolve. This change of precipitation should reduce the rate of deglaciation of the Greenland ice sheet. Furthermore, this unchanged pattern of SMB can be seen when comparing the SMB at the start of the simulation and also after substantial melt (see figure 4.4).

The unchanged pattern of precipitation may have enhanced melt in the 3x and 4x CO_2 simulation. The SMB-elevation feedback was strong enough to lead to substantial melt in both scenarios. However, it is possible that the absence of this negative feedback towards melt may have increased the melt. As the ice sheet retreats, the margins of the ice sheet in the 3x and 4x CO_2 scenarios should have received more precipitation. However, the distribution of precipitation was made with the pre-industrial ice sheet geometry. Therefore, the precipitation pattern is not updated with new ice sheet geometries. This could explain the shorter time-scales of melt in uncoupled simulations such as Aschwanden et al (2019). In addition, this could also explain why the CISM2.1 uncoupled simulation, which were forced by a transient climate, show the same timing of deglaciation compared to the uncoupled simulation.

Assessment of the Climate-Ice Sheet Feedbacks

The albedo-climate feedback can acts as a positive feedback towards Greenland melt, while the change in precipitation due to geometry would act as a negative feedback towards melt.

The warming and recovery simulations show that the albedo feedback may have had a large influence on the ice sheet evolution. The albedo feedback may have been a dominant factor to preventing further deglaciation during the Recovery from 4x CO_2 simulation: with the albedo feedback being dominant towards deglaciation compared to the unchanged precipitation distribution. Furthermore, the decrease in ablation area in the Recovery from 4x CO_2 simulation is pre-dominantly caused by a change in temperature, as the ice sheet geometry at year 139-161 is relatively similar to the present-day ice sheet compared to year 1462.

However, the unchanged precipitation could prove to be an important feedback during the 4x CO_2 simulation: The timing of deglaciation during the 4x CO_2 simulation is similar to coupled simulations, despite the transient climate used for the forcing. Furthermore, this precipitation feedback may also explain why uncoupled simulations, such as Aschwanden et al., 2019, deglaciate faster compared to coupled simulations. However, a quantification of the influence of both feedbacks was unexplored as this would require additional coupled simulations.

5.4 Strengths and Limitations of the CISM2.1 simulations

The CISM2.1 simulations conducted in this thesis were forced with an elevation-SMB field. As a result, the SMB-elevation feedback is modelled in each simulation even though the provided forcing does not change. Furthermore, the SMB in CISM2.1 was derived with a Surface Energy Balance scheme. As a result, the amount of energy that contributes to melt is modelled. This is a more sophisticated method to calculate melt on multi-century and multi-millennium time-scales compared to empirical relations that are often used for ice sheet simulations.

Spin-up ice sheet

The initial ice sheet is 12% larger compared to the present day ice sheet: The present-day ice sheet stores 7.3 meters of sea level rise and the simulated ice sheet stores 8.2 meters.

As shown in figure 5.1, the ice sheet had a larger extent in the North. Due to the larger ice sheet mass, the total potential sea level rise for Greenland is larger compared to the true ice sheet.

