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SESSION 9

CRITICAL CHALLENGES IN MODELLING PAST AND FUTURE EVOLUTION OF THE ANTARCTIC AND GREENLAND ICE SHEETS - SCALES, UNCERTAINTY, PROCESSES, IMPLICATIONS FOR SEA LEVEL

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Co-Convened with the IASC Cryosphere Working Group (Guðfinna Th Aðalgeirsdóttir)

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Using triple water isotopes signatures of surface snow to gauge metamorphism in Antarctica

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Water isotopic composition is a key proxy for past climate reconstructions using deep ice cores from Antarctica. As precipitation forms, the local temperature is imprinted in the snowfalls $\delta^{18}O$. However, this climatic signal can be modified after snow deposition when snow is exposed to the atmosphere for a long time in regions with extremely low accumulation. Understanding this effect is crucial for the interpretation of ice core records from the extremely dry East Antarctic Plateau, where post-deposition processes such as blowing snow or metamorphism affect the physical and chemical properties of snow during the long periods of snow exposure to the atmosphere. Despite the importance of these processes for the reliable reconstruction of temperature from water isotopic composition in ice cores, the tools required to quantify their impacts are still missing. Here, we present a first year-long comparison between (a) time series of surface snow isotopic composition including d-excess and ^{17}O-excess at Dome C and (b) satellite observations providing information on snow grain size, a marker of surface metamorphism. Long summer periods without precipitation tend to produce a surface snow metamorphism signature altering the climatic signal in the surface snow $\delta^{18}O$ Using a simple model, we demonstrate that d-excess and ^{17}O-excess allow the identification of the latent fluxes induced by metamorphism, and their impact on surface snow isotopic composition. In turn, their measurement can help improve climate reconstructions based on $\delta^{18}O$ records ice by removing the influence of snow metamorphism.

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The Ice Shelf Lasagne: effects of marine ice on ice shelf dynamics and stability

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Layers of marine accreted ice form at the base of many Antarctic ice shelves, and can account for a significant proportion of the overall shelf thickness. These layers contain a considerable amount of soluble and insoluble impurities, which have been shown to affect the rheological properties of ice on a small scale. However, it is not clear to what extent these marine ice layers can affect the broader dynamics and thermal structure of an ice shelf. We performed a series of deformation experiments on marine ice from the Amery Ice Shelf under quasi-in situ conditions, and compared the results with experiments performed on pure water ice. These experiments reveal the impact of impurities on material structure and rheology, with implications for the deformation of ice in large scale numerical ice shelf simulations.

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Progress towards coupling ice sheet and ocean models

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With recent developments in the modelling of Antarctica and its interactions with the ocean several coupled model frameworks now exist. This talk will focus on presenting the Framework for Ice Sheet - Ocean Coupling (FISOC), developed to provide a flexible platform for performing coupled ice sheet - ocean modelling experiments. We present progress and preliminary results using FISOC to couple the Regional Ocean Modelling System (ROMS) with Elmer/Ice, a full-Stokes ice sheet model. Idealised experiments have been used that also contribute to the WCRP Marine Ice Sheet-Ocean Model Intercomparison Project (MISOMIP). A recent focus is on testing emergent behaviour of the coupled system and the model numerics. The talk will outline future technological applications and developments conducted as part of a broader international consortium effort. These efforts include coupling to sub-glacial hydrology, sea ice and atmospheres to form a complete system-downscaling technology from which to examine the influence of future climate on ice sheet evolution and hence sea level and global climate impacts. Developments to apply the technology to the Greenland Ice Sheet are presently underway.

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Choice of melt parameterization determines the faith of Totten glacier, East Antarctica

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Totten glacier is draining 68% of the Aurora basin, East Antarctica, - an equivalent to 3.5m global sea level rise. Further, Totten's thickness and velocity have been fluctuating during the last decades showing periodic speed-ups and thinning. We investigate the effect of different ocean forcing on Totten glacier using the state-of-the-art ice sheet model BISICLES and based on the high-resolution data sets BedMachine Antarctica and REMA (Morlighem et al., 2019; Howat et al., 2019). Our simulations (2015-2100) are following the ISMIP6 setup and are based on CMIP5 & CMIP6 AOGCM outputs under RCP8.5 and RCP2.6. The contribution to sea level at 2100 varies between plus 20mm and minus 8mm. For all scenarios, we see thinning at the sides of Totten glacier in the slower flowing areas, but only climate models with sub-shelf melt rates that are at least 8m/a above the reference melt rates (1995 - 2017) lead to thinning and acceleration across Totten's grounding line.
In agreement with ISMIP6 results, nonlocal quadratic melt rates adjusted to present day conditions at Pine island glacier, West Antarctica, results in the highest sub-shelf melt rates for all AOGCMs (up to 80m/a locally).
The ISMIP6 ocean melt scheme is based on a feedback given the simulated ice draft change: the thermal forcing of the ocean model is taken from the ocean layer closest to the bottom of the ice shelf at the current simulation step. Simulations not including this feedback lead to higher mass loss than the standard ISMIP6 scenario including the feedback.

