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The Future Sea-Level Contribution from Antarctica: Projections of Solid Ice Discharge

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Abstract

Future sea level change has a strong impact on the livelihood of a large share of the world's population. Sea-level projections are thus of great importance with respect to an assessment of necessary mitigation and adaptation measures. The major uncertainty in state-of-the-art projections lies within the evolution of the solid ice discharge from Antarctica, the largest ice mass on Earth.

To understand the physical mechanisms underlying a change in solid ice discharge and to quantify the uncertainties in future projections of the sea-level contribution from Antarctica, we have developed the Potsdam Parallel Ice Sheet Model, PISM-PIK, which consistently represents the ice flow in sheet, shelves and the transition zone. In a dynamic equilibrium simulation of the Antarctic Ice Sheet under present-day boundary conditions the model is able to reproduce large-scale geometric properties and the full range of ice velocities observed in Antarctica, from almost zero near the ice divides to a few kilometers per year in ice streams.

With PISM-PIK, I investigate solid ice discharge for the years 1850 to 2500 under climate scenarios based on the Extended Concentration Pathways. I show that the uncertainties of the regional temperature projections and from unknown ice parameters used in PISM-PIK are of similar importance throughout the simulations. The maximum dynamic ice loss from Antarctica caused solely by surface warming within the time-period from 1850 to 2500 is 0.58 m. Additional ocean warming and the resulting increase in sub-shelf melting lead to almost a doubling of sea-level rise until the year 2500. However, the largest contribution to solid ice discharge turns out to be caused by the projected increase in precipitation, tripling the overall ice loss. This is due to a precipitation-induced steepening of the surface gradients across the grounding line which results in an increase in driving stress along almost the entire coastline of Antarctica.

PISM-PIK is able to reproduce the recently observed rate of solid ice loss from Antarctica, but only in later years of the 21^{st} century. The acceleration observed for the years 1992 to 2009 is first reached around year 2077 of the highest emission scenario. The states of the ice-sheet associated with these years are similar in their geometric properties, with a mean difference in ice thickness of only a few meters. However, while the solid ice discharge is maximally 0.07 m within the 21^{st} century, it amounts up to 0.24 m within the century succeeding 2077. Future dynamic ice loss from Antarctica thus crucially depends on the history of the ice-sheet.

Following an alternative approach, I have derived a response function for solid ice discharge which also reflects this finding. This response function provides a relation between surface warming and the increase in outflow through softening of the ice. The resulting sea-level rise compares well with the model results from PISM-PIK on a centennial time-scale. The response function is of the form $R(t) \sim t^{\alpha}$, where the

exponent α is positive because solid ice discharge increases with the amount of accumulated heat in the ice-sheet's interior. This is in contrast to the response functions which I derived for thermosteric sea-level rise and the dynamic ice loss from the Greenland Ice Sheet. While these are found to be of the same functional type, they yield negative exponents α, meaning that the influence of past climate changes on sea-level rise decreases with time.

Zusammenfassung

Zukünftige Meeresspiegelveränderungen haben einen starken Einfluss auf die Lebensgrundlage eines großen Teils der Weltbevölkerung. Im Hinblick auf die Diskussion um notwendige Klimaschutz- und Anpassungsmaßnahmen sind Meeresspiegelprojektionen daher von zentraler Bedeutung. Die größte Unsicherheit aktueller Projektionen liegt darin, welchen Beitrag die Antarktis, das größte Frischwasserreservoir der Erde, aufgrund von Veränderungen in der Eisdynamik liefern wird.

Um die dem Masseverlust zugrundeliegenden physikalischen Mechanismen zu verstehen und die Unsicherheit in Zukunftsprojektionen des Meeresspiegelbeitrags der Antarktis zu quantifizieren, haben wir das Potsdam Parallel Ice Sheet Model (PISM-PIK) entwickelt, in dem der Fluss im Eisschild sowie den Eisströmen und -schelfen einheitlich dargestellt wird. In einer dynamischen Gleichgewichtssimulation des Antarktischen Eisschildes unter heutigen Randbedingungen ist das Modell in der Lage, sowohl die geometrischen Eigenschaften als auch das gesamte Spektrum an Eisgeschwindigkeiten zu reproduzieren, das von beinahe Null nahe den Eisscheiden bis hin zu mehreren Kilometern im Jahr in den Eisströmen reicht.

Mithilfe von PISM-PIK untersuche ich den Eisverlust für den Zeitraum von 1850 bis 2500 unter Klimaszenarien, die auf den sogenannten Extended Concentration Pathways beruhen. Dabei zeige ich, dass die Unsicherheiten, die den regionalen Temperaturprojektionen und der Wahl unbekannter Eisparameter in PISM-PIK entspringen, von ähnlicher Bedeutung sind. In Experimenten, in denen ausschließlich die Eisoberfläche erwärmt wird, beträgt der maximale dynamische Eisverlust der Antarktis 0.58 m bis zum Jahr 2500. Durch die zusätzliche Erwärmung des Ozeans und die dadurch hervorgerufene Erhöhung der Schmelzraten an den Schelfunterkanten kommt es beinahe zu einer Verdopplung des Meeresspiegelanstiegs. Wie sich in den Simulationen herausstellt, entsteht der größte Beitrag jedoch durch die zukünftige Erhöhung des Niederschlags – durch ihn wird der Gesamtmasseverlust verdreifacht. An der Aufsetzlinie kommt es durch den zusätzlichen Niederschlag zu einem steileren Oberflächengradienten, wodurch der Eisfluss in die Schelfe erhöht wird. Dieser Effekt ist beinahe entlang der gesamten Antarktischen Küstenlinie zu beobachten.

