Future sea-level rise from Greenland's major outlet glaciers in a warming climate

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Over the past decade, ice loss from the Greenland Ice Sheet increased as a result of both increased surface melting and ice discharge to the ocean[1,2]. The latter is controlled by acceleration of ice flow and subsequent thinning of fast-flowing marine-terminating outlet glaciers[3]. Quantifying the future dynamic contribution of such glaciers to sea-level rise (SLR) remains a major challenge since outlet-glacier dynamics are poorly understood[4]. Here we present a model that includes a fully dynamic treatment of marine termini. We use this model to

simulate behaviour of four major marine-terminating outlet glaciers, which collectively drain ~22% of the ice sheet. Using atmospheric and oceanic forcing from a mid-range future warming scenario (A1B: 2.8 °C warming by 2100), we project a SLR of 19 to 30 mm from these glaciers by 2200. This contribution is largely dynamic in origin (80%) and is caused by several episodic retreats past overdeepenings in outlet glacier troughs. After initial increases, however, dynamic losses from these four outlets remain relatively constant and contribute to SLR individually at rates of ~ 0.01-0.06 mm yr^{-1}. These rates correspond to ice fluxes that are less than twice those of the late-1990s, well below previous upper bounds[5]. For a more extreme future-warming scenario (RCP8.5: 4.5 °C warming by 2100) the projected losses increase by more than 50%, producing 29 to 49 mm cumulative SLR by 2200.

Greenland's fast-flowing outlet glaciers respond sensitively and rapidly to atmospheric and oceanic perturbations[3,6,7]. Such responses include acceleration, thinning and rapid retreat of outlet glacier termini in the west and east[8], coincident with increases in air and regional ocean temperatures[6]. One of the largest retreats was observed on Jakobshavn Isbræ in west Greenland, followed by more than a doubling in flow speed and continued thinning[9]. Helheim and Kangerdlugssuaq Glaciers in southeast Greenland sped up and thinned substantially[10], but both subsequently slowed modestly as their termini slightly re-advanced[7]. Collectively these observations indicate a complex pattern with rapid changes that may be transient, and not necessarily indicative of long-term trends, or continued contributions to sea-level rise (SLR). Petermann Glacier in north Greenland has been flowing steadily[11],

terminating in a relatively long (~50 km) and wide (~20 km) floating ice tongue, under which high rates of submarine melt occur[12]. The break off of two substantial icebergs in 2010 (~270 km^2) and July 2012 (~120 km^2) raised concerns about this glacier's stability, but did not cause major flow acceleration[13]

Various mechanisms related to atmospheric and ocean forcing have been proposed to explain the recent behaviour of the major outlet glaciers, but large uncertainties in their relative importance remain[14,15]. A warmer ocean can melt submarine ice and thereby cause the grounding line to retreat, especially when subglacial meltwater produces more vigorous buoyancy-driven circulation[16]. Persistent sea-ice or ice mélange may exert a small resistive force that stabilizes retreat[9] by limiting the calving and subsequent rotation of icebergs[17]. Higher air temperatures increase surface meltwater production, which may (a) accumulate in surface crevasses causing hydro-fracturing and thereby increase calving[18] and reduce resistance at the lateral margins[19], and (b) reach the glacier bed to increase basal lubrication[20]. All these factors may lead to acceleration and subsequent thinning.

The complicated behaviour of narrow outlet glaciers, however, has not yet been fully captured by the ice-sheet models used to predict Greenland's contribution to future sea-level. Most such models have insufficient spatial resolution to resolve the narrow outlet glacier channels and inadequately represent processes acting at the marine boundary, such as submarine melt and calving. Moreover, the basal topography for most outlet channels remains poorly resolved.

To overcome these obstacles and to help assess the impact of Greenland ice-sheet

dynamics on SLR, we use a state-of-the-art ice-flow model, designed for single outlet glaciers (see Supplementary Information, S2). Importantly, it includes a fully dynamic treatment of the marine boundary and allows the application of oceanic and atmospheric forcing processes, such as surface melt, ocean melt, sea-ice reduction and basal lubrication. We apply the model to four major outlet glaciers in Greenland; Jakobshavn Isbrae, Helheim, Kangerdlugssuaq and Petermann glaciers.

