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Upper limit for sea level projections by 2100

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Abstract

We construct the probability density function of global sea level at 2100, estimating that sea level rises larger than 180 cm are less than 5% probable. An upper limit for global sea level rise of 190 cm is assembled by summing the highest estimates of individual sea level rise components simulated by process based models with the RCP8.5 scenario. The agreement between the methods may suggest more confidence than is warranted since large uncertainties remain due to the lack of scenario-dependent projections from ice sheet dynamical models, particularly for mass loss from marine-based fast flowing outlet glaciers in Antarctica. This leads to an intrinsically hard to quantify fat tail in the probability distribution for global mean sea level rise. Thus our low probability upper limit of sea level projections cannot be considered definitive. Nevertheless, our upper limit of 180 cm for sea level rise by 2100 is based on both expert opinion and process studies and hence indicates that other lines of evidence are needed to justify a larger sea level rise this century.

Keywords: sea level rise, high end projections, climate change

1. Introduction

With more than 600 million people living in the low elevation coastal areas less than 10 m above sea level (McGranahan *et al* 2007), and around 150 million people living within 1 m of high tide (Lichter *et al* 2011) future sea level rise is one of the most damaging aspects of warming climate (Anthoff *et al* 2009, Hallegatte *et al* 2013). The latest Intergovernmental Panel on Climate Change report (AR5 IPCC) noted that a 0.5 m rise in mean sea level will result in a dramatic increase the frequency of high water extremes—by an order of magnitude, or more in some regions (Church *et al* 2013a). Thus the flood threat to the rapidly growing urban populations and associated infrastructure in coastal areas are major concerns for society (Hallegatte *et al* 2013, Hinkel *et al* 2014). Hence, impact assessment, risk management, adaptation strategy and long-term decision making in coastal areas depend on projections of mean sea level and crucially its low probability, high impact, upper range (Nicholls *et al* 2014).

Subsequently, many nations, cities and regions have developed coastal protection plans and guidance on sea level rise scenarios, including a low probability high impact or worse case scenario, for use in contingency planning and for consideration of the limits of potential adaptations. The Delta Commission in the Netherlands has used projected sea level of 1.1 m as a 'high-end' scenario (Vellinga *et al* 2008). The Scientific Committee on Antarctic Research (SCAR) suggested up to 1.4 m sea level projections by 2100 (Scientific Committee on Antarctic Research 2009) and the Arctic Monitoring and Assessment Programme (AMAP) considered 1.6 m in its latest report (Arctic Monitoring and Assessment Program (AMAP) 2012). The US Army Corps of Engineers used a 1.5 m rise by 2100 as a 'high' scenario for planning civil works programmes (US Army Corps of Engineers 2011), with sea level rise up to 2 m used in US National Climate Assessment (NOAA Technical Report OAR CPO-1 2012) and 1.9 m considered in the United Kingdom Climate Impacts Programme (UKCIP) (Lowe *et al* 2009).

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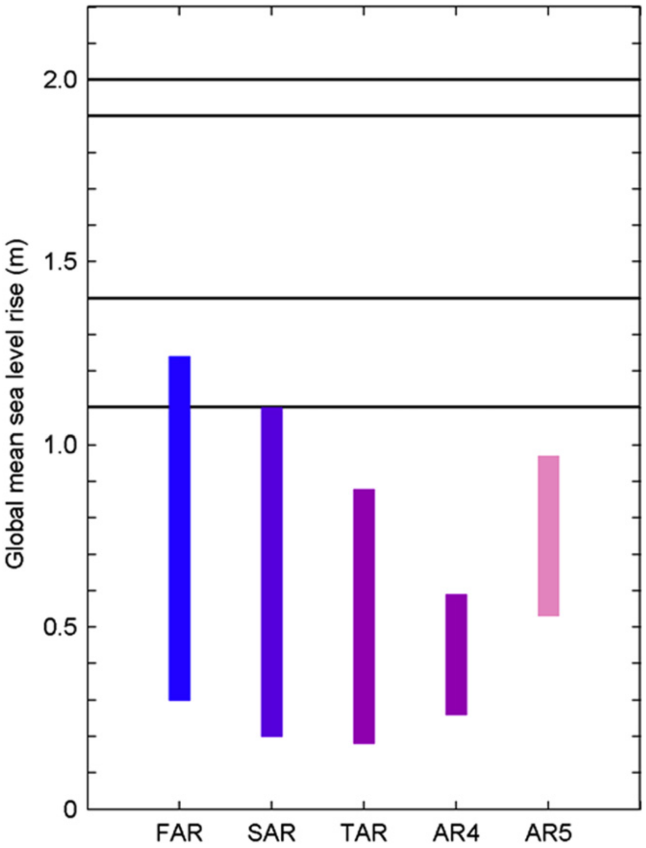

