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An expert judgement assessment of future sea level rise from the ice sheets

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A major gap in predictive capability concerning the future evolution of the ice sheets was identified in the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change. As a consequence, it has been suggested that the AR4 estimates of future sea-level rise from this source may have been underestimated. Various approaches for addressing this problem have been tried, including semi-empirical models and conceptual studies. Here, we report a formalized pooling of expert views on uncertainties in future ice-sheet contributions using a structured elicitation approach. We find that the median estimate of such contributions is 29 cm—substantially larger than in the AR4—while the upper 95th percentile value is 84 cm, implying a conceivable risk of a sea-level rise of greater than a metre by 2100. On the critical question of whether recent ice-sheet behaviour is due to variability in the ice sheet–climate system or reflects a long-term trend, expert opinion is shown to be both very uncertain and undecided.

The Greenland and Antarctic ice sheets (Fig. 1) contain about 99.5% of the Earth's glacier ice. If they were to melt completely, they would raise global sea level by some 65 m. Since continental-scale observations of ice-sheet mass balance began in 1992, the rate of mass loss from Greenland and West Antarctica has been increasing[1]. The observational record is, however, short and, before the 1990s, poor. For reasons explained below, the use of whole ice-sheet numerical models to provide robust projections remains challenging. There is emerging evidence that, in part, recent trends are due to changes in ocean temperatures around the ice-sheet margins[2,3], but that the nature of these changes are related to internal variability in the climate system[4]. It is also apparent that, locally, the response to external forcing is complex, such that adjacent glaciers may respond in markedly different ways[5,6]. Further, the response can be of large amplitude and variable timescale[7]. There is, therefore, a stochastic component to the external forcing and the response of the ice sheets.

In addition to this stochastic behaviour, both the Greenland and West Antarctic ice sheets probably possess state transition thresholds or instabilities that could result in an irreversible reduction in volume. All these factors pose a challenge for the current generation of deterministic ice-sheet models[8] and, as a consequence, alternative approaches for predicting future behaviour have been explored. An approach that is useful for determining the degree of consensus within a scientific community, and for exploring collective views on ranges of uncertainties, is to conduct a structured expert elicitation with formalized pooling of opinions[9,10]. This type of approach is valuable when there is a pressing need to confront scientific issues and to focus future work but with incomplete data or understanding (see also refs 11,12). It is not a substitute for improved process understanding; nor is it intended to remove uncertainty, but rather to quantify it, given limitations in available information. Expert elicitation and judgement pooling is used in a wide range of applications from medicine to engineering and natural sciences (for example, ref. 13).

First, we briefly describe the processes controlling ice sheets before discussing the approach taken and the results. The Greenland ice sheet (GrIS) loses mass via two processes that have, potentially, different environmental controls: via surface melting, termed runoff or ablation, and via solid ice discharge across the grounding line[14]. The former is controlled predominantly by air temperature. The latter, referred to here as the discharge *D*, is controlled by various factors that influence ice dynamics, including changes in ocean temperature and circulation[2].

Antarctica is usually divided into two ice sheets, separated by the Transantarctic Mountains (Fig. 1), with potentially contrasting behaviour. For the West Antarctic ice sheet (WAIS) weakening or thinning of the floating ice shelves and tongues that buttress inland grounded ice is believed to be critical for the ice-sheet stability, and this floating ice is susceptible to accelerated erosion by a warming ocean or altered circulation in coastal seas[3,15].

Most of the East Antarctic ice sheet (EAIS) is not thought to be inherently unstable. Of the three ice sheets shown in Fig. 1, the EAIS is the largest in volume by a factor of ten, but may also be the least sensitive to changes in climate on a centennial timescale. GCM simulations suggest future growth of the EAIS due to increased snowfall, with little effect on ice dynamics[16]. There are, therefore, multiple processes at work, capable of producing varied—and uncertain—effects.

The present study began in 2010 when twenty-six leading experts were invited to provide detailed judgements on their understanding of the key ice-sheet processes, climate drivers and possible short- and long-term evolution of the ice sheets, with a focus on potential behaviour during the twenty-first century. A unique aspect of the study was a repeat elicitation, two years later. The two surveys comprised the same eleven main questions concerning ice-sheet mass evolution and sea-level rise (Supplementary Note S5). For subsets of related questions, participants were asked to self-assess their level of expertise and confidence in their responses and, in the second survey in 2012, to indicate whether they felt their judgements had changed significantly since the 2010 survey (Supplementary Note S5). Respondents were also asked questions about recent behaviour of the ice sheets, for which quantitative observational data exist.

