ADVANCING EARTH AND SPACE SCIENCE

Earth's Future

RESEARCH ARTICLE
10.1029/2022EF002772

Key Points:
- Greenland surface melt is a dominant uncertainty in 21st century contributions from the ice sheets
- Ice shelf buttressing is the dominant uncertainty in Antarctic ice dynamics in the 21st century
- East Antarctic ice dynamics only play a significant role in the 22nd century for a high temperature scenario

Supporting Information:
Supporting Information may be found in the online version of this article.

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Citation:
Bamber, J. L., Oppenheimer, M., Kopp, R. E., Aspinall, W. P., & Cooke, R. M. (2022). Ice sheet and climate processes driving the uncertainty in projections of future sea level rise: Findings from a structured expert judgement approach. *Earth's Future*, *10*, e2022EF002772. https://doi.org/10.1029/2022EF002772

Received 10 MAR 2022
Accepted 16 SEP 2022

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Ice Sheet and Climate Processes Driving the Uncertainty in Projections of Future Sea Level Rise: Findings From a Structured Expert Judgement Approach

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Abstract The ice sheets covering Antarctica and Greenland present the greatest uncertainty in, and largest potential contribution to, future sea level rise. The uncertainty arises from a paucity of suitable observations covering the full range of ice sheet behaviors, incomplete understanding of the influences of diverse processes, and limitations in defining key boundary conditions for the numerical models. To investigate the impact of these uncertainties on ice sheet projections we undertook a structured expert judgement study. Here, we interrogate the findings of that study to identify the dominant drivers of uncertainty in projections and their relative importance as a function of ice sheet and time. We find that for the 21st century, Greenland surface melting, in particular the role of surface albedo effects, and West Antarctic ice dynamics, specifically the role of ice shelf buttressing, dominate the uncertainty. The importance of these effects holds under both a high-end 5°C global warming scenario and another that limits global warming to 2°C. During the 22nd century the dominant drivers of uncertainty shift. Under the 5°C scenario, East Antarctic ice dynamics dominate the uncertainty in projections, driven by the possible role of ice flow instabilities. These dynamic effects only become dominant, however, for a temperature scenario above the Paris Agreement 2°C target and beyond 2100. Our findings identify key processes and factors that need to be addressed in future modeling and observational studies in order to reduce uncertainties in ice sheet projections.

Plain Language Summary The ice sheets covering Antarctica and Greenland are the largest source of future sea level rise but projections of their behavior are extremely uncertain. This is partly because of processes that are poorly understood in terms of their importance and potential contribution in the future. To investigate these issues and the relative importance of different processes in driving uncertainties in projections we solicited expert judgements from a group of scientists actively working on the topic. This exercise revealed that the dominant factors controlling the uncertainties depends on how far into the future one looks and the warming scenario assumed. For the 21st century, surface melting on the Greenland ice sheet is a dominant source of uncertainty alongside possible ice flow instabilities in West Antarctica. The East Antarctic Ice Sheet, the largest ice mass by an order of magnitude, does not play a significant role until the 22nd century and only for relatively high levels of future warming, based on the expert judgements. These findings quantify the relative role of different processes in driving uncertainty and indicate key areas for future focus to improve ice sheet projections and reduce the uncertainty in future sea level rise estimates.

1. Introduction

Substantial sea level rise (SLR) is considered to be one of the most serious consequences of climate warming (Bamber et al., 2019). The largest contributors and uncertainty in projecting future SLR are the ice sheets that cover Antarctica and Greenland (Bamber et al., 2019; Fox-Kemper et al., 2021). These ice sheets respond over timescales ranging from diurnal, for example, tides (Gudmundsson, 2006) to multi-millennial, for example, changes in climate at the end of the last glacial, 12,000 years BP (Huybrechts, 2002).

Observations of the ice sheets at high temporal resolution, however, are limited to just the last few decades and may not be adequate to assess or constrain projections of deterministic numerical models (Fox-Kemper et al., 2021). Conditions at the base of an ice sheet are important for determining its sensitivity to external forcing (Ritz et al., 2015) but are unlikely ever to be definitively observable, due to inaccessibility. During the 1990s, satellite observations indicated relatively rapid and large amplitude changes in ice dynamics in the Amundsen Sea Embayment of West Antarctica and in Greenland that were not reproduced by the numerical models available at that time (Vaughan & Arthern, 2007). This required a re-evaluation of the sensitivity of the numerical models to external forcing. More recently, a process called the Marine Ice Cliff Instability (MICI) has been hypothesized to have contributed to SLR high-stands in the last interglacial and further back in time (DeConto & Pollard, 2016). Including MICI in numerical models can result in a dramatic increase in ice sheet sensitivity to external forcing (DeConto & Pollard, 2016; DeConto et al., 2021) but its importance to past ice sheet behavior and its relevance to the contemporary Antarctic Ice Sheet is unclear, and disputed (Bassis et al., 2021; Edwards et al., 2019).

These two examples of our limited understanding of ice sheet processes illustrate the problem of determining epistemic uncertainties associated with major natural systems that are under-sampled or sparsely observed (Attenberg et al., 2015). Other factors, such as poorly constrained model input data and boundary conditions, present significant challenges for deterministic modeling approaches. The limitations of ice sheet model projections are highlighted in a recent study comparing contemporary observations with an ensemble of state-of-the-art models and the spread in their hindcasts and projections (Aschwanden et al., 2021). Few models are able to reproduce the observations, and for the AIS, estimates are uncertain even on the sign of the contribution both in the recent past and near future.