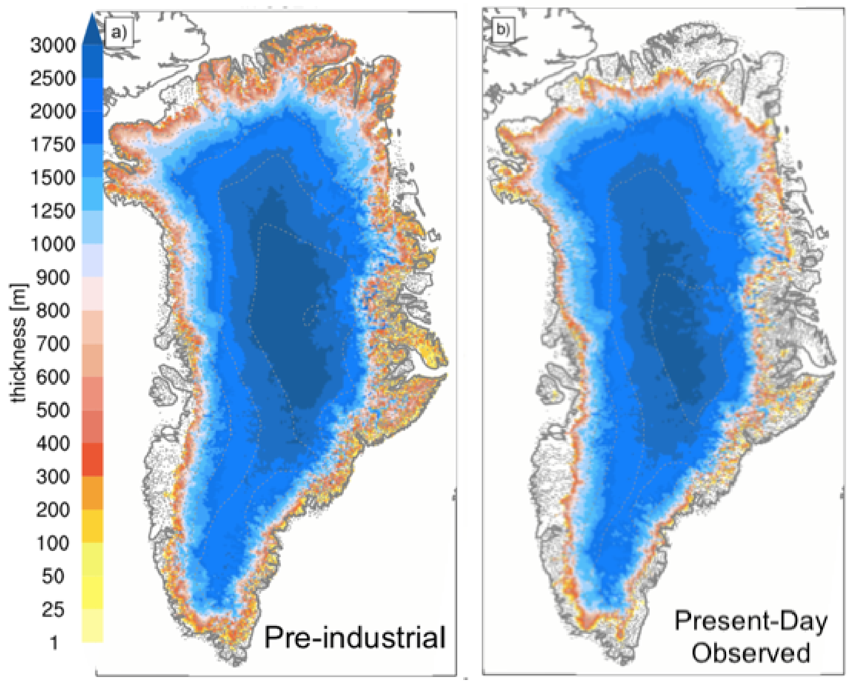


Figure 5.1: **The initial ice sheet in CISM2.1 (a) and the observed ice sheet (b) thickness.**

5.4.1 Transient Climate in the Repeated Forcing

As stated before, the 2x, 3x and 4x CO_2 scenarios used forcing with a transient climate. The climate system has inertia towards the increase in CO_2. As a result, even though an average of 2x, 3x and 4x pre-industrial CO_2 concentrations were considered for the warming simulations, the climate is slightly colder compared to an equilibrated climate. This may have substantially influence the high stability of the 2x CO_2 simulation. For an equilibrated 2x, 3x and 4x CO_2 simulation, forcing would be required with a multi-century fully coupled simulation.

Nevertheless, the warming of the climate by year 139-161 (4x CO_2) was shown to be substantial enough to result into the full deglaciation of the ice sheet. In addition, the 2x, 3x and 4x CO_2 scenarios each resulted into a different ice sheet evolution. The inertia in the climate can be seen in figure 3.7.

Since the climate is transient during the warming simulations, a trend can be found in the SMB during the 23 years used for the forcing. This can be seen in the SMB during the 1% to 4x CO_2 simulation, as shown in figure 3.7. The trend of the simulations are 439 Gt/yr - 2 Gt/yr^2 (2x CO_2), 269 Gt/yr -13 Gt/yr^2 (3x CO_2) and -226 Gt/yr -38 Gt/yr^2 (4x CO_2). The trend is low for the 2x CO_2. However, the trend is more substantial for the 3x and 4x CO_2 simulations. The large trend in the forcing resulted into larger standard deviations of the SMB, MB and SLR for the 3x and 4x CO_2 simulations compared to the pre-industrial and 2x CO_2 simulations (see 4.4). An important benefit of this repeated forcing, however, is that the variability of the climate is similar each time the forcing is repeated. By performing a mean of 230 years, the variability of the climate in the outputted data is removed, which is beneficial when comparing features that are highly dependent on the forcing (e.g. SMB, MB and ice area). The effects of this 230 year averaging can be seen in the figure 4.6.

Output Frequency

To reduce data storage, an output frequency of 10 years was used for each uncoupled simulation. Since each year stores roughly 200 MB of data, an output frequency of 1 year would have exceeded 4 Terabytes of data storage combined for the 2x, 3x, 4x CO_2 and recovery simulation.

By reducing the output frequency to 10 years, the temporal resolution of the output reduces, but the internal time-step in CISM2.1 is unaffected. This does therefore not influence the ice sheet evolution.

Diffusion due to Resolution of CISM2.1

Each CISM2.1 simulation conducted for this thesis was ran using a 4 x 4 kilometre horizontal grid-resolution with eleven vertical layers. While this grid-resolution is finer compared to most multi-millennium time-scale simulations (Huybrechts et al. (2011), Ridley et al., (2005), Huybrechts & de Wolde, (1999)), a finer grid resolution is required to simulate the flow at the margins of Greenland.

To derive the calving per calving front, a classification scheme was used (see figure 4.2). However, due to the 4 x 4 kilometre grid-resolution, the ice flows at the margins are not well represented. Narrow glaciers are not well represented in the ice sheet model, as a 4 x 4 kilometre resolution is too coarse to well represent ice flow.

Figure 5.2 shows the difference in flow velocity between the initial ice sheet of the 2x, 3x and 4x CO_2 simulation, compared to the observed flow velocity between 2000-2012 based on InSar. As can be seen in the figure, the initial simulated flow (figure 5.2a) differs significantly from the observed flow (5.2b). The ice flow that was observed shows sharper flows for NEGIS, Kangerdluqsuaq and Petermann At the Western margins and the Humboldt region, the observed ice flows are smoother in the observed ice sheet compared to the simulated ice flows.