Figure 1. The range of global mean sea level projections with different high emission scenarios by 2100 from five IPCC reports (bars): a scenario from FAR; IS92e scenario from SAR; A1FI SRES from TAR and AR4 (contribution from ice sheet dynamics is not included in AR4 projection), RCP8.5 from the AR5. Black horizontal lines represent the low probability high impact range scenarios used in the national planning from alternative methods to estimate possible sea level rise (1.1 m is the Delta Commission, 1.4 m is SCAR; 1.9 m is H++ scenario in UKCIP; 2 m is NOAA).

These high-end estimates used as worst-case scenarios in national planning come from several alternative methods of estimating sea level rise. Scenario H ++ (1.9 m) in UKCP09 is based on paleo information on sea level rise (Lowe *et al* 2009). A wide range of simulations from semi-empirical models (SEMs) (Rahmstorf 2007, Grinsted *et al* 2010, Jevrejeva *et al* 2012a), and consideration of kinematic limits on ice throughput from land to ocean (Pfeffer *et al* 2008, Katsman *et al* 2011) have also been used as upper bounds. The upper limit scenarios are an essential tool for scientists, engineers and policy analysts tasked with designing responses and adaptation strategy to sea level rise.

Since 1990 each of the IPCC reports have produced a wide range of projections for sea level at the year 2100 with high-end greenhouse gas emission scenarios (figure 1) producing sea level rises ranging from 0.59 m in the Fourth Assessment Report (AR4) (Meehl *et al* 2007) to 1.24 m in the First Assessment Report (FAR) (Houghton *et al* 1990, Houghton *et al* 1996). Some of the differences in these high end sea level projections may be attributed to the changing emission scenarios used in each report. Several centimetres of variation can be explained by the different reference periods chosen. Larger differences come from the components of the sea level budget included in each report. For example, the 0.59 m rise projected under the Special Report on Emissions Scenarios (SRES) A1FI, scenario in AR4 does not include the contribution of ice sheet dynamics in Greenland and Antarctica, which the report explicitly stated could contribute up to a further 0.20 m (Meehl *et al* 2007).

In all five IPCC reports sea level projections have been assembled using the conventional method of estimating sea level rise—by simulating contributions from individual sea level components, such as thermal expansion, and melting ice from glaciers and ice sheets. The latest AR5 IPCC report (Church *et al* 2013a) provides sea level projections spanning a likely range (66%) and with medium confidence only, implying there is a probability of about 1/3 that sea level rise may lie outside the stated uncertainty ranges (Church *et al* 2013b) largely due to difficulties in projecting ice mass loss from the Greenland and Antarctica ice sheets. The AR5 addresses this issue by suggesting that ‘only the collapse of the marine-based sectors of the Antarctic ice sheet, if initiated, could cause sea level to rise substantially above the likely range during the 21st century. This potential additional contribution cannot be precisely quantified but there is medium confidence that it would not exceed several tenths of a metre of sea level rise’ (Church *et al* 2013a). Therefore the upper bound of 0.98 m given in AR5 for the highest emission Representative Concentration Pathways scenario (RCP8.5) should not be misconstrued as a worst-case projection (Church *et al* 2013b). In this article we attempt to quantify the worst-case projection of sea level rise.

In contrast to the IPCC likely range (66%) estimates of sea level rise, the upper limit or worst-case sea level rise projections, by definition, are low probability estimates, unlikely to be reached, but which at the same time, cannot be ruled out given paleoclimate proxy observations and process-based modelling limitations. The tail of the probability distribution function for future sea level calculated from each of the individually modelled components has not been well-explored meaning that reliable estimates from process-based modelling of the upper limit by 2100 are difficult to provide. Evidence from expert elicitations (Bamber and Aspinall 2013, Horton *et al* 2014) suggests that the uncertainty in model projections is highly skewed towards greater potential sea level rise.