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A data-constrained large ensemble of the Antarctic ice sheet evolution over the last glacial cycle: Toward a Bayesian calibration

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To better interpret contemporaneous change of the Antarctic ice sheet and to make improved predictions of its future sea-level contribution, reconstructions of past ice sheet evolution are required. A Bayesian calibration of a glaciological model against paleo and present-day observational constraints offers a rigorous route to quantify robust uncertainty estimates. Transient continental-scale reconstructions over glacial cycles require glaciological models, but the latter depend on parameterisations to account for deficiencies inherent in any numerical model. Recent studies have explored parametric uncertainties with only a few ensemble parameters, this work is distinguished by a much stronger emphasis on quantifying all model uncertainties.

An updated Glacial Systems Model (GSM) is used to simulate the Antarctic ice sheet over the last glacial cycle using more than 30 ensemble parameters. The GSM ice sheet model consists of hybrid SIA-SSA dynamics, Schoof grounding line scheme, hydrofracturing and ice cliff instability mechanisms, temperature-dependent sub-shelf melt scheme, visco-elastic glacial isostatic adjustment, and a broader than previous climate forcing. A Latin hypercube sampling of the parameter space was completed to verify the GSM’s ability to envelope observational constraints. The calibration employs Bayesian neural network emulators of the GSM to permit multi-million MCMC sampling from the posterior probability distribution for GSM ensemble parameter vectors.

The large ensemble results presented here consist of over 10000 data-constrained transient model runs. Preliminary results of the Bayesian calibration are shown as confidence intervals of key metrics including the Antarctic equivalent sea-level contribution to the last interglaciation, LGM, MWP-1a, and present-day glacial isostatic adjustment estimates.

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Exploring the effects of parameter and climate forcing uncertainty on past and future Antarctic Ice Sheet grounding-line retreat

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In future projections of global sea level, the contribution of the Antarctic Ice Sheet (AIS) is one of the most uncertain aspects. In particular, the AIS response to future climate warming scenarios varies widely in numerical ice sheet models, related to uncertainty in model parameter selection and parameterizations of physical processes, such as sub-ice shelf melting. Here, we present the results of two ice sheet model ensembles using the Parallel Ice Sheet Model (PISM) that investigate the influence of model parameter selection on ice sheet sensitivity to ocean and atmosphere forcing. The first ensemble focuses on deglacial ice sheet retreat in the Ross Embayment, Antarctica's largest catchment. The results demonstrate that while the atmosphere forcing influences the initial timing of grounding-line retreat, ocean forcing becomes the dominant control on grounding-line migration following the formation of the Ross Ice Shelf. However, these relationships are strongly modulated by the mantle viscosity and an enhancement factor of the shallow shelf approximation, which can enhance or diminish ice sheet sensitivity to climate forcing. The second ensemble is based on the projection experiments of the Ice Sheet Model Intercomparison Project 6 (ISMIP6) of the next century. Model parameters are systematically explored to demonstrate their influence on the ice sheet response to climate forcing. Additionally, we compare different methods of sub-ice shelf melt parameterization. The results highlight the regions and factors of greatest uncertainty, where additional constraints for numerical ice sheet models are most useful.

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Spatial distribution of englacial layer slope as a constraint on ice sheet basal conditions

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Englacial layers are a ubiquitous indicator of internal deformation within ice sheets, as well as a common finding in radio echo sounding data. In spite of this, placing direct constraints on present or past ice flow through englacial layers remains, to date, a challenging task. Our work leverages recent advances in the processing of airborne radar sounding data along with modelling work to address this challenge. Here we present an application to the case of an abrupt change in basal friction due to a transition from frozen to temperate basal conditions, which we seek to detect from radar sounding data through its signature in englacial layer geometry. We first formulate a first-principle model for ice flow across an abrupt change in basal friction, and use it to show that this setting produces quantifiable, large, anomalies in layer slope. Then we exploit a recently developed layer-optimized, unfocussed SAR processing technique that automatically estimates layer slopes with high accuracy to look for this signature in the onset region of Institute Ice Stream (West Antarctica). We find that observed slopes are incompatible with an abrupt sliding initiation. Our results instead provide evidence for the existence of a slow (in space) transition from fully frozen to temperate beds, as consistent, for instance with a spatially extended region of subtemperate sliding. We conclude by discussing implications of this finding with respect to the present and past history of Institute Ice Stream.