Additionally, all three present-day ice sheets possess hypothesized instabilities (including the MICI), the details of which are outlined in Note S1 in Supporting Information S1. Note that we partition the Antarctic Ice Sheet into the West (WAIS) and East (EAIS) Antarctic Ice Sheets due to the different factors that influence their behavior (see Note S1 in Supporting Information S1 and other studies, e.g., Seroussi et al., 2020). Paleo-proxy records suggest that instabilities drove abrupt ice loss in the past (Liu et al., 2016; Wise et al., 2017). In all three cases, however, the instability thresholds are likely to be state- and rate-dependent and difficult, therefore, to constrain reliably. These factors create a further profound challenge for future SLR projections based on deterministic numerical modeling.

Nonetheless, projections and their uncertainties are required for quantifying SLR estimates for decision support (as are so-called "worst-case" and high-end scenarios (R. E. Kopp et al., 2019; Stammer et al., 2019)). Several approaches have been employed to tackle the gap between policy needs and limitations in deterministic model projections. These include, for example, a plausibility experiment addressing the question "what is the most extreme physically-plausible dynamic response of the ice sheets" (Pfeffer et al., 2008). That study concluded that a SLR in excess of 2 m by 2100CE was "implausible" but without assigning a probability to their upper limit or any other estimates. Interestingly, their estimate for the upper bound for the SLR contribution from the AIS, 62 cm, is roughly half that of 105 cm from the first numerical model simulation that included the MICI process (DeConto & Pollard, 2016). This latter value has, however, been revised in the most recent simulations down to 60 cm for the 95th percentile (DeConto et al., 2021), which is similar to the plausibility limit estimated by Pfeffer et al. (2008) for the AIS. This suggests that the plausibility value in Pfeffer et al., 2008 may be an underestimate for a low probability (>99th percentile) response. Probabilistic approaches, conditioned on expert community assessment, expert judgement and process modeling have also been developed (Robert E. Kopp et al., 2014).

Structured expert judgement (SEJ) using calibrated expert responses provides a formal, rigorous, reproducible and well-established framework for tackling this type of problem (Aspinall, 2010; Bamber & Aspinall, 2013; Oppenheimer et al., 2016). SEJ can capture epistemic uncertainties that are challenging for deterministic modeling approaches to identify (Attenberg et al., 2015). There is, for example, evidence available to the expert about past ice sheet behavior that is difficult to incorporate into a deterministic numerical model. An example of this is paleo sea level records that indicate a rapid SLR of 2–4 cm/yr for multiple centuries at around 14.6–14.3 Kyr BP, known as Meltwater Pulse 1A (Liu et al., 2016). This entailed an 8–15 m SLR which must have been associated with one or more ice sheet instabilities, but the precise source, dynamics and forcing mechanism(s) are unclear (Liu et al., 2016). The longer-term sea level record, covering glacial-interglacial cycles clearly shows a pattern of slow ice sheet growth and rapid decay, providing further evidence of instabilities in ice sheet behavior during or entering a warming inter-glacial period, such as the one we are in today. Further evidence from the paleo-sea level record comes from the last interglacial period when the sea level high stand was about 5–10 m above present-day (Gulev et al., 2021) and when global mean temperatures peaked at about 0.9°C and averaged 0.2°C above the

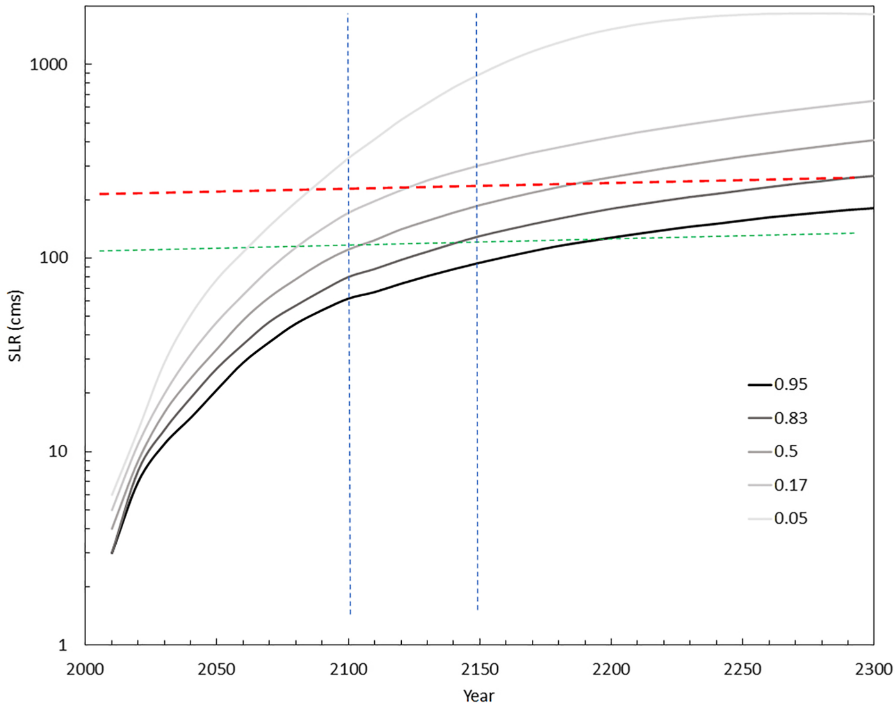

Figure 1. Projected substantial sea level rise (SLR) as a function of time for different probabilities between the 5th and 95th percentile for the High temperature scenario (5°C by 2100). The dashed blue lines indicate the probability of equaling or exceeding a given SLR at a specific date in the future: in this case 1 m by 2100 and 2150 (green) or 2 m (red) by those dates.

pre-industrial value for global sea surface temperatures (Turney et al., 2020). These data provide the expert with evidence that ice sheets can generate high rates of SLR (circa 4 m/century) over centennial timescales and that they can be sensitive to relatively small temperature perturbations.

