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Earth's Future

Supporting Information for

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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Supporting note 1. Ice Sheet Instabilities. For the Greenland Ice Sheet (GrIS), a potential key threshold relates to a concept termed the 'small ice cap instability' (Maqueda et al., 1998). This instability originates from a positive feedback between changes in surface elevation and increased runoff, i.e. it is linked to surface mass balance (SMB). As the ice sheet loses mass, the surface elevation lowers, resulting in warmer surface temperature and increased melting. When the amount of surface melting exceeds the total accumulation, via snowfall, the ice sheet is no longer sustainable in the long-term. The increase in global temperature required to pass this threshold has been estimated to lie between +0.8 to +3.2˚C above pre-industrial with a best estimate of +1.6˚C (Robinson et al., 2012). Recent evidence from satellite observations suggests that the GrIS had reached a state of persistent ice loss by about 2005 (King et al., 2020) and that it experienced its largest recorded mass loss, equivalent to 1.5 mm sea level equivalent, in 2018. About 60% of the mass loss over the last three decades is attributable to SMB and the rest to discharge (King et al., 2020; Sasgen et al., 2020). Whether the GrIS would completely disintegrate or reach a new, smaller metastable state is a topic of current debate (Gregory et al., 2020; Robinson et al., 2012).

The West Antarctic Ice Sheet (WAIS) is termed a marine ice sheet because most of the bedrock it rests on lies below sea level, in some places by as much as 2,500 m (Bamber et al., 2009). In addition, the ice sheet also rests, predominantly, on a retrograde bed slope: one that deepens inland. These two conditions are hypothesised to be necessary (but not sufficient) to invoke the Marine Ice Sheet Instability (MISI) whereby the grounding line is inherently unstable and can rapidly migrate inland (Schoof, 2007; Seroussi et al., 2020). Recent evidence indicates that part of the WAIS may already be experiencing irreversible grounding line retreat as a result of MISI (Joughin et al., 2014). Unlike the GrIS instability mechanism, the WAIS MISI is a dynamic response driven predominantly by ocean forcing.

The East Antarctic Ice Sheet (EAIS) has several marine basins, which could be vulnerable to oceanic erosion but are currently protected by regions of ice grounded above sea level or on prograde bed slopes (Bamber et al., 2009). For the two major marine basins, Aurora and Wilkes, this "safety band" is just tens of kilometers wide (Fig S1 and S2 of (Bamber et al., 2009). In addition, the two largest ice shelves in Antarctica, the Filchner Ronne and Ross, buttress large catchments in both the WAIS and EAIS. Inclusion of enhanced calving via hydrofracture and ice cliff failure (both components that contribute to marine ice cliff instability, MICI) in numerical models can lead to a significant loss of ice from the EAIS by 2100CE under RCP8.5 conditions (DeConto and Pollard, 2016). More recently, the rate of mass loss has been revised downward using updated climate forcing and calibration data (DeConto et al., 2021). Nonetheless, significant mass loss was predicted from the EAIS over the present century for RCP8.5 and a recent study suggests that as many as 60% of Antarctic ice shelves - which buttress inland ice - are vulnerable to hydrofracture if inundated by meltwater (Lai et al., 2020).

Supporting note 2. Explaining variation between ice sheets

In a given year, under a given temperature scenario, sea level rise (SLR) from the ice sheets is simply the sum of contributions from *EAIS, WAIS* and *GrIS:*

$$SLR(ice\ sheets) = EAIS + WAIS + GrIS$$

A natural question is how much the uncertainty of each ice sheet contribution influences the uncertainty in enumerating *SLR(ice sheets)*. Suppose we could observe $EAIS=x$. Given this information our expectation for *SLR* is represented as $E(SLR \mid EAIS = x)$. As we let x vary over its range, $E(SLR \mid EAIS = x)$ will also vary. The question is, by how much? If EAIS had no effect on SLR, then the expected SLR value would not depend on x at all and would always be equal to the unconditional expectation $E(SLR)$. On the other hand, if $E(SLR \mid EAIS = x)$ varied substantially, that would mean that the value of *EAIS* has a big role in determining the value of *SLR*. We can capture that effect by comparing the variance of $E(SLR \mid EAIS = x)$ as x varies, to the unconditional variance of *SLR*. This ratio is called (inappropriately) the 'correlation ratio' (*CR)*, though is better thought of as the fraction of variance of *SLR* explained by variations in *EAIS*:

$$CR(SLR, EAIS) = Var(E(SLR \mid EAIS = x)) / Var(SLR).$$

When the variation of *EAIS* explains all the variation in *SLR*, then the above ratio is one.