In general, the model reasonably reproduces the observed changes such as terminus positions and velocities over the last decade (see Fig. S3 to S6), and confirms the sensitivities to different forcing mechanisms indicated by observations. We find that Helheim and Kangerdlugssuaq largely respond to a reduction in sea-ice and enhanced hydro-fracturing due to surface melt, with little response to submarine melt or basal and lateral lubrication[21]. The dynamics of Jakobshavn are more sensitive to forcing by submarine melt, due to the high submarine melt rate[22] and a more extensive ice-ocean interface when an ice tongue is present. As a result of weak lateral resistance from its thin, wide floating ice tongue, the flow of Petermann Glacier seems currently insensitive to changes at the terminus. Instead, its dynamics tend to be dominated by submarine melt concentrated near the grounding line[13].

Using a selection of tuning parameter sets that best reproduce the current observations, we run the model to determine future behaviour through the year 2200 for a mid-range future warming scenario (A1B). The atmospheric and oceanic forcing for these runs are derived from the regional climate models, MAR and ECHAM5 GCM (see Supplementary Information, S1). For each glacier we ran simulations with 50 parameter sets. Of these results, we present five parameterizations that sample the

full range of retreat (Supplementary Table S2). In order to further examine the sensitivity of our sea-level projection to the chosen climate scenarios, we perform an additional set of runs for an upper-end future warming scenario (RCP8.5)[23].

Focussing first on the mid-range climate-warming scenario (A1B), our modelling predicts that under all parameter choices, all four glaciers will continue to retreat, thin and thereby lose mass (Fig. 2), albeit at variable rates. They collectively lose 30 to 47 Gt yr^{-1} averaged over the 21st century, increasing slightly to 34 to 54 Gt yr^{-1} during the 22nd century (Table 1). This is equivalent to a cumulative SLR of 8.5-13.1 mm by 2100, and 18.6-30.0 mm by 2200 (Fig. 3e).

Partitioning the mass loss into the different components shows that most of the total mass loss (80%) from the four glaciers arises from dynamic effects that are related to retreat and increased discharge. The surface mass balance (SMB) accounts for the remaining 20% of the loss. Helheim and Kangerdlugssuaq gain in SMB due to enhanced accumulation, relative to the average 2000-to-2010 SMB, so that mass loss is entirely of dynamic origin (Fig. 3a,b). Since Jakobshavn Isbræ and Petermann Glacier have larger ablation areas, mass loss by melt is larger, especially in the 22nd century. Whereas dynamically driven discharge dominates Jakobshavn's mass loss, Petermann loses mass almost entirely by surface melt from 2000 to 2100, and dynamic losses reach a similar magnitude only at the end of the 22nd century when submarine melt is high (Fig. 3c,d), forcing substantial grounding line retreat (Fig. S7c). Note that for all our model runs, the SMB does not include the secondary contributions from enhanced ablation due to surface lowering induced by dynamic

thinning; including this effect would further enhance melt contributions to SLR, especially in the 22nd Century.

Dynamic losses are caused by outlet glacier terminus retreat and the related enhanced discharge (Fig. 2 and Fig. S12), which take place as an episodic series of rapid retreats. These step changes are closely related to channel geometry and occur, in particular, after an ice front retreats from a basal high through an overdeepening[21]. In particular, our results indicate that for different parameter choices, episodes of rapid retreat occur at different times, but at the same locations (Fig. S7). Such geometry-controlled retreat behaviour is well known from tidewater glaciers and is related to the strong increase of ice flux with water depth[24]. In these cases, retreat into deeper water and the accompanying acceleration produce pulses of mass loss of several tens of Gt yr^{-1}, but they are often short-lived[3]. Subsequent slow-downs in retreat and mass-loss mostly coincide with a shallowing in water depth as the glacier retreats (readvances) to a new (previous) bathymetric high. In late stages of retreat on Helheim and Kangerdlugssuaq, channel narrowing (Fig. S8) can temporarily slow down the terminus on an upward bed slope (Fig. 2a+b), similar to modelled paleo ice-stream behaviour[25]. Our results show that over the full range of parameters used for each glacier, and despite episodic and short-lived peaks in discharge, century-averaged ice-discharge does not exceed 1.7 times the pre-acceleration values of the late-1990s (Table 1). Indeed, the positive trend in dynamic mass loss plateaus after an initial increase in the early 21st century. The subsequent slight increase in the 22nd century is mainly due to the delayed flux response to warming contributed from Petermann Glacier (Fig. 3c).