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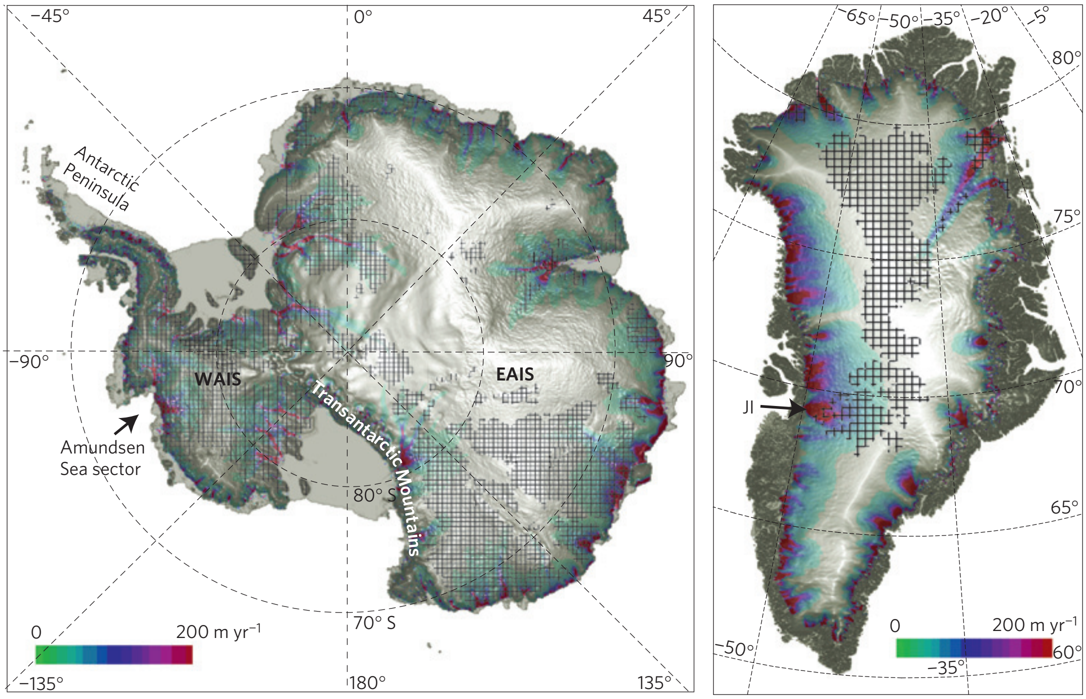

Figure 1 | Shaded relief maps of Antarctica and Greenland showing regions of enhanced flow (in colour) and areas of the ice sheets grounded below sea level (hatched). Also shown are regions discussed in the text. JI refers to Jakobshavn Isbrae, a glacier that doubled in velocity during the late 1990s[7].

The survey was repeated for two purposes: to assess whether and how views had evolved, and to obtain a measure of the stability of question responses where experts stated their view had not changed. In the second survey, participants were asked not to revisit their original survey responses and, in all cases, stated they had not done so. Of the 26 experts originally approached 14 responded to the first survey, and 13 of these repeated the second survey. Each expert was classified as an observational scientist, or a modeller to explore whether any systematic differences exist between these disciplines for any of the questions.

For each question, separate answers were requested for the EAIS, WAIS and GrIS because, as explained above, the drivers, processes and threshold behaviour may differ for each. Key findings are reported in Supplementary Table S1 expressed as parameters of probability density functions (PDFs) obtained from weighted combinations of the elicitation responses (see Methods). Figure 2 shows the PDF of the aggregated rate of sea-level rise (SLR) at year 2100, based on the expert group judgement for future climate change. Range graph plots, showing the experts' credible ranges and best estimate values, together with the equal weights and performance-based weighted solutions obtained by pooling, are given in Supplementary Figs S1–S8. Here we focus on the PDFs resulting from the Monte Carlo analysis, described in the Methods.