For contributions from the three ice sheets, *EAIS*, *WAIS* and *GrIS*, if their variations are independent then:

$$Var(SLR) = Var(EAIS) + Var(WAIS) + Var(GrIS)$$

and the correlation ratios sum to one.

However, if the variations in individual ice sheet contributions are positively correlated then the sum of the correlation ratios is greater than one. In this case knowing, say, that *EAIS = 2m* tells us something about contributions from *WAIS* and *GrIS.* The following table gives the correlation ratios calculated from the expert judgements for High and Low temperature stabilization scenarios (H, L), for 2300CE and 2100CE.

Fraction of variance of SLR explained by each ice sheet				
	2300H	**2300L**	**2100H**	**2100L**
EAIS	0.75	0.41	0.49	0.30
GrIS	0.19	0.32	0.34	0.39
WAIS	0.61	0.63	0.67	0.57
sum	1.55	1.36	1.49	1.26

We observe that in all cases the correlation ratios sum to more than *one*, and that exceedances are greater for High temperature stabilization scenarios. This suggests the experts jointly consider ice sheet responses could be more strongly correlated under higher temperature trajectories, and possibly become even more so further ahead into the future. For instance, there is the implication that, under the High temperature scenario, variations in *EAIS* contributions could be the major influence on total *SLR* uncertainty by 2300CE (*CR* 0.49 → 0.75), while the related effect of *GrIS* variations will be much reduced (*CR* 0.34 → 0.19).

We do not extend this type of analysis down to the physical ice mass processes operating at the individual ice sheets: those processes are inter-dependent, sometimes with tail correlations, and each expert assessed such dependences for themself when making judgements on ice sheet contributions. While it might be possible to decompose, expert by expert, the variance of *SLR* into components – expressing numerically the way these processes appear to act at each individual ice sheet – more insight is gained by examining their joint appraisal of importance rankings for these drivers (Bamber et al, 2019).

Supporting note 3: **Definitions of driving processes included in the rationale questionnaire**. Six ice dynamic drivers and three SMB drivers were included in the expert rationale questionnaire, designed to provide an indication of the rationales for the uncertainties for each of the three ice sheet process elicited: accumulation, A, and runoff, R, (contributing to SMB) and discharge, D, across the grounding line. In the case of the rationale questionnaire, quantile values were not elicited but instead the relative rank order of each factor in driving the change in A, R or D (Bamber et al, 2019). Here, we provide brief descriptors for these drivers

Buttressing, B	This is the influence of back stresses on the grounded ice from floating ice shelves. Discharge is determined by the force balance acting at the grounding line. This force balance is comprised of several terms. On one side is the gravitational driving stress that results in ice flow. Opposing this are transverse stresses (TS) such as at the margins of the glacier or ice stream, basal traction (BT) and the backstress at the grounding line due to the buttressing effect of floating ice.
Basal traction, BT	See Buttressing. BT is the resistive force between the glacier bed and the ice in contact with it. For a frozen bed, this term is not relevant but fast-moving ice at the margins of the ice sheets the bed is not frozen, water is present, and basal sliding occurs. For ice streams, as much as 90% of the ice motion can be due to basal sliding, which is controlled by BT.
Transverse stresses, TS	See Buttressing. TS are largely determined by the large difference in ice speed between the slow-flow margins of a glacier and the fast-moving central trunk. TS act as a resistive force to ice motion and are influenced by damage characteristics of the ice, which in turn is a function of strain history and ice rheology.
Hydrofracture, HF	HF is a process that enhances crevasse propagation on both ice shelves and grounded ice. It weakens the ice by accelerating crevasse growth via water filled crevasses. HF is a key process in the MICI as it leads to rapid ice shelf collapse, with sufficient surface melting.
Ice cliff instability, IC	IC is linked to HF and MICI. After rapid ice shelf collapse, an ice cliff forms at the grounding line (ice above sea level). Above a critical height, this ice cliff is unstable, resulting in brittle failure (the shear stress exceeds the yield stress of ice).
Dissipation of icebergs, DI	This is related to IC and MICI. During IC, icebergs are formed, which, depending on the geometry of the ice shelf and bathymetry beneath can accumulate in an embayment or become rafter on a sill or alternatively can be advected away from the ice edge by ocean currents.
Atmospheric moisture and circulation, AM	In a changing climate, the predominant patterns of atmospheric circulation and strength of multi-annual oscillations such as the Pacific Decadal Oscillation or Arctic Oscillation may change affecting both the source and magnitude of precipitation regionally. Circulation changes can also influence surface ocean heat transport, which in turn can affect buttressing but here we were only concerned with its influence on SMB.
Albedo, AL	Changes in surface AL have a large impact on the radiative