Die momentan in der Antarktis beobachtete Eisverlustrate kann mit PISM-PIK reproduziert werden, allerdings erst zu einem späteren Zeitpunkt des 21. Jahrhunderts. Die zwischen 1992 und 2009 beobachtete Beschleunigung des Eisverlustes wird zum ersten Mal um das Jahr 2077 des höchsten Emissionsszenarios erreicht. Die Zustände des Eisschildes in den Jahren 2000 und 2077 ähneln sich stark in ihren geometrischen Eigenschaften, die Eisdicken weichen dabei im Mittel nur um wenige Meter voneinander ab. Während jedoch der Eisverlust im 21. Jahrhundert maximal 0.07 m beträgt, beläuft er sich in dem Jahrhundert nach 2077 auf 0.24 m. Der zukünftige dynamische Eisverlust der Antarktis hängt demnach

entscheidend von der Geschichte des Eisschildes ab.

Dies zeigt sich auch in einem alternativen Ansatz, in dem ich eine Antwortfunktion für den dynamischen Eisverlust bestimmt habe. Diese Antwortfunktion stellt einen Zusammenhang zwischen der Oberflächenerwärmung und dem durch das Weicherwerdens des Eises hervorgerufenen verstärkten Eisfluss her. Der dadurch verursachte Meeresspiegelanstieg stimmt auf einer Zeitskala von Jahrhunderten gut mit den Simulationsergebnissen aus PISM-PIK überein. Die Antwortfunktion hat die Form $R(t) \sim t^{\alpha}$, wobei der Exponent α positiv ist, da der Eisverlust mit der im Inneren des Eisschildes angestauten Wärmemenge zunimmt. Dies ist ein entscheidender Unterschied zu den Antwortfunktionen, die ich für die thermische Expansion des Ozeans und den dynamischen Eisverlust des Grönländischen Eisschildes bestimmt habe. Während diese die gleiche funktionale Form aufweisen wie die Antwortfunktion für den Antarktischen Masseverlust, sind die jeweiligen Exponenten α in diesen Fällen negativ, das heißt, der Einfluss vergangener Klimaänderungen auf den Meeresspiegelanstieg verringert sich mit der Zeit.

Contents

Please find the full dissertation here.

1 Introduction

1.1 The role of solid ice discharge from Antarctica with respect to future sea-level rise

Sea-level rise is one of the major impacts of anthropogenic climate change which involves various subsystems of the climate system acting and interacting on different time-scales. Recently, the sea-level budget for the time-period since 1970 has been closed (Church *et al.* , 2011), meaning that the observed global sea-level rise can be explained by the observed changes of its individual components – thermal expansion of the ocean and ice loss from mountain glaciers as well as the two ice-sheets on Greenland and Antarctica. The ice-sheets alone have the potential to raise global sea-level by 70 m (Alley *et al.* , 2005). Satellite observations indicate that their contribution to global sea-level rise has rapidly increased over the past decades (Rignot *et al.* , 2011). It has been of similar magnitude as that of thermosteric sea-level rise since 2005 (Church *et al.* , 2011). These observations suggest that Greenland and Antarctica will play a decisive role with respect to future sea-level rise.
In sea-level projections given in the last Assessment Report of the Intergovernmental Panel on Climate Change (Solomon *et al.* , 2007), however, their contribution could not be accurately quantified because the underlying processes, including possible rapid dynamic changes, were insufficiently understood (Meehl *et al.* , 2007). Consequently, prior projections have underestimated observed sea-level rise between the years 2000 and 2007 by about 40% (Rahmstorf *et al.* , 2007).

In order to improve future projections of the sea-level contribution from Antarctica, we need to understand how changes in the climatic boundary conditions affect the dynamics of the ice-sheet and shelves. Figure 1.1 illustrates the various climate forcings acting on the Antarctic Ice Sheet. Precipitation on Antarctica is expected to increase under future climate change, as a consequence of the higher water vapor carrying capacity of the warmer atmosphere (Uotila *et al.* , 2007; Bracegirdle *et al.* , 2008), especially near the ice-sheet margins. Surface melting, on the other hand, is projected to remain small for the near future (Huybrechts *et al.* , 2011; Vizcaino *et al.* , 2010), so that the overall surface mass balance within the 21^{st} century is likely to be positive. The key to explaining the recently observed acceleration of mass loss from Antarctica and to improving future projections of its sea-level contribution lies therefore in understanding the processes determining the solid ice discharge.

Solid ice discharge comprises all changes in the ice flow across the so-called grounding line which separates the grounded ice-sheet from the floating ice shelves. Ice shelves and outlet glaciers surround