Figure 2 provides an estimate of the median total SLR rate at year 2100 (5.4 mm yr^{-1}) and the variability due to uncertainty on the contributions from the three ice sheets. In terms of the resulting PDF properties, there is a remarkably strong correlation between outcomes from the original and repeat surveys (0.988), despite some experts stating that their views had changed. This demonstrates a collective robustness in such elicitations, also seen in other instances[10]. Whilst the PDF central tendency is not influenced by a few experts expressing changed views through revised quantiles, the upper tail of the distribution is affected marginally, being extended to slightly higher values in the 2012 survey. Examination of the range plots (Supplementary Fig. S7) indicates a substantial increase in the upper limit for the contribution of the WAIS from one survey

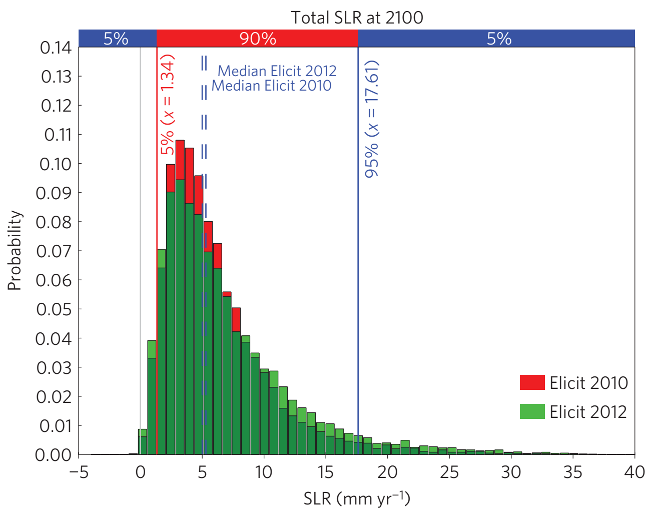

Figure 2 | The PDF for the rate of SLR due to ice-sheet contributions by year 2100. Plotted in red is the PDF for the 2010 elicitation and in green for 2012. The 90% probability range is indicated by the vertical red and blue lines. This, and subsequent PDFs, are based on experts' judgments about future climate change. Views were also obtained for fixed temperature increases of 2 and 4 °C by 2100 and are provided in Supplementary Table S2.

to the next (10.5–16.9 mm yr^{-1}), but with the expected central value remaining almost unchanged. This indicates a growing view that a significant marine ice-sheet instability in the WAIS could initiate in the coming century.

The SLR rate distribution is non-Gaussian (Fig. 2), with a long upper tail. For this reason the median is a more appropriate estimate of central tendency than the mean and has a lower value (5.4 versus 6.9 mm yr^{-1} for the 2012 survey). Much larger rates, however, presumably due to threshold behaviour such as mentioned for the WAIS (ref. 15), cannot be ruled out. In fact, the pooled

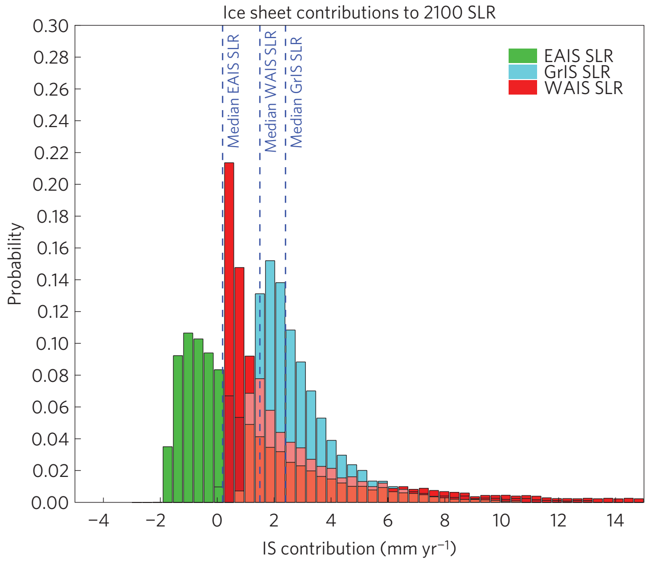

Figure 3 | PDFs for the contributions of each ice sheet derived from the 2012 survey, combined as distributions using the performance weights (PerfWts) pooling option. Median values are shown by the vertical dashed lines; other statistics of the distributions are provided in Supplementary Table S1. Colours are mixed (orange, dark red and pink) where histograms overlap.