Previously, we reported the key findings from an SEJ elicitation undertaken in 2018 via two workshops, one held in the USA and the other in the UK, involving 22 experts in total (hereafter B19) (Bamber et al., 2019). The primary findings presented in B19 were the respective contributions to SLR from each ice sheet, for each time period and temperature change scenario considered. For the high temperature scenario (5°C by 2100; roughly equivalent to the high end emissions scenario RCP8.5), the 95th percentile ice sheet contribution to SLR was 178 cm at 2100CE. When combined with the contribution from glaciers and thermal expansion of the oceans this implied about a 10% chance of exceeding a SLR of 2 m by 2100CE (Bamber et al., 2019) (Figure 1), comparable with the plausibility experiment discussed earlier (Pfeffer et al., 2008) and the high-end scenario for SLR in the Sixth Assessment Report of the IPCC (Fox-Kemper et al., 2021). We present, in Figure 1, these findings expressed in terms of SLR as a function of time for different probabilities from 5 to 95%. This is useful for practitioners who will have different level of risk tolerance depending on the asset and hazard or who may be concerned about the probability of exceeding a specific value of SLR by a certain date (M. Oppenheimer et al., 2019). For example, the blue dashed lines indicate the probability of exceeding 1 m of SLR by 2100 (50%) or 2150 (~90%) for the high temperature scenario. For 2 m of SLR it is 10% and 30%, respectively. The full table of values for 1%–99.9% are given in the Table S1 in Supporting Information S1.

What was not considered in B19 was which ice sheet processes are responsible for the projected upper SLR values, and which of these processes dominate the uncertainty in future projections as a function of temperature scenario and ice sheet. This requires further and deeper interrogation of the expert judgements at the process level. This is what is presented here. To our knowledge, this is the first quantitative analysis of the relative importance of the processes that influence the uncertainty in ice sheet projections using SEJ as opposed to deterministic modeling, which has various limitations as mentioned above.

2. Materials and Methods

The overall approach and methodology used in the SEJ was presented in detail in B19 and we, therefore, summarize only the salient points here. To determine the integrated SLR contribution for each ice-sheet the participating experts quantified their uncertainties for three key physical processes relevant to ice-sheet mass balance: accumulation (A), surface runoff (R) and discharge (D). They did this for each of the Greenland, West Antarctic, and East Antarctic ice sheets (GrIS, WAIS, and EAIS, respectively) and for two schematic temperature change scenarios. The first temperature trajectory (denoted L for low) stabilizes in 2100CE at +2°C above pre-industrial global mean surface air temperature (defined as the average for 1850–1900), and the second (denoted H for High) stabilizes in 2100 at +5°C (Figure S1 in Supporting Information S1). Projections of contributions to SLR from the three ice sheets were elicited for four dates: 2050, 2100, 2200, and 2300 CE.

The experts were weighted according to an impartial and rigorous approach that assesses each expert's informativeness and statistical accuracy via a set of seed or calibration questions from their field based on a well established methodology (Bamber et al., 2019; Cooke, 1991). The calibration questions were used to provide an impartial, repeatable measure of how well an expert is able to characterize their (un)certainty in the system under study (Cooke, 1991). The approach is similar to, for example, weighting a multi-member numerical model ensemble based on the ability to reproduce a desired property of the system being modeled. For each process, temperature and epoch, the experts provided a 5th, 50th, and 95th percentile sea level equivalent anomaly with respect to the 2000–2010 mean (i.e., a change from the historical value). Using the expert weights and Monte Carlo sampling, probability distributions were obtained for each process and ice sheet (Bamber et al., 2019). How these were then combined to produce a total SLR contribution is discussed in Note S2 in Supporting Information S1 but is not important here as we focus, in this paper, on the individual process probability distributions and, in particular, how their relative importance changes with time and temperature scenario.

In addition, we also investigate the role of various drivers of changes in D, A and R. To achieve this, we draw on additional qualitative information acquired during the 2018 SEJ (Note S3 in Supporting Information S1) supported, where available, with relevant literature related to developments in ice sheet process understanding and observations of past and recent ice sheet behavior. Specifically, we examine probability distributions for the SLR contributions of each ice sheet individually, considering the physical mechanisms that drive the response of those ice sheets via atmospheric, oceanic, or internal and surface forcings. In so doing, we quantify the rank-order of factors or processes that are influencing projection uncertainties in relation to each ice sheet independently, and where future research effort could reap the greatest benefits by addressing those sources of uncertainty. Some of the processes display non-Gaussian distributions with long upper tails, which can only be explored and characterized using a probabilistic approach (e.g., Figure 2).

2.1. Ice-Sheet Processes and Drivers

Accumulation, A, and surface runoff, R, relate to what is termed the surface mass balance (SMB) of the ice sheet and are modulated, primarily, by atmospheric processes such as moisture content (affecting snowfall), air mass circulation, cloud cover, surface albedo, air temperature and wind speed (Paterson, 1994). Discharge, D, relates to the speed of the ice at the point that it reaches the ocean, known as the grounding line, where the ice first comes into contact with the ocean (Van der Veen, 1999). It is influenced by forces acting on the ice column including the buttressing effect of floating ice downstream of the grounding line (Van der Veen, 1999). Variations in ocean heat content, due to either changes in water temperature or circulation, can affect the strength of the buttressing force. Thus, discharge is primarily forced by the physical state of the ocean and SMB primarily by atmospheric conditions. In general, changes in discharge are related to ice dynamics, which have a longer time-constant compared to SMB and tend to vary smoothly in time. Surface melting can, however, affect calving rates and ice shelf collapse by hydrofracture and sub-shelf melting so that each process is not necessarily entirely independent (Lai et al., 2020). These correlations may be important when assessing the integrated response of the ice sheet to external forcing (Bamber et al., 2019) but here we consider each process independently as a function of the forcing.