In this paper, we construct a probability density function for global mean sea level rise by the year 2100 and estimate the sea level rise having a less than 5% probability, which we suggest is taken as the upper limit for sea level rise. In addition, we assemble the upper limit for possible sea level rise by 2100 from process based model outputs for individual sea level components. This allows us to assess whether the highest estimates of 1.5–2.0 m published in various national reports can be supported by process-based modelling.

2. Results

2.1. Sea level rise beyond the likely range

The conventional approach to project sea level rise is based on simulation of individual sea level components: contributions from ocean thermal expansion and melting/ dynamics of glaciers and the ice sheets, and then sum them up (Meehl *et al* 2007, Solomon *et al* 2009, Church *et al* 2013a). In our study, we follow this approach by considering projections of the main sea level components:

- Thermal expansion.
- Glacier surface mass balance (SMB).
- Greenland SMB and dynamical changes.
- Antarctica SMB and dynamical changes.
- Changes in land water storage.

The main challenge in providing the upper limit (taken as having only 5% likelihood of being exceeded) for sea level rise by 2100 is to quantify the uncertainty beyond the likely range of sea level projections. The lack of robust simulations of the ice sheet contribution to global sea level rise from process based models led to only a likely range (66%) and with medium confidence being given for sea level projections in the recently released AR5 IPCC report (Church *et al* 2013a). This range leaves roughly a 30% chance of sea level rise being outside the stated uncertainty ranges (Church *et al* 2013b). Thus, the IPCC projections did not exclude the possibility of higher sea levels; AR5 concluded that 'sea levels substantially higher than the 'likely' range would only occur in the 21st century if the sections of the Antarctic ice sheet that have bases below sea level were to collapse' (Church *et al* 2013b). Post-AR5 modelling indicates that Pine Island Glacier in West Antarctica is probably already engaged in an unstable retreat (Favier *et al* 2014), a situation that is projected to extend to the neighbouring Thwaites glacier (Joughin *et al* 2014) and also to the Totten and other glaciers in East Antarctica (Sun *et al* 2014). Over the 21st century the sea level rise contributions from these glaciers are well within the 'likely' range of the AR5 estimate, with ice loss rates increase over the century, consistent with observations that show a widespread and sustained increase in discharge in the Amundsen Sea sector (Mouginot *et al* 2014, Rignot *et al* 2014).

To explore the uncertainties in sea level projections beyond the likely range, we blend the approach from AR5 IPCC report (Church *et al* 2013a) with expert assessment of Greenland and Antarctica ice sheet contributions. The expert elicitation approach has been widely used in various social science and economic impact assessments for many years, for example in the Dynamic Integrated Climate-Economy (DICE) climate change damage model by Nordhaus and Boyer (1999), but has not been widely used in the physical sciences. We regard expert judgement as a useful tool to assess the uncertainty ranges, because the ice sheet experts know which physical processes (e.g. calving, ice sheet-ocean interaction) are insufficiently represented in their ice sheet models. Hence, the expert solicitation is able to explore regions of known ignorance which are traditionally neglected in published process model results (Oppenheimer *et al* 2008). In the case of ice sheet dynamics, (Little *et al* 2013) suggest 'In the absence of robust data or appropriate models, collapse probabilities may be assessed using formalized expert elicitation (Bamber and Aspinall 2013)'. The Bamber and Aspinall (2013) study has been used to derive the uncertainty range of the rate of mass loss from each ice sheet at 2100, and to determine the degree of consensus about these uncertainties within the ice sheet expert community. We do not claim that this is complete or perfect, but this is a source for the uncertainty estimate, and it gives an opportunity to explore the uncertainties in the contribution from ice sheets, which are simply not available from other sources. The advantage of using Bamber and Aspinall (2013) is that we may escape the problem of 'single study syndrome' or having to assess the relative merits of different studies. Bamber and Aspinall (2013) quantify the expert community uncertainty at that time. We acknowledge that this may have changed since its publication. For example, it is quite possible that the recent series of studies of the Amundsen Sea Sector and West Antarctic ice sheet collapse will alter expert opinion.