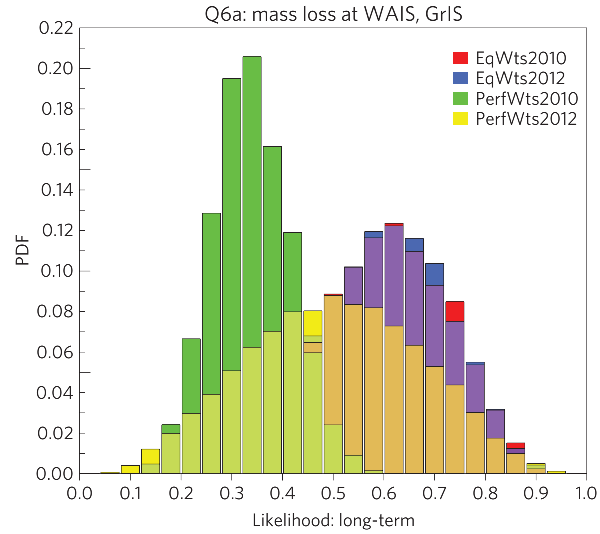

Figure 4 | PDFs of the 2010 and 2012 response to the question related to whether the trends observed in the satellite record over roughly the past decade is due to internal variability or to a secular trend. Shown are the pooled solutions for an equal weights mixing of opinions (EqualWts) and for the performance-based combination (PerfWts), for both surveys. Colours are mixed (lime, gold, purple) where histograms overlap.

elicitation solution indicates a 5% likelihood of the rate reaching 17.6 mm yr^{-1}, or greater, by 2100.

Figure 3 shows the individual PDFs for the three ice-sheet SLR contributions individually, obtained from Monte Carlo simulation. These PDFs are consistent with recent observations: the GrIS has the highest mean rate, but the WAIS has the longest upper tail with a 5% chance of exceeding 11 mm yr^{-1} by 2100. The EAIS is the only ice sheet likely to gain mass and has the smallest mean (Supplementary Table S1). Notably, the GrIS has the smallest 90 percentile range, suggesting that the limits to mass loss from this ice sheet are thought better constrained, in comparative terms. By contrast, both the WAIS and EAIS exhibit perceived potential for larger rates, presumably from dynamically driven changes along their extensive marine-grounded sectors (Fig. 1). The marine-grounded regions of Greenland are limited (Fig. 1) and the mass loss from calving is, therefore, also limited. For moderate warming, increased loss from surface melt is coupled to surface air temperature with a fairly linear relationship[17]. Thus, a sustained large amplitude response of the GrIS seems to be unlikely.

One of the most challenging and important questions arising from the gamut of studies documenting recent increases in mass loss from the ice sheets[1] is whether this is a secular trend or due to internal variability in the ice sheet–climate system. In broad terms, are we observing ice-sheet 'weather' or ice-sheet 'climate' variations, or both? Figure 4 shows PDFs from the responses to this question, and offers some important insights. First, for the case of the Equal Weights combination, there is almost no change in group view between 2010 and 2012, with a mean of about 60% likelihood in favour of a long-term trend. This indicates a judgement—with very weak conviction—that the trend is slightly more likely than not to be secular. The PerfWts solution is markedly different, with a shift of mean from 34 to 50% in the 2010 and 2012 surveys respectively, and a near-Gaussian distribution. What these results indicate is that, collectively, the experts are exceedingly uncertain about the answer to this key question and that even a reasoned scientific hint as to which is more likely is lacking: this is clearly an issue of central importance that needs to be tackled.

We have converted the rates of SLR into cumulative values by assuming a linear increase from the experts' estimate for the past decade (0.9 mm yr^{-1}) to their median annual value at 2100 of 5.4 mm yr^{-1} (Supplementary Note S1). Integrating the range values from 2010 to 2100 results in a median SLR from these ice sheets of 29 cm, and a 90% confidence range of 10–84 cm. The SLR PDF tails are not symmetric about the mean and the distribution is non-Gaussian: there is a longer upper tail (Fig. 2). The lower fifth percentile value implies no increase in mass loss compared to the past decade, with mass gain from the EAIS balancing increased losses from the WAIS and GrIS (ref. 16). The median of 29 cm comprises roughly a two-thirds contribution from the GrIS, one-third from the WAIS and a negligible amount from the EAIS (Fig. 3 and Supplementary Table S1).

A recent, comprehensive model estimate for the contribution of glaciers and ice caps to SLR by 2100 was 12.4 ± 4 cm (ref. 18). Based on the Community Climate System Model 4.0 (CCSM4) model[19], ocean thermal expansion has a range of 14–32 cm for the spread of representative concentration pathway (RCP) scenarios[20] considered in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC; RCP2.8 to 8.5). If we combine our median ice-sheet contribution estimate with these values we obtain a total SLR of 55–73 cm and a value of 62 cm for RCP4.5 (a scenario that has a temperature increase close to the experts' pooled prediction of temperature rise at 2100 of 3.5 °C above pre-industrial[21] (Supplementary Fig. S3)). Combining the upper and lower 5 percentile values for the combined ice sheets, the high/low estimates for glaciers and ice caps (16/9 cm) and the CCSM4 range for thermal expansion leads to range values of 33–132 cm. For comparison, a semi-empirical model estimate based on RCP4.5 has a 90% uncertainty range of 64–121 cm, with a median value of 90 cm (ref. 21). Our upper 95 percentile estimate is identical to the semi-empirical model upper value based on the Copenhagen Accord scenario. Our median, however, is about 35% lower than the semi-empirical model estimate for this scenario (61 versus 96 cm) or even for the RCP3-PD scenario, which involves aggressive mitigation.