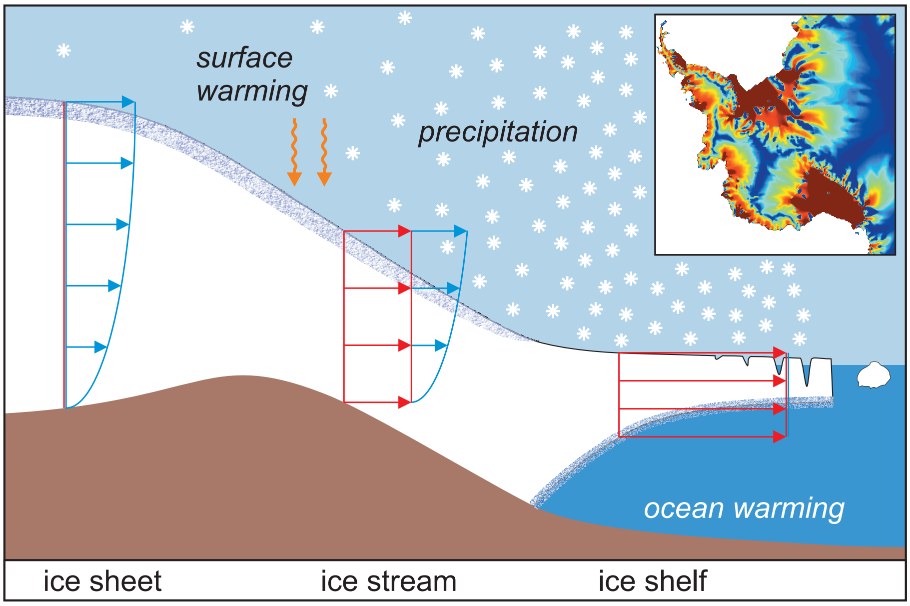

Figure 1.1: Conceptual figure illustrating the different forcings acting on the Antarctic Ice Sheet: In general, mass is gained through accumulation and lost through the outflow across the grounding line or surface melting, which is negligible for present-day Antarctica. Surface warming leads to softening of the ice, thereby increasing the overall ice flux. Ocean warming enhances sub-shelf melting, which is generally strongest near the grounding line. Calving indirectly influences the flow across the grounding line due to the buttressing effect of ice shelves.
The characteristic velocity profiles of the ice-sheet, streams and shelves are illustrated by red and blue arrows. In the sheet, where the ice is frozen to the bed, the velocity is dominated by vertical-shearing, whereas ice shelves experience no basal friction and are thus dominated by longitudinal spreading. The fast ice streams nourishing an ice shelf can be regarded as transitional regions between these two flow regimes. The resulting distribution of ice velocities in the West-Antarctic Ice Sheet as simulated with PISM-PIK under present-day boundary conditions is shown in the inlay.

about 74 % of Antarctica's coastline (Bindschadler *et al.* , 2011). The role of ice-shelf dynamics with respect to solid ice discharge has long been underestimated since ice shelves, as they are afloat, do not directly affect sea-level. However, the retreat or loss of an ice shelf causes the ice upstream of the grounding line to accelerate (Dupont & Alley, 2005; Rignot & Jacobs, 2002). This loss of buttressing and its relevance for solid ice discharge may not be neglected in sea-level projections.

In the context of future climate change, two main mechanisms for dynamic ice discharge from Antarctica have been discussed so far: One is directly caused by the penetration of surface temperature changes into the ice body, which leads to softening of the ice and an overall increase in ice flow. The other is caused by enhanced basal melting due to oceanic warming near the Antarctic ice shelves which induces a change in surface elevation and thereby increases the driving stress across the grounding line, leading to more outflow. This thesis aims at improving the understanding of these processes and their effect on future sea-level rise.

1.2 Scope and contents of the thesis

Aiming at a better understanding of the changes in ice dynamics caused by future warming and their effect on solid ice discharge, the first necessary step is to develop an ice-sheet model capable of simulating them. The first paper of my thesis (Sect. 2.1, Winkelmann *et al.* (2011)) introduces the Potsdam Parallel Ice Sheet Model (PISM-PIK), a continental-scale model for ice sheet and shelves. It incorporates the processes most relevant for investigating solid ice discharge from Antarctica. PISM-PIK is based on the Parallel Ice Sheet Model (PISM, Bueler & Brown (2009)), a three-dimensional thermodynamically coupled model based on a finite difference discretization.

In order to simulate the Antarctic sheet-shelf system as a whole, it is essential for an ice-sheet model to capture the transition from vertical-shearing dominated flow in those parts of the ice-sheet which are frozen to the ground to spreading-dominated flow in ice shelves which do not experience basal friction. An important step towards this goal is made in PISM-PIK by means of the so-called dual approximation based on Bueler & Brown (2009): This approach relies on the two shallow approximations of the Stokes equations, the Shallow Ice Approximation (SIA) and the Shallow Shelf Approximation (SSA). These approximations make use of the fact that the ice thickness is small compared to relevant horizontal scales so that the full Stokes problem can be reduced by scaling the equations with the small depth-to-width ratio. In PISM-PIK, the SIA and SSA equations are solved simultaneously over the whole ice area. The ice velocity is then obtained by superposing the two solutions from SIA and SSA (depicted in Figure 1.1 in blue and red, respectively), which enables a smooth transition between the different stress regimes in the sheet-shelf system. Streams can be diagnosed by means of the dual approximation as those regions of grounded ice which are dominated by the SSA velocities.
The dual approximation has been tested in experiments of the Marine Ice Sheet Model Intercomparison Project (MISMIP, Schoof *et al.* (2009)), showing that grounding line motion in PISM-PIK compares well with the semi-analytical solution by Schoof (2007) for the flowline case. This is crucial with regard to an analysis of solid ice discharge since the position of the grounding line has a strong influence on the stress balance in sheet and shelves and vice-versa.

In aiming at modelling the Antarctic Ice Sheet in particular, new modules have been introduced in PISM-PIK, especially with respect to ice-shelf dynamics. These include a physical boundary condition at the calving front (the interface between an ice shelf and the ocean) as well as a novel scheme capturing subgrid-scale advance and retreat of the calving front. This parameterization – further described in Sect. 4.1 (Albrecht *et al.* , 2011) – enables PISM-PIK to simulate small changes in the ice front position, irrespective of the model resolution.
Calving is of particular importance with respect to solid ice discharge as it determines the stress-field within shelf and sheet via the buttressing effect. In PISM-PIK, the calving rate it determined by the first-order kinematic calving law introduced in Sect. 4.2 (Levermann *et al.* , 2011). It is consistent with the observation that the calving rate depends on the local spreading rate of an ice shelf (Alley *et al.* , 2008) and enables PISM-PIK to reproduce multiple stable ice fronts as for instance observed for the Larsen A and B Ice Shelves (Rignot *et al.* , 2004; Rott *et al.* , 2007).