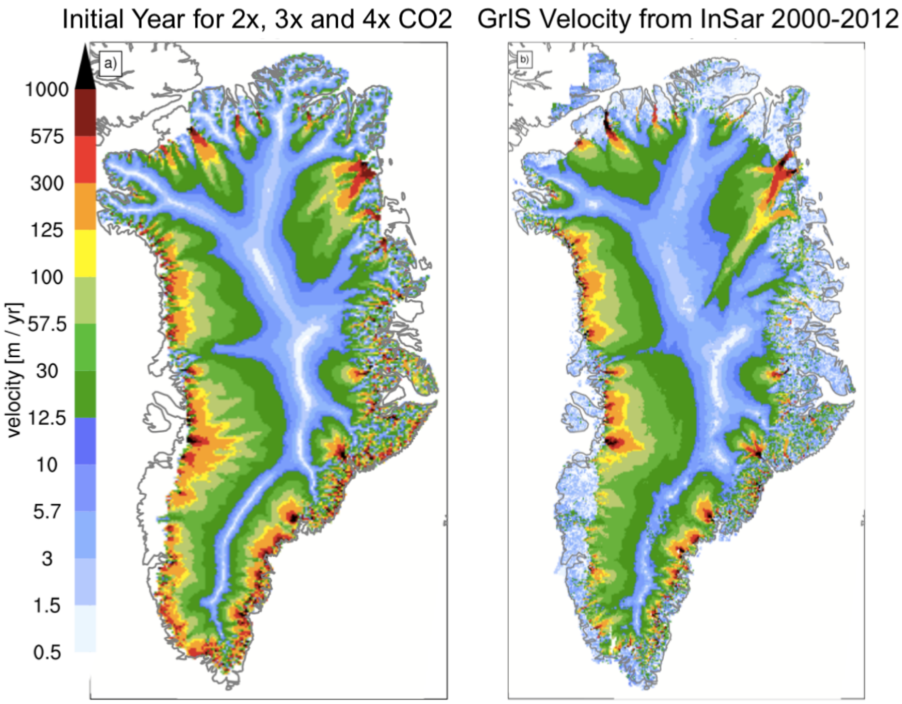


Figure 5.2: The flow velocity at simulation year 1 of the 2x, 3x and 4x CO_2 simulation (a) compared to the observed flow velocity using InSar (b).

Limitations within CISM2.1

There are several limitations within CISM2.1 which were present during the simulations.

First of all, the sea level is not allowed to change in the simulation. Sea level change is expected as the ice sheet melts, however, the sea level rise - or drop - depends on location as the mass of the ice sheet influences the local Greenland sea level. This change in sea level was not derived during the CISM2.1 simulations. As a result, while the static sea level changes may have had an influence, it would require a sophisticated sea level model that would include Antarctica. Furthermore, bedrock topography below 0 meters without ice coverage are considered to be ocean. Therefore, if the Greenland ice sheet melt is fast enough, new calving fronts can start to form in lakes or newly formed estuaries in the interior of the ice sheet. However, the fluxes of water in these lakes were not simulated.

Secondly, a simplification in CISM2.1 is used in which ice that is considered to be floating according to Archimedes law is immediately calved. Since Greenland only has limited ice shelves, this should not have a significant impact on the results.

Chapter 6

Conclusions and Recommendations

In this thesis, for the first time, uncoupled CISM2.1 simulations which were forced by an elevation dependent SMB field derived from a fully coupled CESM-CISM simulation were conducted. Four simulations were conducted to simulate the evolution of melt of the Greenland ice sheet on multi-millennium time-scales in the terms of the eustatic sea level rise, ice thickness, area and ice velocity. Four climate scenarios were analysed: First of all, three climate scenarios that corresponded to elevated greenhouse gas forcing; transient 2x CO_2, 3x CO_2 and 4x pre-industrial CO_2 levels were considered. To assess the response of the ice sheet to a pre-industrial climate after substantial ice retreat, a "Recovery" from 4x CO_2 simulation was performed by re-introducing pre-industrial SMB forcing to the ice sheet after 55% mass loss compared to the pre-industrial ice sheet.