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Modelling the deformation regime of Thwaites Glacier using the ESTAR flow relation

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Polar ice sheets flow by a combination of viscous deformation and basal sliding. Sliding is generally assumed to dominate in fast-flowing regions, while deformation dominates in slow-flowing regions and in ice shelves. The reliability of model estimates of deformation are limited by the Glen flow relation - the standard in most large-scale ice sheet models - that does not capture the steady-state flow of anisotropic ice that prevails in polar ice sheets. We compare the simulated deformation regimes of Thwaites Glacier, West Antarctica, using the Glen flow relation and the ESTAR (empirical, scalar, tertiary, anisotropy regime) flow relation – a new description of deformation that takes into account the impact of different types of stresses on the flow regime. On grounded ice, differences emerge in the balance between basal shear and gravitational stresses via the mediating effect of the membrane stresses. In regions where bed-parallel vertical shear controls flow, the basal shear stresses in the ESTAR simulation are closer to the local driving stresses than in the unenhanced Glen flow relation, the role of the membrane stresses in the latter being correspondingly greater. In slow-flowing regions, ESTAR predicts deformation-dominated flow, but the Glen flow relation simulates physically-unrealistic sliding-dominated flow. On the Thwaites Glacier Tongue, the ESTAR simulation matches observed surface velocities better through accounting for the influence of polycrystalline anisotropy on deformation rates. Our results highlight the importance of considering anisotropic ice and its influence on simulated stress configurations, including how the local driving stresses are transmitted to the bed.

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Hiatus of mass losses from Hurd and Johnsons glaciers, Livingston Island, during the regional cooling period 2002-2016 of the Northern Antarctic Peninsula

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The Antarctic Peninsula (AP) region and its surroundings, including the South Shetland Islands, underwent a sustained and intense warming during the second half of the 20th century. However, during the first fifteen years of the current century, the northern part of the AP and the South Shetland Islands have experienced a sustained cooling, with a decrease in average temperatures in the order of 1ºC over such a short period. The regional temperatures over the last 4 years seem to indicate that the regional cooling has come to an end. In spite of the short temporal scale of this cooling period, glacier surface mass balance (SMB) is a non-delayed response of glaciers to changes in atmospheric forcing. Therefore, it is not surprise that the SMB of the small glaciers in this region (among them, Hurd and Johnsons glaciers, on Livingston Island) have experienced a change in mass-balance regime, from mass losses until fairly recently to mass gains during the second part of the cooling period. In this contribution, we analyse the mass-balance evolution of Hurd and Johnsons glaciers in the context of recent regional climate variations. The set of glaciological SMBs for the period 2002-2016 is complemented by the calculation of the geodetic mass balance over the period 2000-2013, the estimate of the mass losses by iceberg calving from Johnsons Glacier, and the estimation of the total mass balance of Hurd and Johnsons glaciers during 2002-2016, which shows that both glaciers have been close to equilibrium during this period.

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Aurora Basin, the weak underbelly of East Antarctica

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The East Antarctic Ice Sheet (EAIS) is a major component of the global sea level budget; yet, uncertainty remains in how this ice sheet will evolve in a changing climate system. To address this uncertainty, we model the most dynamic catchments of EAIS out to 2100 using the Ice Sheet System Model. We employ three basal melt rate parameterizations to resolve ice-ocean interactions and force our model with anomalies in both surface mass balance and ocean thermal forcing from both CMIP5 and CMIP6 model output. We find that this sector of EAIS gains up to 20 mm SLRe by 2100 under high emission scenarios and loses mass under low emission scenarios. All basins within the domain either gain mass or are in near mass balance through 2100 except the Aurora Subglacial Basin. The primary region of mass loss in this basin was located within 50 km upstream of Totten Glacier's grounding line, which loses up to 6 mm SLRe by 2100. Glacial discharge is modulated by buttress supplied by a 10 km ice plain, located along the southern-most end of Totten's grounding line. This ice plain is sensitive to brief changes in ocean temperature and once ungrounded, glacial discharge from Totten accelerates by up to 70% of it present day configuration. In all, we present plausible bounds on the contribution of a large sector of EAIS to global sea level rise out to the end of the century and target Totten as the most vulnerable glacier in this region.