	energy balance of the snow or ice surface, which affects melt rates. Several factors that are currently not included in SMB models are known to influence albedo such as organic and inorganic impurities deposited or growing on the surface.
Sea ice, SI	SI acts as a barrier to moisture and heat exchange between the atmosphere and ocean and changes in sea ice extent or concentration can, therefore, influence both of these factors locally, affecting rates of precipitation and air temperatures.

Supporting note 4: Importance of gravitational, rotational and deformation effects

Recent observations and developments in numerical modeling have suggested that gravitational, rotational and solid Earth deformation (GRD) effects on regional sea level and isostatic bedrock elevation caused by changes in ice mass loading could have a stabilising effect on, in particular, grounding line migration associated with MISI. Fig S7 shows the results of the experts' judgement on the importance of GRD for the stability of the three ice sheets where D implies decreasing stability, I is increasing stability and N is no impact. The GrIS has limited sectors that satisfy the MISI criteria: a retrograde bed slope that is below sea level close to, or at, the present-day grounding line. Consequently, GRD effects are considered of negligible significance here. The WAIS is the ice sheet that is most susceptible to the MISI and is thus the ice sheet where GRD may act as a negative, stabilising feedback. However, only 50% of the experts consider this to be the case and recent modeling suggest the effect is, however, small (Larour et al., 2019). For the EAIS, about a third of the experts consider GRD to be of relevance and, as for the WAIS, any reduction in grounding line migration due to GRD effects is likely to be small (Larour et al., 2019). Consequently, we do not discuss GRD effects further and consider them to be of second-order importance.

Supporting Figures

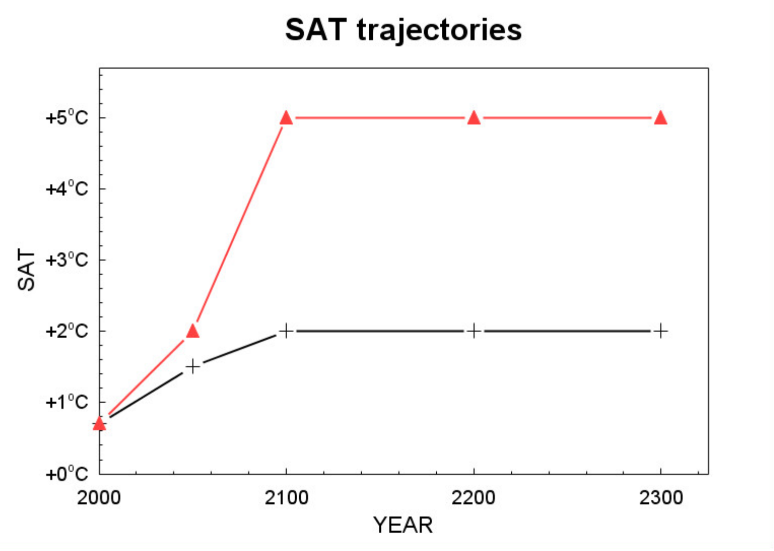

Fig S1. The two temperature scenarios prescribed: L (+2° C) and H (+5° C)