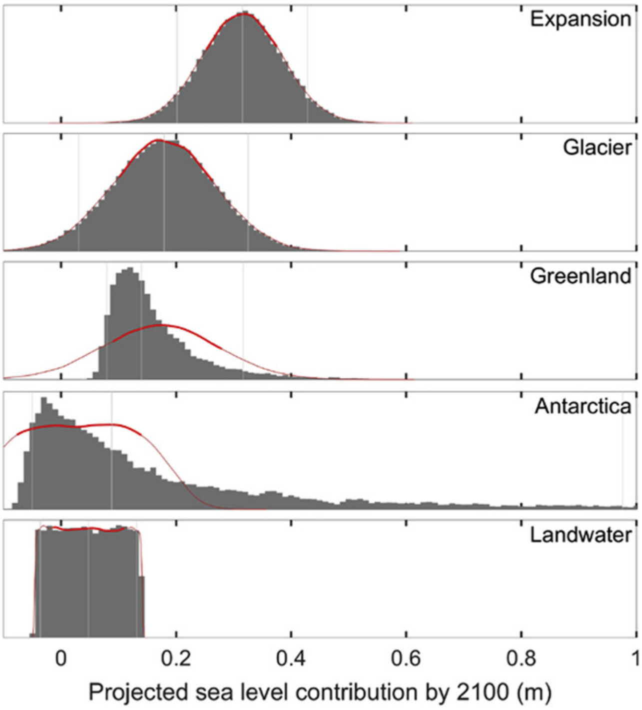

Figure 2. Projected component of global sea level rise by 2100 relative to 2000 and their uncertainty. Vertical light grey bars indicate the 5, 50 and 95th percentiles in the uncertainty distribution. Dark grey bars represent projected sea level components calculated in this study. Thick red lines show the likely range of the sea level contributions from the AR5 and red thin lines are our fit to the AR5 distribution assuming symmetric tails.

From the AR5 uncertainty distribution of each individual sea level component, that is thermal expansion, melting of glaciers, water land storage and ice sheets we draw samples using a Monte Carlo method. We reproduce the AR5 projection uncertainty ranges using uniformly distributed

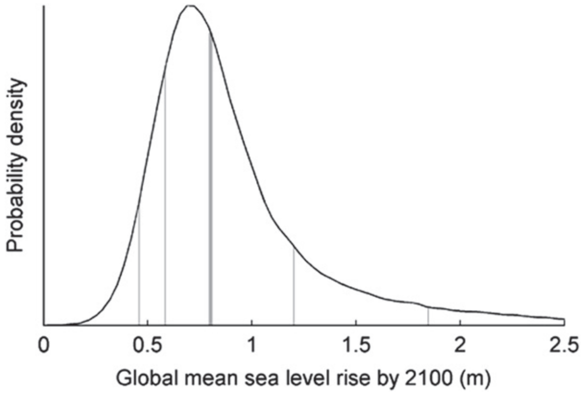

Figure 3. Projected global mean sea level rise by 2100 relative to 2000 for the RCP8.5 scenario and uncertainty. Vertical grey bars indicate the 5, 17, 50, 83, and 95th percentiles in the uncertainty distribution.

uncertainties for the contributions from land water storage and ice sheets, and a multivariate normal distribution for the thermal expansion and glaciers (figure 2, red lines). The uncertainty covariance structure is fitted to be consistent with the AR5 likely ranges for each individual contributor and their sum (Church *et al* 2013a). We emphasize that AR5 did not specify the shape of the uncertainty distribution and explicitly stated that sea level rise beyond the likely range is poorly constrained and considerably larger increases are possible.

From AR5 we adopt the uncertainty distributions for the thermal expansion, glaciers and water land storage. However, we replaced the AR5 projection uncertainties for both ice sheets with probability distribution function calculated from the collective view of thirteen ice sheet experts (Bamber and Aspinall 2013). The ice sheet expert elicitation allows construction of the covariance and shape of the uncertainty distribution of the rate of each ice sheet mass loss in 2100 (Bamber and Aspinall 2013), which we Monte Carlo sample to obtain the rate of mass loss by Antarctica and Greenland in 2100. We calculate the net sea level rise by integrating ice sheet mass loss rate assuming a linear increase in these rates from their present day values taken from the comprehensive review of Shepherd *et al* (2012). Figure 2 panels for Greenland and Antarctica, show the difference in probability distributions from the approach in this study (grey colour), the AR5 likely range (red thick line), and our symmetric fit to the AR5 projections (red thin line). In particular, there is a large difference in the shape of the uncertainty distribution for the Antarctic ice sheet, with a long skewed fat-tail at the high rise end of the distribution.