We find an overwhelming lack of certainty about the crucial issue of the origin of recent accelerated mass loss from the ice sheets. Without a clearer understanding of the role and importance of internal variability in ice sheet–climate behaviour[5,6], predictions based on numerical modelling or extrapolation of observed trends are compromised. The present expert elicitation findings suggest a smaller contribution from the ice sheets than implied by semi-empirical models, but larger than proposed in the last IPCC report[22]. The impacts of a SLR rate of the magnitude indicated by this elicitation are potentially severe, implying a conceivable risk of forced displacement of up to 187 million people within this century[23].

Methods

For the quantitative questions in the 2010 survey, repeated in the 2012 survey, individual expert judgements on parameter values and associated uncertainty spreads were provided as three quantile values—each expert defining his or her 90% credible range and a median value. These quantiles are used to construct individual elemental probability distributions for each question, and these distributions are then combined, first with equal weights, and then with differential expert pooling weights. The latter weights were determined by scoring experts' performances on empirical tests of statistical accuracy and informativeness on four seed questions from the survey (Supplementary Note S2) with known bounds (ideally, a larger number of seed items would have been desirable). An individual expert's statistical accuracy (sometimes called 'calibration') is determined objectively using the principles embodied in the 'Classical model' for structured expert elicitation[9]. This calibration score is derived from a threshold significance level for accepting the hypothesis that the seed realizations could be drawn jointly as valid samples from the expert's distributions. 'Informativeness' is an information entropy score for the overall joint kurtosis (peakedness) of the individual's uncertainty distributions, when each is compared to a suitable reference uniform (or loguniform) background distribution. The two measures—which evaluate competing, orthogonal properties of an expert's ability to judge uncertainty—are multiplied together to give a single grading score, leading to a relative weighting within the group when the set of individual scores is optimized collectively, and results normalized across the group. The outputs of this process are two 'new' sets of (three) quantile values for each target question, comprising: an equal weights combination, as reference; and a performance-based weighted pooling solution. The latter provides a rational characterization[10] of the group's collective judgement, given that individual experts' abilities to provide informative uncertainty estimates can vary, and can be empirically measured by Cooke's approach[9].

For the total SLR contribution, we aggregate estimates for the three ice sheets using Monte Carlo re-sampling to produce a single, overall rate. To represent SLR contributions from each of the three ice sheets as continuous variables, the weighted and pooled 5%, 50% and 95% quantile values from the 2012 elicitation are fitted with individual lognormal distributions. It is presumed also that, under real conditions, the contributions to SLR by each ice sheet may be correlated or anti-correlated in response to climate change—for example, positively due to common forcing, or negatively due to opposing processes. The following correlations are assumed here: EAIS − WAIS = −0.2; EAIS − GrIS = −0.2; WAIS − GrIS = +0.7. These are based on the ranking of climate drivers provided by experts for the three ice sheets (Supplementary Note S5) and the correlation in the pooled response for a fixed temperature change. The three separate ice-sheet SLR contribution PDFs were resampled 10,000 times each and values at each iteration summed to give an estimate of total SLR, in mm yr^{-1}. We used Vose ModelRisk Professional v4.3 software for the Monte Carlo analysis. Generally, for Monte Carlo simulation, sampling correlations need to be recognized—otherwise spurious or physically implausible combinations can arise. Sensitivity analyses, performed with some extreme endmember correlation structures, showed that when the individual ice-sheet contributions are aggregated, such correlations had a minimal impact on the PDF median value, but some effect on the upper tail (Supplementary Note S3). The impact on the upper tail warrants study in future work.

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Author contributions

J.L.B. conceived and carried out the study and solicited the expert judgements. W.P.A. analysed the elicitations and carried out the Monte Carlo simulations. Both authors wrote the paper.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to J.L.B.

Competing financial interests

The authors declare no competing financial interests.