Some processes that affect A, R, and D are comparatively well understood, such as the relationship between ice thickness and strain rate in the ice, while others are either poorly understood or poorly constrained. In particular, all three ice sheets may possess thresholds in their behavior beyond which an irreversible response in part of the ice sheet is initiated. However, the precise location of the threshold in parameter space is highly uncertain (Bassis

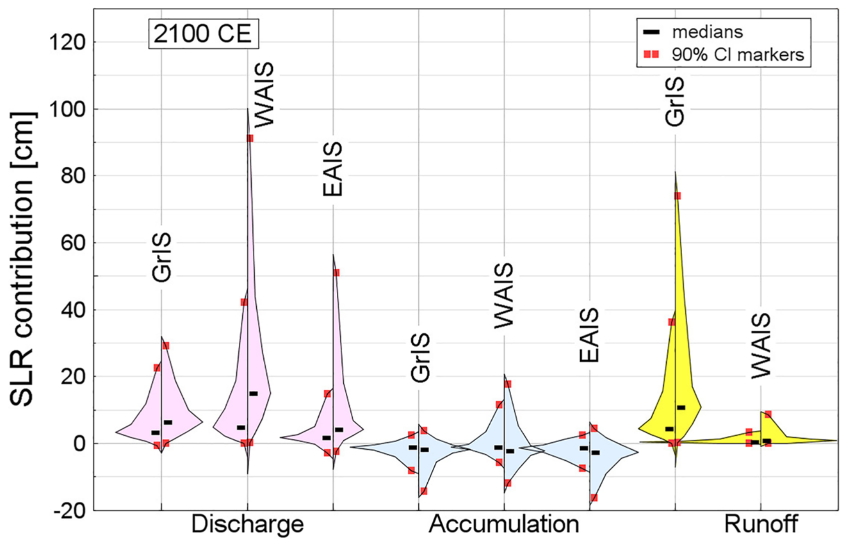

Figure 2. Indicative probability distribution plots for substantial sea level rise (SLR) contributions by 2100CE from the three ice sheets and for three physical processes, identified on the *x*-axis (runoff from East Antarctic Ice Sheet (EAIS) is omitted as this is presumed zero under either temperature rise scenario). Results are derived from expert elicitation for the 2100L (low +2°C) global temperature trajectory (left hand curves) and for the 2100H (high +5°C) global temperature trajectory (right hand curves); probability density curves are approximate and extend from values corresponding to a 99% chance of SLR being exceeded to a 1% chance of SLR being exceeded. The 5th, 95th and 50th percentile values of the distributions are shown by red and black rectangles, respectively.

et al., 2021; DeConto & Pollard, 2016; Edwards et al., 2019; Gregory et al., 2004, 2020; Joughin et al., 2014; Seroussi et al., 2020). The relative importance of various factors influencing A, R, and D were elicited as part of the SEJ workshops (Note S3 in Supporting Information S1 and (Bamber et al., 2019)).

3. Results and Discussion

In the following discussion we consider the 5th, 50th, and 95th percentile SLR contribution values for different processes and the numbers are presented in that order in centimeters. Figures 2 and 3 are distribution plots that approximate the probability density functions, plotted along the *y* axis for 2100 and 2200, respectively. Similar

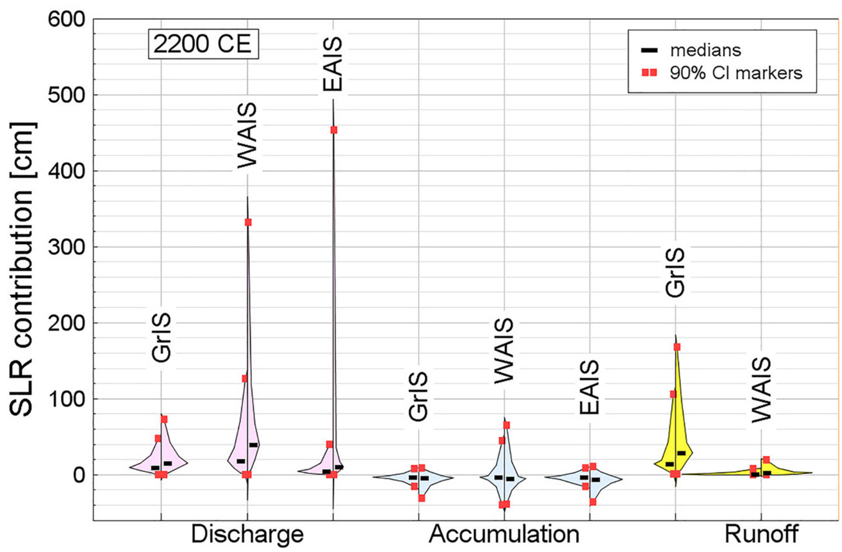

Figure 3. As for Figure 2 but for 2200.

Table 1
5th, 50th, and 95th Percentile Elicited Estimates for SLR Contributions by Each Ice Sheet and Each Process (G Denotes GrIS, W WAIS, E EAIS; A Denotes Accumulation, R Runoff, D Discharge)

2100L	GrIS A	WAIS A	EAIS A	GrIS R	WAIS R	GrIS D	WAIS D	EAIS D	Total
5%ile	2.4	11.6	2.3	0.1	0.0	-0.6	0.0	-2.8	-5.0
50%ile	-1.2	-1.1	-1.4	4.4	0.3	3.2	4.8	1.7	18.0
95%ile	-8.1	-5.8	-7.6	36.1	3.3	22.5	42.0	14.7	73.0
2100H	3.8	17.7	4.4	0.2	0.0	0.0	0.1	-2.5	-1.0
	-1.7	-2.2	-2.6	10.9	0.8	6.4	15.0	4.2	43.0
	-14.3	-11.9	-16.4	73.8	8.5	29.1	91.1	51.0	170.0
2200L	7.5	39.7	8.1	0.3	-0.7	-2.3	0.0	0.0	-10.0
	-3.3	3.7	-3.3	14.6	0.6	9.1	18.4	4.4	57.0
	-16.2	-44.3	-15.8	105.8	7.5	46.1	126.9	40.0	216.0
2200H	8.7	64.9	10.6	0.9	-1.5	0.0	0.0	0.0	-10.0
	-4.4	-5.1	-5.8	29.1	2.3	15.3	39.2	10.5	115.0
	-31.3	-39.1	-36.0	165.8	18.1	72.0	322.7	436.0	735.0
2300L	11.9	75.3	14.0	0.0	-1.6	-2.8	0.0	-3.7	-23.0
	-5.2	-6.4	-6.6	22.9	1.9	16.3	29.6	7.3	97.0
	-25.1	-74.9	-30.4	174.2	28.4	68.9	246.0	108.2	403.0
2300H	15.0	110.5	18.2	0.0	0.0	-2.2	0.0	-1.2	-9.0
	-7.2	-9.4	-11.3	52.4	4.7	28.7	67.9	21.1	202.0
	-52.2	-69.2	-71.5	242.7	57.9	143.4	350.7	577.8	965.0