6.1 Conclusions

The effects of the greenhouse gas forcing scenarios on the ice sheet evolution

The warming of the climate in the three scenarios control the timing and extent of ice sheet melt. By year 4,000, eustatic sea levels increased by 0.49 m, 2.98 m and 8.18 m respectively for the 2x, 3x and 4x CO_2 simulation. The margins of the ice sheet for each warming scenario show retreat, leading to a reduction in the calving rate. By simulation year 500, the calving rate decreases from 572 Gt/yr to 446 Gt/yr, 289 Gt/yr and 70.1 Gt/yr for the 2x, 3x, and 4x CO_2 scenarios respectively. This decrease in ice discharge partly compensates the drop in SMB from 592 $\pm$ 82 Gt/yr to 430 $\pm$ 85 Gt/yr, 150 $\pm$ 111 and -876 $\pm$ 289 Gt/yr in the 2x, 3x and 4x CO_2 scenarios.

In the 3x and 4x CO_2 simulations, the retreat in the margins is followed by asymmetric melt towards the centre of the ice sheet. The East, South and patches in the North and West show more resilience to ice sheet melt, while glaciers with high velocity are show more retreat. This spatial different in melt rate leads to the formation of elongated ice sheets attached to the main ice sheet.

The 2x CO_2 simulation reaches a quasi-equilibrium by year 4,000, as the decrease in SMB is fully compensated by the decrease in ice discharge that resulted from thinning and retreat at the margins. In the 3x CO_2, mass loss persists for at least 8,000 years. The SLR is low throughout the 3x CO_2 simulation, with a minimum Mass Balance of -288 ± 124 Gt/yr (0.80 ± 0.34 mm/yr) By year 8,000 the ice sheet has lost 50% compared to the initial mass. The 4x CO_2 simulation fully deglaciated within 3,000 years and reaches a minimum SMB of -1,273 ± 310 Gt/yr by year 1,000.

What is the response of the Humboldt, Jacobshavn and Hellheim glaciers towards greenhouse forcing scenarios

Transects of the Humboldt, Jacobshavn and Hellheim glaciers were made in terms of velocity, SMB and elevation. These glaciers are amongst the largest glaciers in Greenland and can be found in three distinct areas; the North-West, West and South-East.

The three glaciers show distinctly different responses to the 2x, 3x and 4x CO_2 simulations. Hellheim shows virtually no change in time for the 2x CO_2 scenario. In the 3x and 4x CO_2 simulations, Hellheim becomes land-terminating by year 3,500 and 1,000. Retreat at the ocean margin is limited. Retreat from the South-West is more substantial compared to Hellheim which results in a decrease in elevation West of Hellheim..

The Jacobshavn glacier shows some thinning and a decrease in SMB in the 2x CO_2 scenario, but does not retreat. Jacobshavn becomes land-terminating by year 1,500 and 500 in the 3x and 4x CO_2 scenario. The Humboldt glacier shows substantial retreat is all scenarios. In the 2x CO_2 scenario, the glacier retreats 30 kilometres by year 3,000 after which the margin is stable. Both the 3x and 4x CO_2 scenario show full melt of the Humboldt glacier. However, while by year 3,000 the Humboldt margin has retreated with 120 kilometres in the 3x CO_2 scenario, the 4x CO_2 simulations takes only 750 years to retreat 120 kilometres.

The response of a partially deglaciated Greenland to restoration of pre-industrial conditions SMB forcing

A Recovery from 4x CO_2 simulation was conducted. This simulation is a branching simulation after 55% of the mass of the initial ice sheet was lost. The pre-industrial climate was introduced which was established using the pre-industrial ice sheet extent. Therefore, the climate was never updated with the new ice sheet extent.

The Recovery simulation shows an immediate response to SMB forcing. The introduction of pre-industrial conditions reduces the 230 year average SMB shifts from -1085 Gt/yr to 243.2 Gt/yr at year 1462. This positive SMB persists throughout the simulation, resulting in a positive MB and a sea level drop of 42 cm per 1,000 years. The ice sheet expands towards the East due to a positive SMB at the margins, resulting in an increase of calving from -22 Gt/yr to -187 G/yr by year 2000.

Due to high flow velocities at the start of the simulation and a decrease in SMB in the interior, the ice sheet starts to flow outwards resulting in a decrease of elevation in the centre of the ice sheet. The thinning in the high enough to result in the collapse of the ice sheet.

The most substantial area increase occurs within the first 300 years. Due to small ablation areas and localised accumulation areas along the margins of the ice sheet, the ice sheet starts to steadily expand outwards. The area increase accelerates after 4,200 years, as the ice sheet grows towards the South, in which the SMB is high due to the initial pre-industrial precipitation pattern. By year 4,000, the ice sheet has expand from 46% to 67% of the initial ice sheet mass.