The Potsdam Parallel Ice Sheet Model has first been applied to the Antarctic sheet-shelf system in a dynamic equilibrium simulation under present-day boundary conditions. The second paper of my thesis (Sect. 2.2, Martin *et al.* (2011)) shows that PISM-PIK is able to reproduce large-scale characteristics of the Antarctic Ice Sheet, such as the ice volume and the position of grounding line and calving fronts. The modelled velocity field is compared to observational data (Liu *et al.* , 1999; Joughin *et al.* , 2002; Jezek *et al.* , 2003), demonstrating that the large range of observed surface speeds is well-captured.

By means of the newly developed ice-sheet and shelf model PISM-PIK, I investigate future solid ice discharge in the third paper of this thesis (Sect. 2.3, Winkelmann *et al.* (2012b)). For this purpose, I apply climate scenarios based on the four Extended Concentration Pathways (ECPs, Meinshausen *et al.* , 2011), which extend the Representative Concentration Pathways (van Vuuren *et al.* , 2011) to the year 2500 and span a wide range of possible future greenhouse gas emissions.
Projections of solid ice discharge from Antarctica as presented in Sect. 2.3 are subject to two main sources of uncertainty, arising from the spread in the climate projections and the model input parameters. In order to analyze these uncertainties, I perform the simulations of future solid ice discharge for the likely ranges of surface and ocean warming under the emission pathways based on a perturbed-physics ensemble. The three ice parameters which are identified as most relevant with respect to the ice flow across the grounding line concern the ice softness and the friction between ice sheet and bedrock. In order to quantify the uncertainty in sea-level projections resulting from the unknown physics captured in them, I vary them in such a way that a broad range of potential ice dynamics is covered. This yields a 81-member ensemble of equilibrium states of the Antarctic Ice Sheet, all closely resembling present-day

Antarctica in their geometric properties but differing in their sensitivity to climate change. Each of these 81 initial states is forced with the temperature anomalies corresponding to the 33^{rd}, 50^{th} and 66^{th} percentiles of the range of temperature projections for a given ECP scenario. These are computed from global temperature projections via the down-scaling approach by Frieler *et al.* (2011). Both the climate and the parametric uncertainty are combined into a probability distribution for the projected solid ice discharge from Antarctica.

In order to separate the effects of the different forcings acting on the Antarctic Ice Sheet, I investigate future solid ice discharge in three sets of experiments, consecutively adding surface warming, ocean warming and precipitation under the ECP-scenarios. In the analysis of these experiments, I find that the increase in precipitation over Antarctica expected in a warming climate has a surprisingly strong influence on solid ice discharge.
I focus on this significant effect in the fourth paper of my thesis (Sect. 2.4, Winkelmann *et al.* (2012a)). The solid ice discharge caused by enhanced precipitation is quantified and compared to that caused by surface and ocean warming. This comparison reveals that precipitation-induced ice loss constitutes by far the largest contribution to future solid ice discharge. In Sect. 2.4, the simple underlying mechanism is identified and shown to be robust, leading to additional outflow along almost the entire coastline of the Antartic Ice Sheet compared to the warming-only case.

The effect of surface warming on solid ice discharge is further investigated by means of a linear response function in the fifth paper of my thesis (Sect. 2.5, Winkelmann & Levermann (2012)). The derivation of the response function is based on a certain learning period. This is also the case for semi-empirical approaches which have been used in order to reproduce and project global sea-level rise from the global mean temperature increase (Rahmstorf, 2007; Vermeer & Rahmstorf, 2009; Grinsted *et al.* , 2010) or changes in radiative forcing (Jevrejeva *et al.* , 2010).
Comprehensive models such as PISM-PIK allow for investigating the sea-level response of a single component to a given climate forcing. I find that the sea-level response of Antarctica to surface warming, as presented in Sect. 2.3, exhibits a general functional form which I aim at capturing by use of a linear response function. In the response function formalism, sea-level rise can be described as the convolution of the climate forcing, in this case the change of surface temperatures over the Antarctic Ice Sheet, and the system-specific response function. I construct this function based on the knowledge about past surface warming and solid ice discharge from Antarctica. I can then use it to predict future solid ice discharge and compare the results to the projections obtained with PISM-PIK. The prospects and limitations of this approach are explored in Sect. 2.5 of this thesis.

1.3 Overview

This thesis is organized around five scientific articles, which are either published or under review. Here, I give an overview of the contents of each individual article which is presented in Section 2. I have been involved in the work for two additional papers which are given in the Appendix.

Article 1

The Potsdam Parallel Ice Sheet Model (PISM-PIK) – Part 1: Model Description

R. Winkelmann, M.A. Martin, M. Haseloff, T. Albrecht, E. Bueler, C. Khroulev, A. Levermann

This article describes the Potsdam Parallel Ice Sheet Model including the dual approximation used for the computation of ice velocities and new modules for a better representation of ice-shelf dynamics. The model is based on the Parallel Ice Sheet Model (PISM, Bueler & Brown (2009)), version stable 0.2. Together with Maria Martin, Ricarda Winkelmann merged PISM-0.2 and all newly-developed modules into a consistent version of PISM-PIK. They also developed the scheme for excluding freely-floating icebergs together. Together with Ed Bueler, Ricarda Winkelmann implemented the first basic routine for coupling the ice-sheet model to the ocean. The modifications concerning the calving front boundary condition were jointly developed by Torsten Albrecht, Marianne Haseloff, Anders Levermann, Maria Martin and Ricarda Winkelmann. The paper was written by Ricarda Winkelmann.