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An ensemble of dynamically simulated deglacial models constrained by geological observations

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There is still significant uncertainty in the volume of Antarctic ice at the last glacial maximum and its evolution to present day. The change in surface loading through time is a primary input into glacial isostatic adjustment models used to correct gravimetry measurements of present-day change. We use the Parallel Ice Sheet Model (PISM) to simulate the evolution of the Antarctic Ice Sheet from the last interglacial to the present day. Using the coupled earth deformation model within PISM and an ensemble method we test four palaeo-climate scenarios, three mantle viscosities and sixteen different glaciological parameter sets which vary ice flow enhancement and basal resistance to create 196 deglacial histories. We sieve the simulation for present day volume and ice shelf area , then score the performance of each model member against palaeo and present-day observations of ice thickness, ice thinning rates and ice area. Using the climate scenario and mantle viscosity that provided the best fit to the observational constraints, we expand the glaciological parameter space, with 440 additional ensemble members. The top 10 scoring simulations have an additional volume range of 11 to 14 m sea level equivalent at the last glacial maximum compared to the present day. These top members retreated to a minimum ice sheet volume range of -0.1 to -1.55m below present-day volume in the mid-Holocene before regaining volume towards the present day.

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The Priestley Glacier Deformation experiment

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Ice deformation plays a critical role in ice sheet and glacier flow. Flow laws used to model ice deformation come primarily from laboratory experiments. A laboratory experiment to simulate steady-state deformation needs a strain of at least 20%. Experiments that achieve this strain, using an isotropic starting material, are only realistic at rates that are two or more orders of magnitude faster than natural deformation rates. Using flow laws always requires extrapolation to lower strain rates and because of this it is important to identify natural systems that provide a test of that extrapolation.
Lateral shear zones at the margins of outlet glaciers and ice streams can be considered as natural experiments, in that it is possible to measure the strain rate and temperature and to characterise the ice anisotropy through seismology and radar methods. It is also possible to collect samples that allow ice physical properties to be measured and ice chemistry to be analysed. Critically difficult is the constraint of the stress tensor in the shear zone: modelling approaches and re-deformation experiments of samples both provide possible pathways to constraining components of the stress tensor.
We have completed two field seasons on the shear margin of the Priestley Glacier, that flows into the Nansen Ice shelf, Terra Nova Bay, Antarctica. We conducted field geophysics and collected cores to 58m depth in the shear zone. We will present preliminary results from seismic, pRES and surveying data. The seismic data highlight anisotropy consistent with shear constrained from the survey data.

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Flow laws for ice sheet modelling: what do experiments tell us?

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Researchers are recognising rapid changes occurring at the ice-ocean interface: changes that potentially increase the driving force for sea-ward motion of ice sheets. Estimation of the time-scale of the ice sheet response and resultant sea-level rise depends critically on realistic ice flow laws. Ice deformation is a significant component of ice flow: data from laboratory experiments can be extrapolated to natural strain-rates.

The strain rate at a given stress results from the addition of the rates related to grain-size sensitive and grain-size insensitive mechanisms. All ice experiments, where grain-size has been varied, show grain-size dependency at low strain (< 3%). As strain increases to intermediate (~20%) values, viscosity reduces corresponding to changes in fabric and grain-size. At strains higher than 20% to 50% an approximately steady-state viscosity is achieved, corresponding to microstructural steady-state.

At low strains, the strain rate dependency on stress (stress exponent: n) depends on ice grain-size and conditions (particularly stress) and varies between ~ 2 and ~ 4. Intermediate n values (3 to 3.5) are common and have little relevance to ice deformation at high strain.

Grain-size at steady-state is inversely proportional to the flow stress, through a piezometer relationship. At steady-state, grain-size sensitive mechanisms contribute significantly to deformation, but because the stress controls the grain-size, which in turn controls the viscosity these effects are hidden. Experimental steady-state flow laws have n values of ~ 4 or higher: these are applicable to ice at high strain and match recent estimates from natural systems.

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Glacial isostatic adjustment and how the past can help constrain the future: The GLAC-GR2 joint glaciological and earth rheology Bayesian calibration for the last glacial cycle of the Greenland ice sheet

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What impact does glacial isostatic adjustment (GIA) and how it's represented have on centennial scale future projections of Greenland ice sheet change? And how should the process be confidently represented?

To answer these questions, we use the 3D Glacial Systems Model (GSM) with coupled GIA (global visco-elastic rheology with first order gravitational correction and accounting for ice load contributions from other sheets). To answer these questions confidently, we carry out a Bayesian calibration of the GSM. Calibration constraints include a large set of relative sea level observations, cosmogenic ages, and borehole temperature records from the Greenland ice core sites. Bayesian artificial neural network emulators of the GSM enable multi-million point MCMC sampling. The calibration is over two model grid resolutions (0.5X0.25 degrees lonXlat and 0.25X0.125 degrees) and model runs are over the last two glacial cycles. Calibrated model parameters address uncertainties in: ice calving and submarine melt, basal drag, deep geothermal heat flux, and earth viscosity structure.