Note. GrIS, Greenland ice sheet; EAIS, East Antarctic Ice Sheet; SLR, sea level rise; WAIS, West Antarctic Ice Sheet. The orange shaded cells denote values that are greater than 25% of the total combined SLR contribution from the ice sheets in the final column. The totals are not the sum of the components because of dependencies between processes and ice sheets (see Note S3 in Supporting Information S1). NB all numbers in the table exclude the 2000–2010 baseline of 0.7 mm/yr because this was added post-hoc to the values elicited from the experts (Bamber et al., 2019).

plots for 2050 and 2300, alongside the tabulated percentile values are provided in Figures S2 and S3 in Supporting Information S1.

For 2100L, the dominant processes in terms of SLR contribution and uncertainty are GrIS runoff, [0.06, 4.4, 36] cm and WAIS dynamics, [0, 4.8, 42] cm, respectively, although EAIS dynamics becomes a significant factor at the 95th percentile (Table 1). The total SLR from the ice sheets for 2100L is [−5, 18, 73] cm. Thus, GrIS runoff and WAIS dynamics account for approximately half of the median total contribution from the ice sheets. The large 5th–95th percentile credible range for GrIS runoff is surprising given that SMB is considered to be a relatively well understood and reliably modeled component of ice sheet mass balance (Hofer et al., 2019). It is noteworthy, however, that both the modeled runoff magnitude and trend from a recent SMB intercomparison exercise varied by a factor 3 between models despite using identical climate forcing fields for 1980–2012 (Hofer et al., 2019). Thus, while the process may be well understood, there remain tuneable parameters in the models, such as albedo, that have a controlling influence on the sensitivity of runoff to changes in the climate forcing (Hofer et al., 2019). In addition, the record mass loss in 2019 over the GrIS, more than double the mean for 2003–2018, was driven primarily by exceptionally high runoff rather than any other process (Sasgen et al., 2020). As a consequence, we examine in further detail the potential factors that might be causing the large uncertainty in runoff for the GrIS.

For each of the three primary processes elicited (D, A, R), there are several potential atmospheric, oceanic or ice-sheet variables that could act as drivers of change. To identify which factors were considered important,

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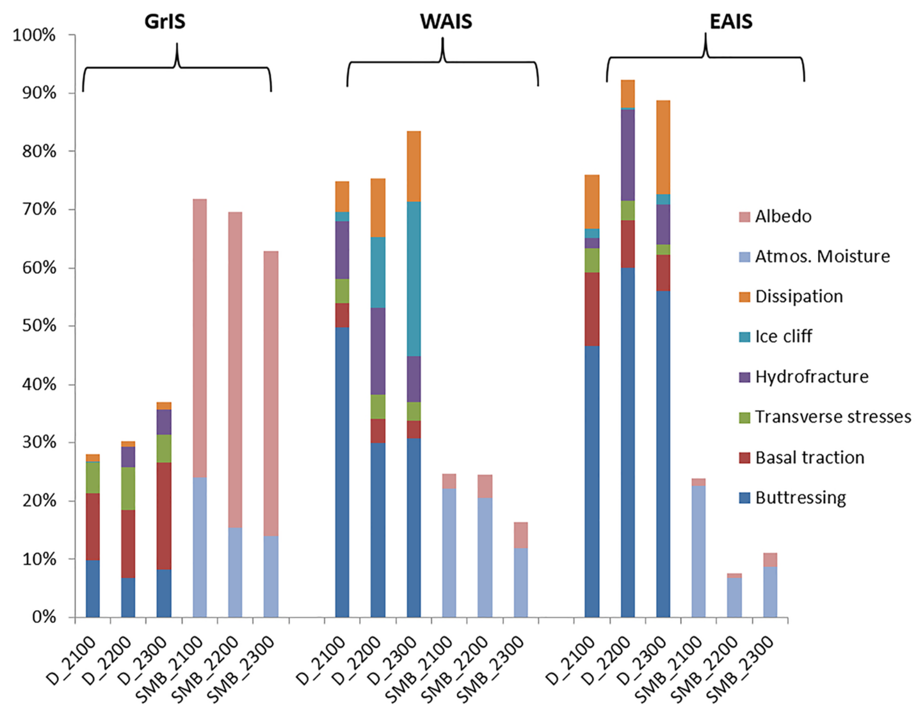

Figure 4. Expert judgements on the relative role to the overall uncertainty for six drivers of changes in ice dynamics: buttressing by ice shelves, basal traction, transverse stresses, hydrofracturing, ice cliff instability, and dissipation after iceberg formation at exit gates; and two drivers for changes in surface mass balance (SMB): atmospheric moisture and circulation, and albedo. Note that buttressing is directly related to the initiation and evolution of MISI and also hydrofracture and ice cliff instability. Descriptive definitions for these factors are provided in the Note S3 in Supporting Information S1. SMB processes were considered separately for grounded and floating ice and shown here are the results for the former only. This figure is for the three ice sheets at 2100, 2200, and 2300 for the High temperature scenario only. SMB and D are scaled according to their relative contribution to the integrated ice sheet substantial sea level rise. The equivalent plot for the Low temperature scenario including floating ice is shown in Figure S4 in Supporting Information S1 and for the High scenario including ice shelves in Figure S5 in Supporting Information S1.

during the SEJ workshops we asked the experts to rank climate drivers in relation to the primary ice sheet processes. Here, qualitative information about the rank order of the drivers was obtained rather than the quantiles elicited for the three processes: D, A, and R (see Note S3 and Figures S4–S6 in Supporting Information S1). Not all experts answered all sections of the rationale questionnaire and our findings are based, therefore, on the qualitative responses that were obtained. As such, these should be regarded as indicative of the relative importance of different drivers.