Article 2

The Potsdam Parallel Ice Sheet Model (PISM-PIK) – Part 2: Dynamic Equilibrium Simulation of the Antarctic Ice Sheet

M.A. Martin, R. Winkelmann, M. Haseloff, T. Albrecht, E. Bueler, C. Khroulev, A. Levermann

The performance of PISM-PIK in a dynamic equilibrium simulation of Antarctica is analyzed and compared to observations. Maria Martin, Anders Levermann and Ricarda Winkelmann discussed the model performance under present-day boundary conditions together and developed and adapted the modelling strategy, especially with respect to the choice of input parameters. Ricarda Winkelmann participated in the interpretation of the results and the improvement of the manuscript.

Article 3

Uncertainty in Future Solid Ice Discharge from Antarctica

R. Winkelmann, A. Levermann, K. Frieler, M.A. Martin

Future solid ice discharge is investigated under climate scenarios based on the Extended Concentration Pathways. Ricarda Winkelmann introduced further modules in PISM-PIK (in addition to the ones presented in Articles 1 and 2) which were needed for the purpose of investigating future solid ice discharge: In particular, she extended the one-dimensional ocean box model by Olbers & Hellmer (2010) for the use in PISM-PIK. She also implemented the parameterization for precipitation changes based on Huybrechts & Wolde (1999). Together with Anders Levermann and Katja Frieler, Ricarda Winkelmann derived the procedure to combine climate and parameter uncertainty. Ricarda Winkelmann produced the perturbed-physics ensemble, performed and analyzed the simulations of future solid ice discharge and wrote the manuscript.

Article 4

Snowfall Increases Future Ice Discharge from Antarctica

R. Winkelmann, A. Levermann, M.A. Martin, K. Frieler

The effect of enhanced snowfall on future solid ice discharge from Antarctica is analyzed and compared to the ice loss caused by surface and ocean warming. Ricarda Winkelmann performed the simulations, found the basic mechanism, and analyzed the results. The manuscript was written by Ricarda Winkelmann, supported by Anders Levermann.

Article 5

Linear Response Functions to Project Contributions to Future Sea-Level

R. Winkelmann, A. Levermann

In this manuscript, linear response functions are presented in order to estimate the solid ice discharge from Antarctica caused by surface warming, the dynamic sea-level rise from Greenland and thermosteric sea-level rise. Together with Anders Levermann, who initiated this work, Ricarda Winkelmann advanced the conceptual idea. She applied the response functions derived for each subsystem and compared the results to the respective results from comprehensive models. Ricarda Winkelmann also wrote the manuscript.

2 Original manuscripts

2.1 The Potsdam Parallel Ice Sheet Model (PISM-PIK) – Part 1: Model Description

We present the Potsdam Parallel Ice Sheet Model (PISM-PIK), developed at the Potsdam Institute for Climate Impact Research to be used for simulations of large-scale ice sheet-shelf systems. It is derived from the Parallel Ice Sheet Model (Bueler & Brown, 2009). Velocities are calculated by superposition of two shallow stress balance approximations within the entire ice covered region: the shallow ice approximation (SIA) is dominant in grounded regions and accounts for shear deformation parallel to the geoid. The plug-flow type shallow shelf approximation (SSA) dominates the velocity field in ice shelf regions and serves as a basal sliding velocity in grounded regions. Ice streams can be identified diagnostically as regions with a significant contribution of membrane stresses to the local momentum balance. All lateral boundaries in PISM-PIK are free to evolve, including the grounding line and ice fronts. Ice shelf margins in particular are modeled using Neumann boundary conditions for the SSA equations, reflecting a hydrostatic stress imbalance along the vertical calving face. The ice front position is modeled using a subgrid-scale representation of calving front motion (Albrecht *et al.* , 2011) and a physically-motivated calving law based on horizontal spreading rates. The model is tested in experiments from the Marine Ice Sheet Model Intercomparison Project (MISMIP). A dynamic equilibrium simulation of Antarctica under present-day conditions is presented in Martin *et al.* (2011).

Please find the full manuscript, published in *The Cryosphere 5, 715-726 (2011)*, here.

2.2 The Potsdam Parallel Ice Sheet Model (PISM-PIK) – Part 2: Dynamic Equilibrium Simulation of the Antarctic Ice Sheet

We present a dynamic equilibrium simulation of the ice sheet-shelf system on Antarctica with the Potsdam Parallel Ice Sheet Model (PISM-PIK). The simulation is initialized with present-day conditions for bed topography and ice thickness and then run to steady state with constant present-day surface mass balance. Surface temperature and sub-shelf basal melt distribution are parameterized. Grounding lines and calving fronts are free to evolve, and their modeled equilibrium state is compared to observational data. A physically-motivated calving law based on horizontal spreading rates allows for realistic calving fronts for various types of shelves. Steady-state dynamics including surface velocity and ice flux are analyzed for whole Antarctica and the Ronne-Filchner and Ross ice shelf areas in particular. The results show that the different flow regimes in sheet and shelves, and the transition zone between them, are captured reasonably well, supporting the approach of superposition of SIA and SSA for the representation of fast motion of grounded ice. This approach also leads to a natural emergence of sliding-dominated flow in stream-like features in this new 3-D marine ice sheet model.

Please find the full manuscript, published in *The Cryosphere 5, 727-740 (2011)*, here.