We combine the uncertainty distributions for each component (figure 2) and construct the probability distribution function for global sea level rise by 2100 (figure 3). This combined distribution has a fat-tail. Roe and Baker (2007) suggest that such a distribution is a ubiquitous, and inevitable feature of the climate system (or at least how we observe it). The AR5 ice sheet contribution to sea level rise is almost climate-scenario independent, suggesting the same amount of ice loss with, for example a global mean temperature rise of 2 °C or 4 °C. By using the probability distribution functions for ice sheets from Bamber and Aspinall (2013), we acknowledge and accommodate the collective view of the thirteen ice sheet experts that mass loss during the 21st century more than doubles with temperature increasing from 2 °C to 4 °C (Bamber and Aspinall 2013).

We estimate an upper limit of 180 cm for the global sea level rise with probability of 5%; the median (50%) in our probability distribution function is 80 cm, which is close to the median of 73 cm in AR5. An important caveat of our approach utilizing results based on expert opinion is that predictions by experts are often overconfident (Capen 1976). Therefore we ask the question: could we support our upper limit estimate of 180 cm by the results from process based model simulations?

2.2. High end estimates of sea level rise from process based model simulations

In table 1 we present the highest estimates of projected sea level components from the latest publications with projections driven by the RCP8.5 scenario, which is the highest radiative forcing used by AR5. Current climate models are in reasonably good agreement on predicting ocean thermal expansion (Yin 2012, Church *et al* 2013a), with a thermosteric sea level for RCP8.5 scenario calculated from 34 models of 32 cm, with 5–95% range of 25–39 cm (Church *et al* 2013a; AR5 supplementary material, datafiles for chapter 13, www.climatechange2013.org/report/full-report/).

A recent development in glacier modelling has been the compilation of the Randolph Glacier Inventory (RGI), which covers the entire world for the first time (Arendt *et al* 2012). Here we consider only projections of the contribution from glaciers to sea level rise published since the RGI has been available. The model by Marzeion *et al* (2012) is the most temperature sensitive of the glacier projections and results in more ice loss than simulations from Radic *et al* (2013) or Giesen and Oerlemans (2013). However, the projections in Marzeion *et al* (2012) do not include ice loss from relatively small glaciers fringing the Antarctic periphery, which could increase contribution by variously 14%, 23%, 18%, or 22% as estimated by Giesen and Oerlemans (2013), Radic *et al* (2013), Slangen and van de Wal (2011), and Radic and Hock (2011) respectively. For our upper limit estimate we use a contribution of 35 cm calculated from the largest projection of 28 cm from Marzeion *et al* (2012) adjusted for a 20% missing Antarctic fraction (see table 1). However, the glacier models do not adequately account for several processes, particularly calving (Cogley 2009, Jevrejeva *et al* (2012b), Moore *et al* 2013). As a check on the process models we can also estimate dynamical changes with a different rough and ready approach: the total area of glacier basins (excluding the Greenland and Antarctic ice sheets) draining through marine outlets is about 280 000 km^2 (Gardner *et al* 2013). If we assume a basin thinning rate in all these marine outlets of 5 m yr^{-1}, the same as rate of the ice loss for Columbia Glacier since 1982 (Rasmussen *et al* 2011), then at most 30 cm would

Table 1. The highest estimates of projected sea level components by 2100 relative to 2000 with RCP8.5 scenario (or other high end scenario, or scenario independent estimate described under 'comments').

Contributors	AR5 RCP8.5 likely range (cm)	Highest estimate (cm)	Comments
Thermal expansion (T), (Yin 2012)	25–39	39	CMIP5, 34 AOGCMs
Glaciers, SMB (GSMB), (Marzeion *et al* 2012)	10–26	35	SMB only, no ice dynamics, (adjusted for a 20% missing Antarctic fraction, see text)
Greenland SMB (GrSMB) (Fettweis *et al* 2013)	4–22	20	
Greenland dynamics (GrD), (Bindschandler *et al* 2013)	2–9	44*	High end scenario, SMB is excluded (see text)
Antarctica SMB (ASMB), (Church *et al* 2013a)	−9–−2	−2	
Antarctica dynamics (AD), (Hinkel *et al* 2014)	−2–19	41	High land ice scenario, four models
Land water (LW), (Church *et al* 2013a)	−1–11	11	Scenario independent

Note: * Estimate of 44 cm (66–22 = 44 cm) calculated as a difference between the total contribution from Greenland ice sheet (SMB+ice dynamics, Bindschandler *et al* (2012)) of 66 cm and 22 cm of SMB taking from AR5 (Church *et al* 2013a, AR5 supplementary material, datafiles for chapter 13, www.climatechange2013.org/report/full-report/).

be added to global sea level by 2100. This is a very extreme possibility, if only 30% of these marine outlets will lose ice mass due to dynamical changes, then 10 cm may be added. This estimate is far too crude to use as a quantified estimate, it simply illustrates the range that glacier calving may contribute to sea level. We do not add any such contribution to our estimate of the upper limit from process based model simulations.