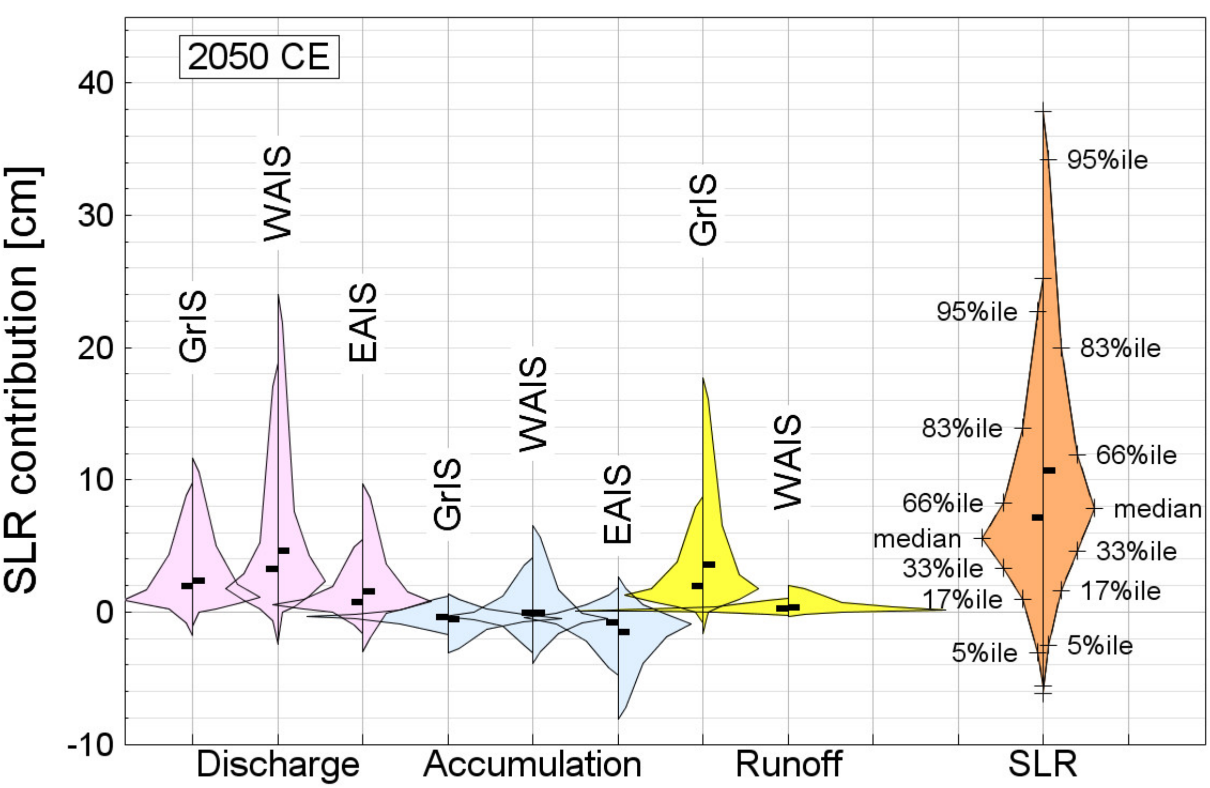

Fig S2. *Indicative probability distribution plots for SLR contributions by 2050CE from the three ice sheets and for three physical processes, identified on the x-axis (runoff from EAIS is omitted as this is presumed zero under either temperature rise scenario). Results are derived from expert elicitation for the 2050L (low +2°C) global temperature trajectory (left hand curves) and for the 2050H (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. Median values are shown by the black rectangle and the total SLR contribution from the ice sheets is shown in orange.*