2.3 Uncertainty in Future Solid Ice Discharge from Antarctica

Future solid ice discharge from Antarctica under climate scenarios based on the Extended Concentration Pathways is investigated with the Potsdam Parallel Ice Sheet Model (PISM-PIK), a shallow model with a consistent representation of the ice flow in sheet, shelves and the transition zone. Both the uncertainty in the climate forcing as well as the intra-model uncertainty are combined into a probability distribution for solid ice discharge from Antarctica until the year 2500 under the ECP scenarios: All simulations are performed for a 81-member perturbed-physics ensemble and the likely ranges of surface and ocean warming under the emission pathways derived from the results of 20 CMIP3-AOGCMS. The effects of surface warming, ocean warming and increased precipitation on solid ice discharge are separately considered. We find that solid ice discharge caused by enhanced sub-shelf melting exceeds that caused by surface warming. Increasing precipitation leads to a change from net sea-level rise to sea-level drop. Our results suggest that the history of the ice-sheet plays an important role with respect to projections of solid ice discharge. Although all climate-change-forced simulations begin with the year 1850, the ice discharge around 2000 is significantly smaller than observed. Observed changes in ice discharge are reached around 2077 under the ECP-8.5 scenario. During the subsequent century, ice discharge reaches up to 0.24 m.

Please find the full manuscript, published in *The Cryosphere Discussions 6, 673-714 (2012)*, here.

2.4 Snowfall Increases Future Ice Discharge from Antarctica

Future sea level rise is one of the major impacts of anthropogenic climate change. While enhanced snowfall over Antarctica as projected in regional as well as global climate models constitutes a comparably certain negative future contribution to global sea level, the largest uncertainty arises from the dynamic ice discharge from Antarctica. Here we show that these two processes are not independent, but that future ice discharge is enhanced up to three times due to additional snowfall under global warming. The effect exceeds that of surface warming as well as that of basal ice-shelf melting and is due to the difference in surface elevation change caused by snowfall on grounded and floating ice. As a result of their dynamic similarity, the ratio between basal-melt-induced- and snowfall-induced ice loss is relatively independent of the specific representation of the transition zone. In an ensemble of simulations, capturing ice-physics uncertainty, the additional dynamic ice loss along the coastline compensates between 30 and 65% of the ice gain due to enhanced snowfall over the entire continent. The reported effect thus strongly counters a potential negative contribution to global sea level by the Antarctic Ice Sheet.

Please find the full manuscript here or see the final publication in *Nature 492, 239-242 (2012).*

2.5 Linear Response Functions to Project Contributions to Future Sea-Level

We propose linear response functions to separately estimate the sea-level contributions of thermal expansion and solid ice discharge from Greenland and Antarctica. The response function formalism introduces a time-dependence which allows for future rates of sea-level rise to be influenced by past climate variations. We find that this time-dependence is of the same functional type, $R(t) \sim t^{\alpha}$, for each of the three subsystems considered here. The validity of the approach is assessed by comparing the sea-level estimates obtained via the response functions to projections from comprehensive models. The pure vertical diffusion case in one dimension, corresponding to $\alpha = -0.5$, is a valid approximation for thermal expansion within the ocean up to the middle of the 21^{st} century for all Representative Concentration Pathways. The approximation is significantly improved for $\alpha = -0.9$. For the solid ice discharge from Greenland we find an optimal value of $\alpha = -0.7$. Different from earlier studies we conclude that solid ice discharge from Greenland due to dynamic thinning is bounded by 0.42 m. Ice discharge induced by surface warming on Antarctica is best captured by a positive value of $\alpha = 0.1$ which reflects the fact that ice loss increases with the cumulative amount of heat available for softening the ice in our model.

Please find the full manuscript here or see the final publication in *Climate Dynamics 38 (2012), online first.*

3 Discussion and conclusions

Solid ice discharge from the Antarctic Ice Sheet plays an important role for global sea-level rise. It is therefore essential to understand the processes which determine solid ice discharge, their interlinkage within the Antarctic sheet-shelf system as well as their interactions with other parts of the climate system. The uncertainty in projections of solid ice discharge needs to be assessed and included in sea-level projections.

In my thesis, I have studied the dynamic sea-level contribution from Antarctica using two different approaches, (1) by means of the newly-developed Potsdam Parallel Ice Sheet Model, PISM-PIK, and (2) using the linear response function formalism.

Process-based models such as PISM-PIK are essential to understand and simulate the changes in ice-dynamics caused by changes in the climatic boundary conditions. Such models allow for the analysis of uncertainties and the separation of the effects of different forcings acting on the ice-sheet, as I have done in this work for changes in surface temperature, ocean temperature and precipitation. The model results can also be used to identify more basic mechanisms, as has been done here for the increase of future solid ice discharge caused by enhanced precipitation.

However, projections with process-based models have limitations. Sea-level rise can be misjudged due to an under- or overestimation of certain effects, or because there are further contributing processes which are not identified yet. Approaches such as the response functions presented in my thesis provide an important alternative to project future sea-level rise, since they are designed to capture the sea-level response to a certain forcing in a comprehensive manner, without relying on the full understanding of each of the processes involved. They are based on the assumption that each subsystem contributing to sea-level rise will respond to future climate changes in the same way as it has responded in the past. The fundamental uncertainty arising from this assumption cannot be quantified. The two types of approaches are thus subject to different sources of uncertainty and need to be understood as complementing each other in the investigation of future sea-level rise. In this thesis, I present findings from both approaches for the solid ice discharge from Antarctica.