These results show that if only the SMB-elevation feedback is present, the ice sheet could regrow. During the Recovery from 4x CO_2 simulation, the climate is never updated and therefore the climatic effect of a reduced ice sheet are accounted for. Despite reduced surface elevation by year 1462, compared to the control ice sheet, the ablation area becomes relatively small with the re-introduction of pre-industrial forcing.

What is the response of the mass, area as well as the ice sheet velocity and equivalent sea level rise on multi-century and multi-millennium time-scales when assessed by CISM2.1?

In this thesis, a 2x, 3x and 4x CO_2 and a Recovery from 4x CO_2 simulation were performed to show the response of mass, area as well as ice sheet velocity and equivalent sea level rise on multi-century and multi-millennium time scales.

The 4x CO_2 simulation resulted in full deglacation within 3,000 years resulting in a total sea level rise of 8.2 meters. The North-West and Western margins of Greenland were the first regions that showed substantial melt resulting in the acceleration of the surface flow. By year 500, the decrease in calving due to thinning compensates one-third of the SMB decrease. Since areas with large flow velocities and low bedrock topography melt faster, the ice sheet starts to asymmetrically melt. This asymmetric melt forms elongated ice caps which are attached to the main ice sheet or can eventually become detached.

The Greenland ice sheet in the 3x CO_2 simulation melted at a persistently low rate. The maximum SLR never exceeded 0.8 mm/yr. As a result, the 3x CO_2 simulation did not reach stability by year 8,000 which corresponds to 4.9 meters of eustatic sea level rise. Similar to the 4x CO_2 simulation, the deglaciation starts at the margins of Greenland in the West followed by asymmetric melt. The 4x CO_2 fully deglaciates by year 3,000.

The extent of melt and melt rate in the 2x CO_2 scenario are limited and the ice sheet is in stability by year 4,000. The retreat of the ice sheet is mostly limited to the Western and North-Western margins. As a result of climate warming and ice thinning, by year 500, the SMB has decreased by 30% compared to the pre-industrial simulation. Thinning and retreat at the margins results in a decrease in ice discharge that compensates for the decrease in SMB, resulting in a low MB. By year 500, two-thirds of the SMB is compensated by the ice discharge. By simulation year 4,000 in the 2x CO_2 simulation, the ice discharge fully compensates the drop in SMB. By year 6,000, sea levels have risen by 0.565 m and the mass balance is -6.3 Gt/yr (0.017 mm/yr) with a standard deviation of 85 Gt/yr (0.23 mm/yr).

6.2 Recommendations

For the first time, uncoupled CISM2.1 simulations were performed that were forced by an elevation dependent SMB field provided by a coupled CESM2.1 simulation. This thesis gives context towards the evolution of melt for future CESM2.1-CISM2.1 simulations. Furthermore, this work used a more sophisticated method that accounts for the available for melt to derive the SMB compared to the widely used Positive Degree-Day scheme.

During the CISM2.1, ice caps were removed as the ice sheet model was not designed to simulate ice caps. In this thesis, detached areas of ice were removed if the thickness in these areas does not exceed 2,000 meters. However, this had two consequences for the simulations. First of all, large peaks in the calving rate formed as the mass that is removed is added to the ice discharge mass budget. Secondly, the ice cap code does not include a threshold for a maximum of area or mass that was removed. This issue does not have a large impact on uncoupled simulations and the timing of deglaciation is unaffected. However, if the ice sheet is coupled with the climate, this can cause biases. Due to, amongst others, the results of this thesis, the ice cap removal issue has been found and identified. The threshold for detached ice areas has been changed from 2,000 meters to 10 or 100 meters. This change has been implemented in new fully coupled CESM2.1 simulations.

Simulations with Equilibrated Climate

The 2x, 3x and 4x CO_2 scenarios were conducted with a transient climate. Each warming scenario was conducted with the same 1% to 4x CO_2 fully coupled CESM2.1 simulation. The only difference between each scenario is the years of the CEMS2.1 simulation used to force the ice sheet.

Due to inertia in the climate system, each of the climate scenarios represent transient climate and are therefore colder compared to equilibrated 2x, 3x and 4x CO_2 scenarios. To conduct the 2x, 3x and 4x CO_2 scenarios, three separate coupled climate scenarios should be conducted which are simulated until equilibrium. However, it should be noted that these simulations are computationally expensive, as a fully coupled CESM2.1 simulates roughly 10 years per day, while a CISM2.1 simulation can run 24,000 years per day. A further benefit of a stable climate is that the trend in the SMB is reduced.