This apparent upper limit in long-term ice-flux is crucial regarding interpretation of the recent dramatic acceleration of outlet glaciers in Greenland. It implies that even when after the modelled glaciers undergo multiple episodic retreats, ice-fluxes do not continue to increase indefinitely; indicating that current short-term acceleration trends cannot be extrapolated into the future.

For the more extreme warming scenario (RCP8.5), mass loss increases by more than 50% (Table 1), which is equivalent to a cumulative SLR of 11.3-17.5 mm by 2100, and 29-49 mm by 2200 (Fig. 3e). While all four glaciers retreat faster and farther inland compared to the A1B scenario, the general dynamic behaviour, responsible processes, and partitioning between SMB and dynamic mass loss are similar. Helheim and Kangerdlugssuaq retreat behind the narrow part of their respective valleys and into deeper, wider areas (Fig. S8 and S10), resulting in faster flow. This retreat continues until their glacier termini reach shallow water, leading to a reduction in discharge and calving rate. The Jakobshavn grounding line retreats farther back into its deep trough and forms a longer ice-shelf slowing down its retreat. Petermann, on the other hand does not show much higher mass loss and retreat, since its grounding line reaches the shallow region already in the A1B scenario simulations. Therefore the sensitivity of our projection to a warmer climate is largely controlled by the fjord geometry, width and depth, which tend to be unique to each glacier, perhaps explaining the large degree of observed variability occurring under similar climate forcings[8].

The only other comprehensive modelling assessment of dynamic mass-loss from the three major outlet glaciers Jakobshavn, Helheim and Kangerdlugssuaq suggested an

equivalent of ~1.1 mm of increased sea level by 2100[26]. That study, however, applied a single dynamic perturbation at the beginning of the 21st century that produced mass losses similar to present, but the model did not have the ability to simulate retreat. When including dynamic perturbations and feedbacks induced by glacier retreat, we produce a substantially larger estimate of 8-17 mm SLR in dynamic mass-loss from these glaciers by 2100. The four glaciers studied here drain 22% of the entire ice sheet. A first order upscaling of their dynamic mass loss to the whole of Greenland by multiplying by a factor five, results in 40-85 mm SLR by 2100 from dynamic changes. The SMB-only contribution from different climate models has previously been estimated to be between 25-98 mm of SLR by 2100[23]. Combined with our dynamic upscaling, this would produce a total SLR contribution from Greenland of 65-183 mm by the year 2100. We stress, however, that such an estimate has large uncertainties and ignores important variations in the geometry of individual outlet glacier systems.

We have produced a first estimate of sea-level contribution from four of Greenland's major marine outlet glaciers that fully accounts for effects of dynamic retreat and is driven by specific emission scenarios (A1B and RCP8.5). At 19-50 mm SLR contribution by the year 2200, our estimate is consistent with the upper-bound estimate of a recent semi-empirical model study[26], but lower than previous estimates based on extrapolation of current trends[5,26,27]. Further model development and application to other marine terminating outlet glaciers are essential to improve these projections.

Methods Summary

Our model incorporates realistic and fully dynamic marine boundary conditions (e.g. processes of calving, grounding line retreat and submarine melting), it has a robust treatment of grounding line migration[28] and calving[29], and reproduces the current observed dynamical behaviour of several narrow marine outlet glaciers well[13,14,21]. The model is applied to four major outlet glaciers in Greenland; Jakobshavn Isbræ, Helheim, Kangerdlugssuaq, and Petermann glaciers. For each of these glaciers we have detailed basal topography[30], velocity, surface elevation and terminus position records[3,8].

We simulate future behaviour of each glacier by running suites of model experiments with different relative weighting applied to forcing processes, which include variations in (a) water level in surface crevasses, (b) submarine melt rate, (c) seasonal duration and magnitude of sea-ice induced modulation of longitudinal stress at the calving front, and (d) basal and lateral resistance. We use simple parameterizations to link each of these processes to atmospheric and oceanic variables such as air temperature, deep ocean temperature, sea surface temperature, and glacier surface meltwater runoff, which are provided by regional climate models (see Supplementary Information, S1).

Before simulating future behaviour, we adjust the model to match observed behaviour. Specifically, we perform a series of 50 runs for each glacier to tune various parameters so that the model accurately reproduces the observed (2000-2010) velocity changes and retreat/advance rates for each glacier[8,11] (Fig. S3-S6). This tuning exercise also allows us to determine the sensitivity of each glacier to the different parameters and involved processes (see Supplementary Information, S5).