In a first step, PISM-PIK has been developed in order to simulate the processes which are most relevant for investigating solid ice discharge. Since it is the flow across the grounding line which elevates global sea level, it is especially important for ice-sheet models to capture the dynamics in the transition zone between the grounded ice sheet and floating ice shelves. The dual approximation, for the first time applied to the Antarctic sheet-shelf system in PISM-PIK, provides a continuous representation of the ice flow in this region. The strength of this approach can be seen in a comparison of the model results under present-day boundary conditions to recent observations of the ice topography and surface velocities of the Antarctic Ice Sheet. A grid-point-by-grid-point analysis shows that PISM-PIK is able to reproduce the large range of ice velocities observed on Antarctica, spanning three orders of magnitude.

In contrast to some other numerical models of the Antarctic Ice Sheet, the grounding line is not kept fixed in PISM-PIK, but evolves according to the floatation criterion. This means that its position is fully determined by the evolution of the ice thickness which results from the velocity distribution within the entire sheet-shelf system. The position of the grounding line is thus indirectly influenced by different dynamic processes, such as calving and sub-shelf melting. Basal melt rates are generally highest near the grounding line, but differ greatly among the ice shelves surrounding Antarctica. The highest melt-rates are observed underneath the floating tongue of Pine Island Glacier, exceeding those of other ice shelves by several orders of magnitude. In order to capture this wide range of basal melt rates and consequently model the flow across the grounding line more accurately, I have used an approach based on the ocean-box model by Olbers & Hellmer (2010) in the simulations with PISM-PIK. The ocean-box model captures the basic overturning circulation in sub-shelf cavities which is driven by the differences in local freezing point temperature at the underside of the ice shelf. When initiated with observed temperatures and salinities, PISM-PIK is able to reproduce recently observed melt rates of the Ross, Filchner-Ronne, Amery and Pine Island Ice Shelves.

Based on the good performance for present-day boundary conditions, I have investigated future solid ice discharge under climate scenarios based on the Extended Concentration Pathways. Similar to other ice-sheet models as well as climate and ocean models, PISM-PIK relies on the use of parameterizations for a number of processes. These form a source of uncertainty which had not been assessed in prior projections of solid ice discharge from Antarctica. In order to quantify this uncertainty, I produced an ensemble of present-day ice sheet simulations with varying parameter combinations. From this ensemble, I selected 81 parameter settings which reproduce the presently-observed ice geometry within reasonable error bars. The resulting realizations of the Antarctic Ice Sheet differ in ice softness and basal friction which are associated with the processes most relevant for the ice flow across the grounding line. Uncertainty in projections of solid ice discharge also arises through the applied climate forcing. I have therefore forced the 81 initial states with the median as well as the 33$^{\text{rd}}$ and 66$^{\text{th}}$ percentiles of the uncertainty distributions derived for the Antarctic surface and ocean temperatures.

In the simulations with PISM-PIK, I have shown that both sources of uncertainty are similarly important and lead to a spread of up to 54 % of the mean sea-level response to future warming. It is therefore essential to include them in future projections of the sea-level contribution from Antarctica.

In order to understand the different contributions from atmospheric surface warming, ocean warming and precipitation, I performed the 4 x 3 x 81 simulations as detailed above for all different forcings separately as well as all forcings combined. This revealed that the softening effect of surface warming has a similarly strong influence on Antarctica's sea level contribution as the basal ice-shelf melting induced by ocean warming.

Surprisingly, by far the largest contribution arose from the additional accumulation that is caused by the enhanced moisture-carrying capacity of a warming atmosphere. Its influence on ice discharge had been dismissed in earlier studies on the basis of an ice sheet model with a different representation of the transition zone (Huybrechts & Wolde, 1999; Gregory & Huybrechts, 2006). In my simulations, I found that the snowfall-induced outflow can increase the ice loss by up to 200% compared to the warming-only simulations. The basic mechanism responsible for this increase in ice discharge is a steepening of the surface gradient at the grounding line: Since about 90% of the ice gain on shelves is depressed below sea-level, the surface elevation is not much affected by enhanced precipitation, in contrast to that of the grounded ice-sheet. This difference causes an increase of the driving stress at the grounding line.

Enhanced basal melting acts on the driving stress in the same manner. However, a simple scaling analysis shows that an increase in sub-shelf melting would have to be nine times larger than the increase in precipitation for it to have the same effect on solid ice discharge. For projections of the dynamic ice loss, it is therefore crucial to simulate the basal melt rates and precipitation on Antarctica as accurately as possible.

The increase of the ice flow across the grounding line caused by enhanced precipitation compensates between 30 and 65 % of the corresponding ice gain. In response to the climate changes projected for the ECP scenarios, sea-level drops within the 21^{st} and 22^{nd} centuries, but stabilizes thereafter. For some of the realizations of Antarctica captured in the perturbed-physics ensemble, the ice-sheet loses mass towards the end of the scenarios. It would be interesting to extend these simulations further into the future in order to see if this trend continues.

In all future projections, I observed a time-delay between forcing and ice-sheet response such that the sea-level contribution of Antarctica is limited to a few centimeters within the 21^{st} century, thereafter rapidly increasing throughout the simulations. I have shown that this time-delay is neither caused numerically through the initialization procedure nor by the time-delay between ocean warming and global mean temperature rise applied in the simulations. It is possibly related to the rather coarse resolution of about 18 km used in PISM-PIK. As many of the actual Antarctic ice streams are narrower, they are not resolved in the simulations, so that the overall ice discharge might be underestimated.