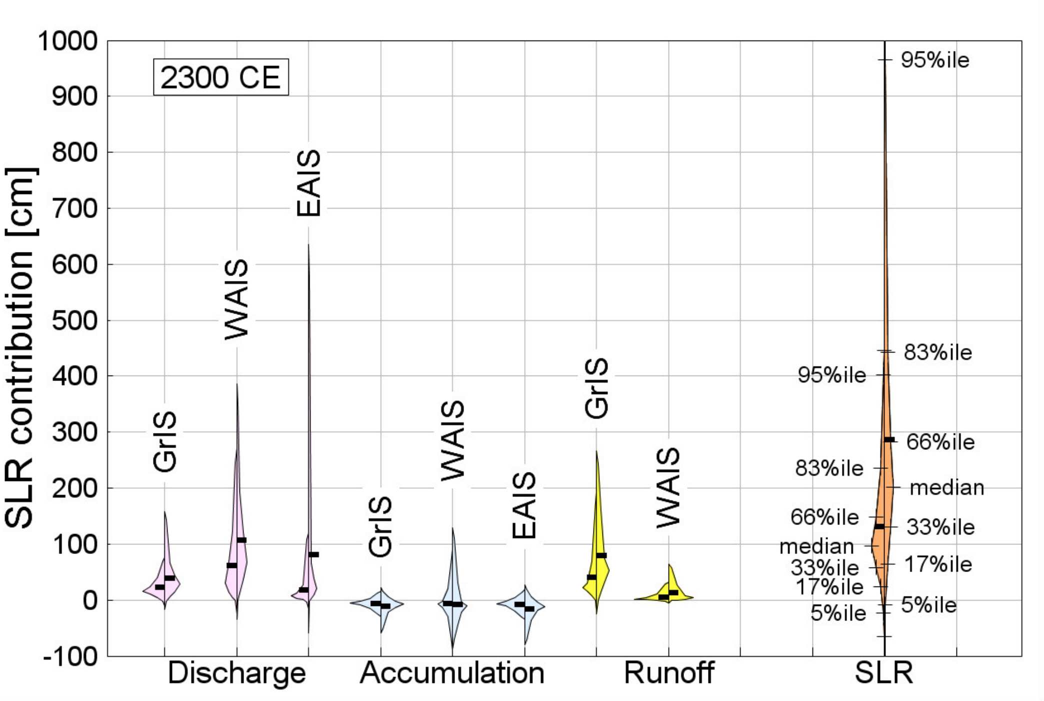

Fig S3. As for figure S2 but for 2300.

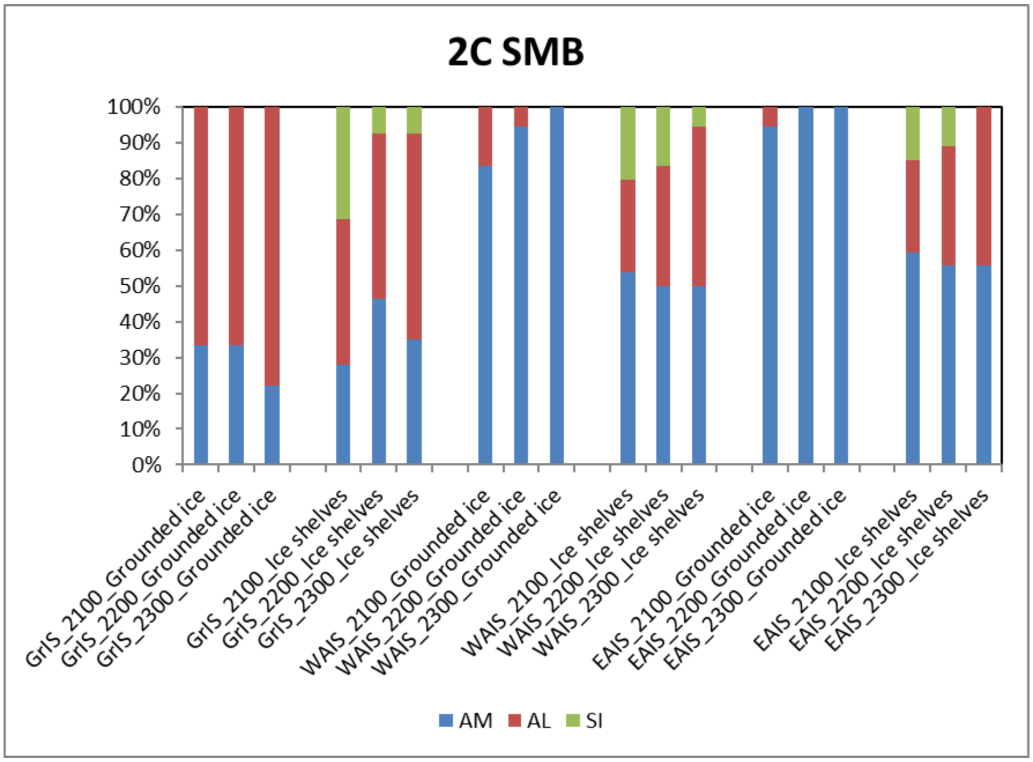

Fig S4. Expert judgements on the relative role of the three drivers for changes in SMB: atmospheric moisture and circulation (AM), albedo (AL) and sea ice extent (SI) for both grounded and floating ice for the Low temperature scenario.