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

Author contributions

F.M.N., A.V. and M.L.A. were responsible for the numerical modelling. A.J.P., T.L.E. and I.J. provided the climate and observational data. F.P. and R.vdw. are the P.I. of the projects under which this research has been carried out. F.P. contributed to the model refinement. F.M.N. wrote the manuscript with substantial contribution from A.V., M.L.A. and I.J..

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Table1. Total mass loss and sea level rise by the end of the 21st and 22nd centuries for two climate scenarios.

	Initial Flux (Km³ yr⁻¹)		2000-2100				2000-2200			
			ML (Gt)	ML_rate (Gt yr⁻¹)	SLR (mm)	Flux (Km³ yr⁻¹)	ML (Gt)	ML_rate (Gt yr⁻¹)	SLR (mm)	Flux (Km³ yr⁻¹)
Helheim	**25**	A1B	476-1348	4.8-13.5	1.3-3.7	28.5-38	1403-2269	7.0-11.4	3.9-6.3	30.5-36
		RCP8.5	442-1142	4.4-11.4	1.2-3.2	31-38	1667-2900	8.4-14.6	4.6-8.0	34-38
Kanger	**28**	A1B	351-470	3.5-4.7	1.0-1.3	36-36.5	575-1178	2.9-5.9	1.6-3.3	34.5-35.5
		RCP8.5	572-832	5.7-8.3	1.6-2.3	34-35.5	1321-4028	6.6-20.2	3.6-11.1	33-46.5
Petermann	**12**	A1B	368-639	3.7-6.4	1.0-1.8	11.5-14	1022-2927	5.1-14.7	2.8-8.1	11-22
		RCP8.5	615-968	6.1-9.7	1.7-2.7	11.5-15.5	2394-3551	12-17.8	6.6-9.8	16-23
Jakobshavn	**22**	A1B	1870-2281	18.7-22.8	5.2-6.3	49-52.5	3750-4476	18.8-22.5	10.4-12.4	48-52
		RCP8.5	2471-3407	24.7-34.1	6.8-9.4	48.5-58.5	5131-7227	25.8-36.3	14.2-20	49.5-61
Total	**87**	A1B	3065-4739	30.6-47.4	8.5-13.1	125-141	6750-1085	33.9-54.5	18.6-30	124-145.5
		RCP8.5	4100-6349	41-63.5	11.3- 17.5	125-147.5	1051-1770	52.8-89	29-49	132-168.5

Flux$_{int}$: Initial pre-acceleration ice discharge. ML: estimated range of mass loss in gigatonnes (10^{12} kg). ML_rate: average mass loss rate per year. Flux$_{av}$: averaged ice discharge from grounding line**.**

Figure1 | **Major Greenland outlet glaciers examined in this study**. Catchments for glaciers in this study are highlighted on the velocity map of Greenland[8]. Jakobshavn Isbræ in the west, drains ~7.5% of the Greenland Ice Sheet area. Helheim and Kangerdlugssuaq Glacier in the southeast, drain about 3.9% and 4.2%, respectively. Petermann Glacier, in the north, drains ~ 6% of the ice sheet area.

Figure2 | **Modelled evolution of surface elevation and velocity.** Along-flow profiles of surface elevation (red lines) and velocity (green lines) of Helheim (**a**), Kangerdlugssuaq (**b**), Petermann (**c**) and Jakobshavn Isbræ (**d**) for one of the high mass loss sets. The profiles are shown at one-year intervals during 2000-2010 and at 10-year intervals from 2010 to the end of the 22nd century. The profiles are colour coded and range from black (year 2000) to red and green respectively (year 2200).

Figure 3 | **Projected sea-level rise from the four major outlet glaciers.** Modelled cumulative total mass change (black), cumulative surface mass balance anomalies (red), and dynamic mass change anomalies (blue dashed line) at Helheim **(a),** Kangerdlugssuaq **(b),** Petermann **(c)**, and Jakobshavn **(d)** glaciers for selected forcing parameter sets. **e,** Predicted cumulative minimum and maximum total sea-level rise contributions from four major outlet glaciers forced by A1B (black) and RCP8.5 (yellow) future warming scenarios. It indicates the contributions from surface mass balance for A1B (Red) and RCP8.5 (orange) and from dynamic retreat and thinning for A1B (dashed blue) and RCP8.5 (dashed-dotted green) scenarios. Shaded areas cover the range of projected sea level rise for all selected forcing parameter sets.