Next to a finer resolution, additional improvement of the model results could be achieved by a subgrid treatment of grounded marine margins in analogy to the subgrid-treatment of the calving front introduced in PISM-PIK. Furthermore, the representation of basal friction needs to be improved: In PISM-PIK, it is modelled via a simple parameterization which crucially depends on the porewater-fraction, one of the parameters I have varied in the perturbed-physics ensemble. The results I have presented in my thesis confirm the central role of basal friction for the outflow across the grounding line.

A third source of uncertainty in projections of solid ice discharge became evident in a comparison of two modelled states of the Antarctic Ice Sheet which are associated with the currently observed solid ice discharge and its acceleration. I have shown these states to be indistinguishable based on the numerical criteria which are applied to assess the ensemble of present-day Antarctica. However, their response to the climate changes in the succeeding century differs between 0.07 m and 0.24 m sea-level equivalent. This difference arises solely through the past climate changes the ice-sheet has undergone, even if the effect of these past changes cannot be detected from its current state. Our limited knowledge about the history of the ice-sheet therefore provides an additional source of uncertainty which needs to be further explored. A comparison of state variables such as the ice volume and the position of the grounding line as used in the projections presented here might not be sufficient for this purpose. Other criteria are needed in order to assess how well the present-day state of the Antarctic Ice Sheet is reproduced with numerical models, which forms the basis for more accurate future projections. Additional observations of dynamic properties such as surface velocities over a longer period will help to further constrain the uncertainty in model projections.

Finally, I was able to generalize the sea level projections obtained with PISM-PIK within the framework of linear response theory. The sea-level response to surface warming can be comprised in a linear response function $R(t) \sim t^{\alpha}$, in its basic form derived from the vertical diffusion of surface temperatures. I showed that while this approach is able to capture the behaviour of the Antarctic Ice Sheet, it is also valid for thermal expansion of the ocean and solid ice discharge from Greenland.

Motivated by this finding, I have proposed to formulate a universal response function comprising the sea-level components considered in this thesis. While I have used regional climate forcings in the derivation and application of each of the three response functions, these are possibly directly linked to changes in global mean temperature. A link is presented in my thesis for the surface temperature changes on Antarctica as well as the ocean temperature changes in the vicinity of Pine Island Glacier and the Ross, Filchner-Ronne and Amery Ice Shelves. All of these are found to exhibit a close-to-linear relation to global mean temperature changes in the CMIP3-AOGCM results which were used to derive the regional climate forcings under the ECP emission scenarios.

Future dynamic sea-level rise from the Greenland Ice Sheet is triggered by a reduction in mechanical frontal stress in the simulations by Price *et al.* (2011) considered here. If a relation between this stress reduction and global mean temperature changes were to be found, the response functions for each of the individual components could be reformulated in terms of global temperature changes. In order to include further contributions to global sea-level rise, the response function approach might however need to be extended to the non-linear case.

In general, the response functions presented here are applicable on time-scales of decades to centuries. Thereafter, the assumption that the sea-level response of each contributing subsystem will qualitatively stay the same as in the past is no longer valid. Possible strong dynamic changes can only be captured by means of process-based model, such as PISM-PIK in the case of solid ice discharge from Antarctica. On longer time-scales, feedbacks between the ice-sheet and the ocean as well as the atmosphere might require the use of a coupled Earth system model.

I hope that my thesis helps to improve our understanding of Antarctica's contribution to future sea level changes.

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4 Appendix

4.1 Parameterization for Subgrid-Scale Motion of Ice-Shelf Calving Fronts

A parameterization for the motion of ice-shelf fronts on a Cartesian grid in finite-difference land-ice models is presented. The scheme prevents artificial thinning of the ice shelf at its edge, which occurs due to the finite resolution of the model. The intuitive numerical implementation diminishes numerical dispersion at the ice front and enables the application of physical boundary conditions to improve the calculation of stress and velocity fields throughout the ice-sheet-shelf system. Numerical properties of this subgrid modication are assessed in the Potsdam Parallel Ice Sheet Model (PISM-PIK) for different geometries in one and two horizontal dimensions and are verified against an analytical solution in a flow-line setup.

Please find the full manuscript, published in *The Cryosphere 5, 35-44 (2011)*, here.

4.2 Kinematic First-Order Calving Law Implies Potential for Abrupt Ice-Shelf Retreat

Recently observed large-scale disintegration of Antarctic ice shelves has moved their fronts closer towards grounded ice. In response, ice-sheet discharge into the ocean has accelerated, contributing to global sea-level rise and emphasizing the importance of calving-front dynamics. The position of the ice front strongly influences the stress field within the entire sheet-shelf-system and thereby the mass flow across the grounding line. While theories for an advance of the ice-front are readily available, no general rule exists for its retreat, making it diffiult to incorporate the retreat in predictive models. Here we extract the first-order large-scale kinematic contribution to calving which is consistent with large-scale observation. We emphasize that the proposed equation does not constitute a comprehensive calving law but represents the first order kinematic contribution which can and should be complemented by higher order contributions as well as the influence of potentially heterogeneous material properties of the ice. When applied as a calving law, the equation naturally incorporates the stabilizing effet of pinning points and inhibits ice shelf growth outside of embayments. It depends only on local ice properties which are, however, determined by the full topography of the ice shelf. In numerical simulations the parameterization reproduces multiple stable fronts as observed for the Larsen A and B Ice Shelves including abrupt transitions between them which may be caused by localized ice weaknesses. We also find multiple stable states of the Ross Ice Shelf at the gateway of the West Antarctic Ice Sheet with back stresses onto the sheet reduced by up to 90 % compared to the present state.

Please find the full manuscript here or see the final publication in *The Cryosphere 6, 273-286 (2012).*

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