As part of the elicitation, factors influencing A and R were grouped into SMB processes that could be modified by changes in atmospheric moisture or circulation, albedo changes and changes in summer sea ice extent; the influences of these factors were elicited separately for floating and for grounded ice (Figure 4 and Figure S4 in Supporting Information S1).

From these expert judgements, changes in albedo are determined to be the dominant control on the SMB response of the GrIS (Figure 4). This is not surprising as surface albedo is the single most important variable in modulating the surface energy balance of the GrIS and, as a consequence, melt rates (Fitzgerald et al., 2012). Nonetheless, that GrIS runoff has a comparable uncertainty range to WAIS discharge for both temperature scenarios for 2100 was an unexpected result and we examine, therefore, both the modeling and observational evidence that supports this finding.

Albedo is sensitive to several variables that are poorly constrained in climate models, including changes in cloud cover characteristics and extent (Hofer et al., 2019), impurity and algal content of the surface (Tedstone et al., 2020), and the seasonality of changes in precipitation and air temperature. For example, most General Circulation Models (GCMs) project the largest temperature increase in the Arctic to occur in winter (Koenigk et al., 2013) as reflected by the observational record (Hanna et al., 2021), resulting in increased winter precipitation. This can act to reduce runoff by depositing a high-albedo insulating snow layer in winter (Day et al., 2013). Conversely, increased summertime precipitation can have the opposite effect as it results in greater rainfall, which acts to accelerate melting and reduce the surface albedo (Fausto et al., 2016). Indeed, non-radiative energy fluxes such as rain are generally poorly captured in GCMs, and hence also regional climate models, but will become increasingly important as temperatures rise above the freezing point of water (Fausto et al., 2016). Hence, seasonal atmospheric changes play a critical role in modulating R, but are, in general, not well constrained by GCMs.

Changes in future cloud cover are inconsistent between climate models and these discrepancies can have a greater impact on R than the difference in radiative forcing between RCP2.6 and RCP8.5, for example, (Hofer et al., 2019). Since 1985, despite a step-change increase in D in about 2005, SMB has dominated the mass loss trends on the GrIS (King et al., 2020), and the ice sheet currently dominates the land ice contribution to SLR (Sasgen et al., 2020). These trends are generally not well captured by ice sheet models forced by GCM output (Goelzer et al., 2020). For example, the ensemble mean SLR for the GrIS under RCP8.5 from the latest ice sheet model intercomparison exercise (ISMIP6) is 9.0 cm with a 5th–95th range of ±5.0 cm by 2100 (Goelzer et al., 2020). RCP8.5 results in a warming over Greenland by 2100 of about 9–10°C above pre-industrial, yet the mean present-day rate of mass loss from the ice sheet for 2010–2019 is already equivalent to 8 cm/century (Sasgen et al., 2020), suggesting that the models used have a weak sensitivity to climate forcing relative to recent observations. Further, a recent study using a glacier-resolving ice sheet model combined with a comprehensive uncertainty analysis obtained a 16th–84th (equivalent to one sigma) percentile range of 14–33 cm for RCP8.5 by 2100 for the GrIS (Aschwanden et al., 2019). The authors of that study concluded that the uncertainty was driven by the climate forcing and surface processes, in agreement with our interpretation of the expert judgements presented here (c.f. Figures 2 and 4). We conclude that these are the primary factors responsible for the elicited uncertainties in GrIS runoff, which are comparable with WAIS discharge for both 2100L and 2100H scenarios.

In Table 1, the dominant processes driving the median and 95th percentile SLR are highlighted in orange. For both temperature scenarios and all epochs GrIS runoff and WAIS dynamics are the two processes dominating the uncertainty. EAIS dynamics becomes important mainly for the High temperature scenario except for 2300L where the 95th percentile value is about 26% of the total SLR. This suggests that improvements in modeling these two processes would reduce SLR projection uncertainty. This is, however, not limited to improvements in ice sheet modeling but also in reducing uncertainties in the driving climate forcing that influences GrIS runoff on the one hand and WAIS dynamics on the other. The former relates to atmospheric processes while the latter is primarily oceanic.

Some drivers shown in Figure 4 are not independent of others (see also Note S3 in Supporting Information S1). Ice shelf buttressing, for example, will be affected by hydrofracture, ice cliff instability and dissipation of icebergs, which are also the three processes that control the MICI. The results are shown for each ice sheet and for three time periods, 2100, 2200, and 2300. For the GrIS, basal traction is considered the dominant process in influencing discharge for all time periods. This is not unexpected, as floating tongues and ice shelves are limited in extent in Greenland. The second most important process is buttressing but this decreases with time as the ice sheet shrinks in size, its marine margins recede and floating tongues disappear. For 2100L and H, GrIS dynamics provides the third largest uncertainty, after GrIS runoff and WAIS discharge (Figure 2). By 2200, however, it has been overtaken by WAIS accumulation (2200L and 2200H) and EAIS dynamics for 2200H (Figure 4), most likely because of a retreating marine margin over time.