Calibration results will be presented for regional lithospheric thickness, and (upper and lower) mantle viscosity. To answer our opening question about the impact of GIA on future projections, we present the results of running a high probability subset of model runs into the future, and examine the sensitivity to imposed earth rheology and the turning off of the physical memory of past GIA. The calibration has a much higher posterior probability for soft earth models (thin lithosphere and soft upper mantle viscosity) compared to that of previously published ensemble based inversions.

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Water chemistry and ice mechanics

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Laboratory experiments have been used to quantify the creep behaviour of pure polycrystalline ice. These are the basis of flow laws, such as the Glen flow law, which describe the strength of ice for given applied stresses and temperatures and are crucial in modelling the flow of bodies of ice, and their response in a warming climate. However, these laws typically assume ice is free of soluble (chemical) and insoluble (particulate) impurities. This is unrealistic in natural ice. Past work has shown impure ice tends to be weaker than pure ice, as intracrystalline impurities should encourage the internal deformation of grains. As ice flows, the impurities are swept to grain boundaries and inhibit grain growth by grain boundary pinning. This is seen in natural ice cores, with higher concentrations of ionic species found in finer grained bands of ice. The effects of chemistry have proven difficult to quantify, as different chemical species appear to behave differently; Recent work has shown Ca2+ ions have a hardening effect, while H2SO4 enhances creep rates in ice. In this study, ice with major ion chemical compositions comparable to coastal and central Antarctic ice has been synthesised, and deformed in a series of uniaxial compression experiments at varying strain rates (10-4, 10-5, 5x10-6 s-1) and temperatures (-10 and -30°C) at the University of Pennsylvania. Mechanical data suggest chemistry has no significant effect on the strength of ice. This suggests insoluble impurities or higher ionic concentrations than those studied contribute to the softening of natural ice.

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Ice front blocking of ocean heat transport to an Antarctic ice shelf

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Mass loss from the Antarctic Ice Sheet to the ocean has increased in recent decades, largely because the thinning of its floating ice shelves has allowed the outflow of grounded ice to accelerate. Enhanced basal melting of the ice shelves is thought to be the ultimate driver of change, motivating a recent focus on the processes that control ocean heat transport onto and across the seabed of the Antarctic continental shelf towards the ice. However, the shoreward heat flux typically far exceeds that required to match observed melt rates, suggesting other critical controls. Here we show that the depth-independent (barotropic) component of the flow towards an ice shelf is blocked by the dramatic step shape of the ice front, and that only the depth-varying (baroclinic) component, typically much smaller, can enter the sub-ice cavity. Our results arise from direct observations of the Getz Ice Shelf system and laboratory experiments on a rotating platform. A similar blocking of the barotropic component may occur in other areas with comparable ice-bathymetry configurations, which may explain why changes in the density structure of the water column have been found to be a better indicator of basal melt rate variability than the heat transported onto the continental shelf. Representing the step topography of the ice front accurately in models is thus important for simulating the ocean heat fluxes and induced melt rates.

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Influence of the bathymetry and pinning points on the Lambert-Amery glacial system ice flow

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The Lambert-Amery Glacial System (LAGS) is a major drainage basin of East Antarctica, one of the largest glacial systems on Earth, but the spatial variability of the bathymetry underneath the AIS is largely unknown. This bathymetry has a strong control on ice dynamics, through the presence of pinning points and its impact on the evolution of the grounding line. Here we use a numerical ice sheet model at 5 km resolution to assess the influence of the bathymetry, and topographic rises on ice dynamics. We first simulate a present day configuration to obtain a steady state that fits closely to present day observations. The steady state is perturbed by changing the geometry to investigate the sensitivity of the LAGS to bathymetry, on both large and small scales. Our results show that the bathymetry is not only crucial for reproducing grounding line dynamics, but also that the presence of pinning points on the floating ice shelf can have far-reaching impacts on ice flow, even when the pinning points are of small topographic scale. Pinning points are found to be critical for reconstructing the calving front position of the ice shelf. On the basis of these sensitivity tests, we show that an undersampled bathymetry can lead to undue emphasis on poorly constrained parameters to reproduce ice shelf extent. This shows the complex feedback between ice dynamics and the geometry of the bathymetry, and its importance in future modelling for the LAGS.

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