Asynchronously Coupled Simulations

The results from the recovery simulation have shown the importance of an asynchronously or synchronously coupled simulation. The Recovery from 4x CO_2 simulation was forced by the same climate that was established with the pre-industrial ice sheet extent. Therefore, the climate was never updated with the new ice sheet topography and only the SMB-elevation feedback is present. However, the SMB-elevation feedback is not strong enough to result into the eventual deglacation of the ice sheet, leading to the expansion of the ice sheet which persists during the 4,000 simulation years. In contrast, Ridley et al 2010 showed that the ice sheet regrowth is limited and an initial ice mass of 40 or 50% compared to the pre-industrial ice sheet converges towards a mass of 20%. In a more realistic scenario, the climate would be adapted to the smaller extent of the ice sheet, which would result into warmer temperatures as glaciated regions with high albedo have shifted to bare ground and tundras with low albedo.

These results show that it is important to have a coupling between the ice sheet and climate during multi-millennium time-scale simulations. However, a fully coupled CESM2.1 simulation is unfeasible for multi-millennium time scales, as running 4,000 simulation years would take at least 1 full year. A more feasible option is to asynchronously couple the CISM2.1 simulation with the climate for a 2x, 3x and 4x CO_2 scenario. Therefore, the climate is updated with the new ice sheet topography after a given amount of time or change in ice sheet area. Asynchronously coupled simulations, similar to Ridley et al., 2010, will likely lead to a more realistic recovery simulation.

This asynchronously coupling also applies to the warming scenarios. For example, the 3x and 4x CO_2 simulations have substantial loss of area. An asynchronously coupled simulation could allow the climate to be updated with the new ice sheet extent, while still retaining a relatively computationally cheap simulation.

CISM2.1 simulation with Ice Inception

Each of the CISM2.1 simulations conducted does not allow for in-situ ice inception: If the SMB is positive in a grid-cell and this grid-cell is unconnected to a glaciated region, no ice will accumulate in the model. CISM2.1 was designed to simulate ice sheets and is not designed to simulate smaller ice caps. Furthermore, the 4 x 4 kilometre resolution of the ice sheet model is not sufficient enough to realistically simulate small ice caps. The absence of ice inception should not affect the 2x, 3x, and 4x CO_2 simulation substantially, it is relevant for the Recovery from 4x CO_2 simulation. Once pre-industrial conditions are introduced after 55% volume loss, regions outside the ice sheet in the North show a strong positive SMB. However, since these regions are unconnected to the ice sheet, no ice will accumulate during the simulation. Allowing ice inception in CISM2.1 could result in the accumulation of an ice cap outside the main ice sheet.

Ensemble Simulations

The uncoupled CISM2.1 simulations are computationally cheap, with a simulation output of 1000 years per hour on NCAR's Cheyenne computer environment. As a result, uncoupled CISM2.1 simulations are suitable to conduct ensemble simulations by varying the ice sheet parameters for each simulation.

Chapter 7

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Chapter 8

Appendix

A

Table 8.1: Greenland ice sheet Mass in Gigatons

Simulation Year	2x CO_2	3x CO_2	4x CO_2	Regrowth
500	$2.905 * 10^6$	$2.851 * 10^6$	$2.573 * 10^6$	-
1000	$2.876 * 10^6$	$2.763 * 10^6$	$1.974 * 10^6$	-
1500	$2.853 * 10^6$	$2.661 * 10^6$	$1.326 * 10^6$	$1.375 * 10^6$
2000	$2.835 * 10^6$	$2.538 * 10^6$	$7.78 * 10^5$	$1.444 * 10^6$
2500	$2.820 * 10^6$	$2.399 * 10^6$	$3.03 * 10^5$	$1.506 * 10^6$
3000	$2.807 * 10^6$	$2.256 * 10^6$	$7.50 * 10^4$	$1.576 * 10^6$
3500	$2.796 * 10^6$	$2.112 * 10^6$	$2.11 * 10^4$	$1.652 * 10^6$
4000	$2.788 * 10^6$	$1.885 * 10^6$	$2.93 * 10^3$	$1.725 * 10^6$
5000	$2.773 * 10^6$	$1.654 * 10^6$	-	$1.897 * 10^6$
6000	$2.758 * 10^6$	$1.472 * 10^6$	-	-
7000	-	$1.332 * 10^6$	-	-
8000	-	$1.211 * 10^6$	-	-