For 2100H, WAIS discharge [0.1, 15, 91] cm and GrIS runoff [0.2, 11, 74] cm again account for close to half the median total ice sheet contribution of 51 cm [−1, 43, 170] and dominate the uncertainty with 5th–95th percentile credible ranges of 91 and 74 cm, respectively. However, for this high-end warming scenario, which after accounting for polar amplification, implies a temperature increase over the Antarctic Ice Sheet of about +7°C to +10°C, EAIS dynamics is responsible for the third largest uncertainty with a 5th–95th percentile range of 54 cm (Table 1). For 2100H relative to 2100L, the 5th–95th percentile credible range has roughly doubled for WAIS discharge and GrIS runoff, but approximately trebled for EAIS dynamics. This indicates that the experts consider that instabilities in the latter could be triggered by 2100 under +5°C warming, while for both temperature scenarios the experts infer it is plausible that the marine ice sheet instability (MISI) would be invoked for the WAIS with the amplitude of the response sensitive to temperature. This is in contrast with the latest ice sheet model intercomparison project for Antarctica, where the sign and sensitivity of the WAIS response to warming scenario, for example, varies between models (Seroussi et al., 2020).

For the WAIS, buttressing is the dominant ice sheet process for all the time periods considered (Figure 4), reflecting the view that this is the primary control on the MISI and grounding line migration rates (Schoof, 2007). However, its relative importance declines from 2100 to 2300, with ice cliff instability increasing in significance, presumably as ice shelves recede or collapse, leaving exposed ice cliffs—close to the grounding line—that may be susceptible to ice cliff failure (Seroussi et al., 2020). The MISI is driven by changes in the amount of buttressing afforded by floating ice shelves that "protect" the inland, grounded ice. This, in turn, is sensitive to sub-shelf melting which is affected by changes in ocean temperature and/or circulation. The experts considered two drivers for changes in ocean circulation in the elicitation process. These were alterations to: (a) circumpolar deep water intrusion onto the continental shelf (CDW) and (b) the meridional overturning circulation (AMOC). Of these, experts considered the first to be by far the most important for influencing Antarctic sub-shelf melt rates over all the time periods and both temperature scenarios. For the GrIS, changes in the AMOC were considered most important as the former two are primarily related to Southern Ocean circulation (Figure S6 in Supporting Information S1).

Gravitational, rotational and solid Earth deformation (collectively GRD) effects have been hypothesized to influence the stability of grounding lines on retrograde slopes (Whitehouse et al., 2019) and were considered as part of the rationale analysis but have been demonstrated to be of second order importance (Larour et al., 2019) (Note S4 and Figure S7 in Supporting Information S1). Over millennial timescales they may, however, be of first-order significance (Pan et al., 2021).

For the EAIS, the experts concluded that buttressing is the dominant and primary factor for all time periods (Figure 4). It is interesting to note that for 2200H the 95th percentile estimate for EAIS discharge is larger than any other ice sheet process and hydro-fracture is considered to be increasingly important (Table S2 in Supporting Information S1) and also, but to a lesser extent, for 2100H (Figure 4). This is consistent with recent evidence that suggests that as much as 60% of Antarctic ice shelf area is vulnerable to hydrofracture from surface meltwater, including almost all of the Filchner Ronne, Ross and Amery ice shelves that buttress large drainage basins in East Antarctica (Lai et al., 2020).

Conversely, because runoff is limited over both the WAIS and EAIS at present, it is considered to play a limited role in direct mass loss (as opposed to an indirect role in accelerating ice shelf collapse) under the high temperature scenario up to 2100 (Figure 2 and Table 1) and even up to 2200 (Figure 2, Table 1). Hence, albedo changes are considered to be of limited importance over grounded ice for both Antarctic ice sheets. In this case, it is changes in moisture content and circulation that are identified as the dominant control on SMB. Thus, for example, increased accumulation of the WAIS has a 5% probability of mitigating the ice sheet contribution to SLR by at least 65 cm for 2200H. This is also reflected in ice sheet model simulations using climate model output, particularly for the EAIS (Seroussi et al., 2020). The experts conclude that changes in summer sea ice extent will have some impact on ice shelf SMB for all three ice sheets up to 2200 (Figures S4 and S5 in Supporting Information S1), with the largest contribution over the GrIS.

Finally, we asked the experts whether they considered the recent (decadal) trends in mass balance for the GrIS and WAIS, as observed from satellite data, were due predominantly to internal variability (IV) or external forcing (EF) (Figure 5). This is an important question for four reasons. First, these same observations are used to initialize numerical ice sheet models (DeConto et al., 2021; Seroussi et al., 2020). To do this, it is necessary to assign the recent trends to either IV or to EF, or some combination of the two. That is because, as for GCMs, ice sheet models are not aimed at reproducing the conditions of one particular day, a season or a year, but to model climatically forced trends. Second, this is a central question for process understanding and also for probabilistic approaches that are conditioned on the observations, as are semi empirical models (Little et al., 2013). Third, recent observations have been used to calibrate tuneable parameters in an ice sheet model (DeConto et al., 2021). This requires assigning the trend in the observations to IV or EF. Note that model calibration and initialization are not, in general, the same process. Fourth, observations are an important tool for verifying the performance of a numerical model but only if the signal(s) in the observations can be assigned to some combination of IV and EF (Randall et al., 2007). The experts concluded that the trends in Greenland are predominantly driven by EF,