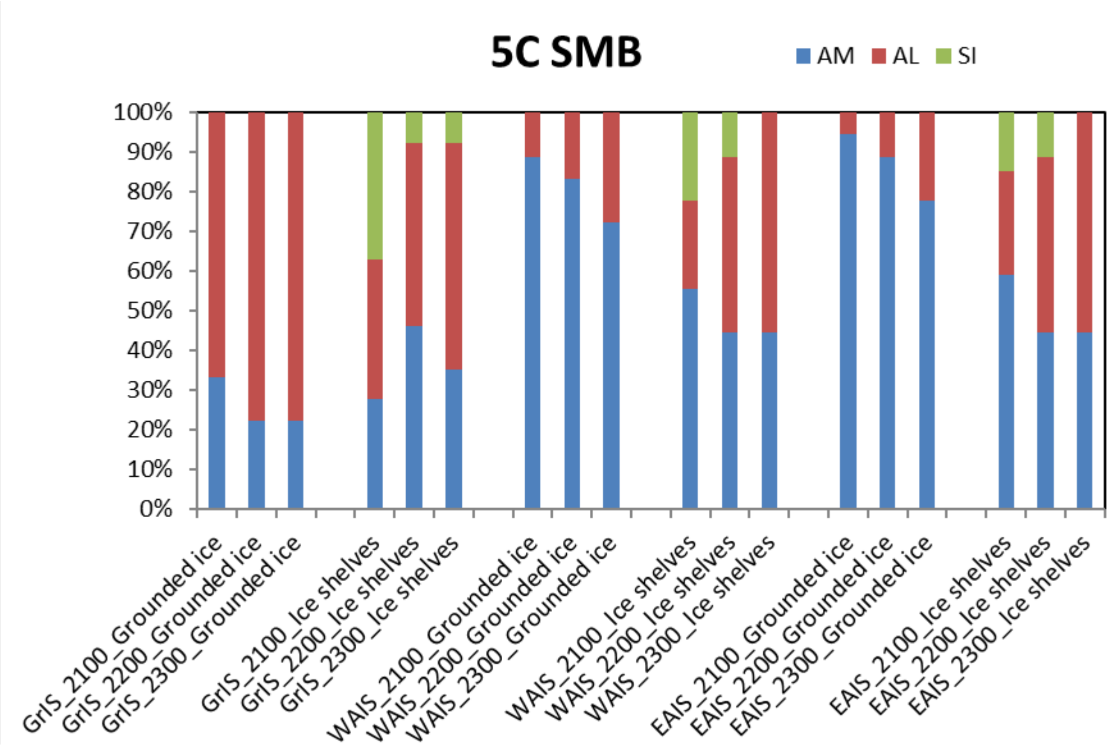

Fig S5. Expert judgements on the relative role of the three drivers for changes in SMB: atmospheric moisture and circulation (AM), albedo (AL) and sea ice extent (SI) for both grounded and floating ice for the Low temperature scenario.