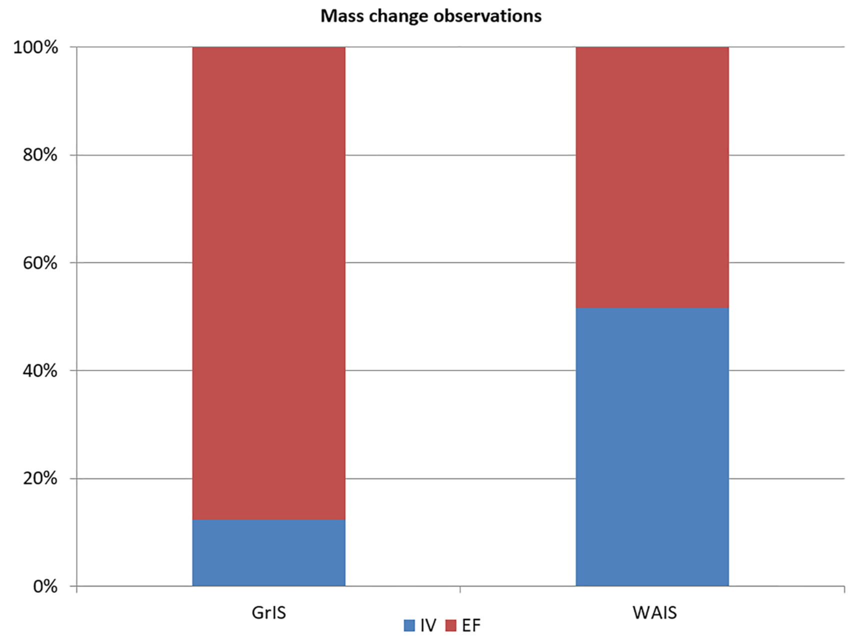

Figure 5. Expert judgements for whether internal variability (IV) or external forcing (EF) is the dominant driver of recent (last two decade) observational trends in mass balance for the Greenland Antarctic ice sheets (GrIS) and West Antarctic Ice Sheet (WAIS).

whereas for the WAIS there was no consensus and no certainty (Figure 5) as was also the case in a previous SEJ exercise (Bamber & Aspinall, 2013).

4. Conclusions

The findings just described, which are drawn from the SEJ exercise presented in B19, are generally consonant with recently reported observational evidence but are in sharp contrast to the latest ice sheet model intercomparison analyses in terms of both the dominant drivers of uncertainty and their magnitudes (Goelzer et al., 2020; Seroussi et al., 2020). An important contribution we have been able to provide through our analysis is to express these influences—on sea level projections and associated uncertainties—in probabilistic terms. We can, thus, quantify the relative role of different processes not just for their median response but also for the tails of the distributions, which are lower probability but higher impact. Where the distributions display high kurtosis (e.g., WAIS dynamics and GrIS runoff) the median and standard deviation do not capture the full uncertainty and risk associated with that process. In IPCC assessment reports prior to the AR6 (Fox-Kemper et al., 2021) this has been a major limitation in their sea level rise projections, which were limited to the likely range, equivalent to ± one standard deviation (Bamber et al., 2019).

We found that for all time periods out to 2300 CE, quantified uncertainties are dominated by WAIS dynamics and GrIS runoff. The former is influenced by the marine ice sheet instability, MISI, which in turn, is influenced by changes in ocean circulation and heat content in ways that are not well understood or, as yet, adequately modeled (Seroussi et al., 2020). Subglacial topography has an important controlling influence on the initiation of the MISI and how rapidly it evolves but is imperfectly known for many key sectors of the WAIS (Cornford et al., 2020; Rosier et al., 2021). GrIS runoff is relatively well understood as a process, but is sensitive to climate drivers that are poorly captured in GCMs and, therefore, imperfectly represented in future projections. For example, changes in cloud properties, such as optical depth, altitude and seasonality, can have a dramatic impact on melt rates but are inconsistent between GCMs and are known to be poorly modeled in general (Hofer et al., 2019). Runoff is also sensitive to albedo. Relatively small concentrations of both inorganic and organic material on the ice sheet surface can have a significant impact on albedo and, therefore, melting, but this is a factor that is yet to be included in ice sheet models (Williamson et al., 2020). The seasonality of both temperature and precipitation changes over Greenland has a strong influence on SMB trends but is also not consistently projected by GCMs. Reducing future uncertainties in ice sheet projections will require, therefore, improvements in ice sheet process understanding and modeling of those processes as well as more robust projections of the climate forcing for a given greenhouse gas emissions pathway.

An important challenge, building on this analysis, is to extend and refine our expert judgement elicitation so that we can better quantify critical parameters, variables and processes related to model projections of ice sheet contributions to sea level rise. For instance, while the uncertainties in our experts' assessments likely include some elements that relate to processes that are not formally identified in the present exercise, an elicitation could be designed that would enable us to disaggregate these complexities, and their associated uncertainties, in more detail. This would allow us to quantify the role of additional factors in limiting process certainty. As is usual with structured elicitations of this type, such additional findings—based on informed expert judgements—will almost certainly highlight specific topics meriting further research and analysis. As discussed above, this is not limited to ice sheet processes but also to the climate projections used to force them.

Data Availability Statement

The SEJ software is free to use and available from the developers at www.lighttwist-software.com/excalibur. Code to localize the SLR projections from this study is available at github.com/bobkopp/LocalizeSL. The anonymized responses of the experts to the SEJ questionnaire, alongside workshop materials and presentations are available at https://data.bris.ac.uk/data/dataset/23k1jbtan6sjv2huakf63cqgav.

Acknowledgments
The authors would like to thank the experts for their time and commitment. They also thank R. Westaway for help drafting figures and formatting the Supporting Information S1. JLB was supported by European Research Council Grant 694188 (GlobalMass) and the German Federal Ministry of Education and Research (BMBF) in the framework of the international future AI lab "AI4EO—Artificial Intelligence for Earth Observation," Grant: 01DD20001. Support for subject participation in the study was provided by the Rutgers University School of Arts and Sciences, The Princeton University Program on Science, Technology, and Environmental Policy, the City of New York, the New York City Department of Environmental Protection the European Research Council, and Resources For the Future. R.E.K. was supported in part by the US National Science Foundaiton (Grant ICER-1663807 and, as part of the Megalopolitan Coastal Transformation Hub, Grant ICER-2103754) and the US National Aeronautics and Space Administration (awards 80NSSC17K0698 and 80NSSC20K1724 and JPL task 105393.509496.02.08.13.31).

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