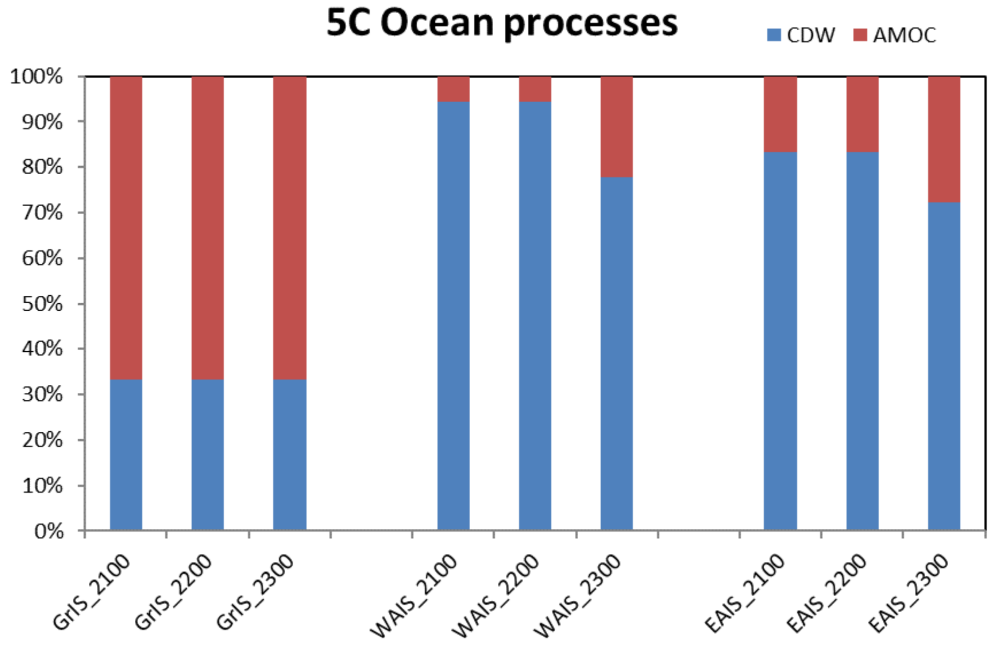

Fig S6. Expert judgements on the relative role of the two ocean processes: circumpolar deep water (CDW) and the Atlantic Meridional Overturning Circulation (AMOC) for the High temperature scenario.

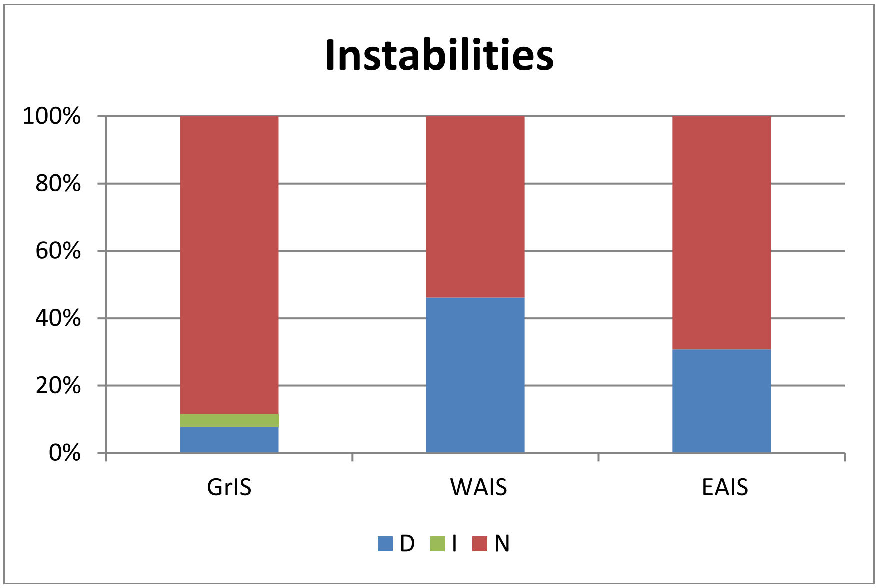

Figure S7. Relative importance of GRD effects for decreasing ice stability (D), increasing it (I) or having no effect (N).

Supporting Tables

Probabilit	0.01	0.05	0.17	0.5	0.83	0.95	0.99	0.995	0.999
2010	2	3	3	4	5	5	6	6	6
2020	6	7	8	9	11	12	13	14	15
2030	9	11	13	16	20	24	29	32	37
2040	12	15	19	24	32	41	51	56	68
2050	16	21	27	34	47	61	78	84	104
2060	22	29	36	48	65	84	108	118	141
2070	29	37	47	63	88	114	147	161	186
2080	35	46	57	78	114	150	195	217	246
2090	40	54	68	95	142	191	254	281	325
2100	45	62	80	111	172	238	329	361	435
2110	46	67	88	124	198	288	412	456	537
2120	50	74	98	141	225	345	518	567	663
2130	53	81	108	156	253	410	631	691	804
2140	56	88	119	172	278	480	762	820	952
2150	59	95	130	188	303	551	892	964	1113
2160	61	102	140	203	327	622	1032	1108	1260
2170	65	109	150	218	352	690	1170	1257	1412
2180	68	116	160	233	375	756	1297	1400	1561
2190	70	122	170	248	399	820	1420	1536	1694
2200	73	128	180	262	423	880	1523	1651	1832
2210	76	134	189	276	448	934	1611	1741	1951
2220	78	140	198	291	471	977	1682	1820	2054
2230	81	146	207	305	494	1017	1738	1880	2142
2240	83	151	215	320	517	1049	1782	1930	2215
2250	86	157	224	335	541	1081	1810	1965	2271
2260	89	163	233	349	564	1104	1830	1986	2315
2270	92	168	242	364	586	1122	1835	1997	2349
2280	95	173	250	378	608	1141	1839	1996	2362
2290	100	178	259	393	630	1157	1833	1988	2366
2300	103	182	266	407	652	1166	1821	1975	2363

Table S1. SLR for different probabilities from 1-99.9% and at ten year increments from 2010-2300. All values are relative to the year 2000 baseline for the High temperature scenario. Values are in cms.

Dynamicals	**B**	**BT**	**TS**	**HF**	**IC**	**DI**
GrIS_2100	**0.13**	**-0.04**	**-0.04**	**-0.03**	**-0.03**	**0.02**
GrIS_2200	**0.02**	**-0.15**	**0.04**	**0.10**	**-0.02**	**0.02**
GrIS_2300	**0.03**	**0.08**	**-0.07**	**-0.02**	**-0.02**	**-0.01**
WAIS_2100	**-0.17**	**0.00**	**0.00**	**0.11**	**0.00**	**0.05**
WAIS_2200	**-0.33**	**0.00**	**0.00**	**0.07**	**0.14**	**0.12**
WAIS_2300	**-0.28**	**0.00**	**0.00**	**0.10**	**0.10**	**0.09**
EAIS_2100	**-0.02**	**-0.02**	**-0.02**	**-0.02**	**-0.02**	**0.09**
EAIS_2200	**-0.06**	**-0.17**	**0.00**	**0.17**	**0.00**	**0.05**
EAIS_2300	**-0.07**	**-0.08**	**-0.02**	**0.08**	**0.02**	**0.07**

Table S2. Change in process significance between Low and High temperature scenarios for ice dynamic processes.

Change score = (5C score – 2C score) / Σ2C scores for all processes
Cells highlighted where change scores <-0.1 (red) or >0.1 (green) (i.e. change exceeds 10%)

SMB	**AM**	**AC**	**SI**
GrIS_2100_Grounded ice	**0.00**	**0.00**	**0.00**
GrIS_2200_Grounded ice	**-0.11**	**0.11**	**0.00**
GrIS_2300_Grounded ice	**0.00**	**0.00**	**0.00**
WAIS_2100_Grounded ice	**0.06**	**-0.06**	**0.00**
WAIS_2200_Grounded ice	**-0.11**	**0.11**	**0.00**
WAIS_2300_Grounded ice	**-0.28**	**0.28**	**0.00**
WAIS_2100_Ice shelves	**0.02**	**-0.04**	**0.02**
WAIS_2200_Ice shelves	**-0.06**	**0.11**	**-0.06**
WAIS_2300_Ice shelves	**-0.06**	**0.11**	**-0.06**
EAIS_2100_Grounded ice	**0.00**	**0.00**	**0.00**
EAIS_2200_Grounded ice	**-0.11**	**0.11**	**0.00**
EAIS_2300_Grounded ice	**-0.22**	**0.22**	**0.00**
EAIS_2100_Ice shelves	**0.00**	**0.00**	**0.00**
EAIS_2200_Ice shelves	**-0.11**	**0.11**	**0.00**
EAIS_2300_Ice shelves	**-0.11**	**0.11**	**0.00**

Table S3. As for Table S1 but for SMB processes.

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