Greenland ice sheet SMB has been modelled with the regional climate model (Modèle Atmosphérique Régional, (MAR)) by Fettweis *et al* (2013), which suggests that SMB is strongly correlated with global mean surface warming. An upper limit of 20 cm for Greenland SMB was calculated using the range of projected global surface temperatures under the RCP8.5 scenario (Fettweis *et al* 2013), we adopt the upper bound of 22 cm from IPCC AR5 (Church *et al* 2013a, AR5 supplementary material, datafiles for chapter 13, www.climatechange2013.org/report/full-report/). For Antarctica simulations suggest that increased snow fall in warming climates dominates rising melt water run-off, therefore SMB contributes negatively to global sea level rise over the 21st century (Ligtenberg *et al* 2013). We adopt the upper bound of −2 cm from IPCC AR5 (Church *et al* 2013a, AR5 supplementary material, datafiles for chapter 13, www.climatechange2013.org/report/full-report/), as there appears to be no support from the current generation regional climate modelling for larger contributions (Ligtenberg *et al* 2013).

Greenland and Antarctica ice sheets also contribute to sea level via the dynamic discharge of ice into the ocean. Several studies show that this dynamic discharge can respond to changes in climate (Hellmer *et al* 2012, Bindschadler *et al* 2013, Hinkel *et al* 2014). However, the coupling between the ice sheet dynamics and climate is a challenging task (Moore *et al* 2013). This is illustrated by the almost constant projections for the ice sheet dynamical contribution in the latest AR5 IPCC (Church *et al* 2013a). Bindschadler *et al* (2013) forced an ensemble of ice sheet models with a bespoke 'R8' scenario intended as an approximation to the RCP8.5, which included imposed changes in ice-shelf basal melting and ice sheet basal sliding. The average contribution from Greenland was 22 cm and the largest was 66 cm, however, these estimates included the SMB contribution as well, which may be up to 22 cm (Church *et al* 2013a, AR5 supplementary material, datafiles for chapter 13, www.climatechange2013.org/report/full-report/). Therefore we use 44 cm as the ice dynamics contribution from Greenland in table 1. For Antarctica the largest dynamical contribution from ice sheet is 41 cm, as reported in recently published estimates from four models forced with RCP8.5 (Hinkel *et al* 2014). These ice dynamics estimates are far beyond the IPCC likely range (see table 1).

The sum from the sea level component projections by 2100 in table 1, obtained as the highest estimates from process based models with high emission scenarios, $(39^{T} + 35^{GSMB} + 22^{GrSMB} + 44^{GrD} - 2^{ASMB} + 41^{AD} + 11^{LW})$ is 190 cm. These simple calculations demonstrate that using the highest estimates from process based models for individual sea level components (largely published after the AR5 and Bamber and Aspinall 2013), provides support for the upper limit of sea level projection by 2100 of 180 cm, estimated from the probability analysis in section 2.1.

3. Uncertainties in upper limit estimates

3.1. Uncertainties associated with emission scenarios

There are several sources of uncertainties in upper limit of sea level projections. The first key uncertainty is high emission scenario itself, in which the implications of anthropogenic and natural climate change for environment and society depend not only on the response of the Earth system to radiative forcing, but also on the potential responses by humans through changes in economies, technology, policy and lifestyle, which are largely unknown and therefore impose large uncertainties. In addition, climate models have many other uncertainties: climate sensitivity to radiative forcing, complex feedbacks, large internal climate variability and the parameterization of many processes. Alternative approaches, such as kinematic limits (Pfeffer *et al* 2008, Katsman *et al* 2011) provide scenario independent assessment of maximum physically plausible contributions from ice sheets, glaciers and thermal expansion.

3.2. Uncertainties in ice sheet contribution to future sea level rise

As we have seen, the crucial question for sea level rise in the twenty-first century is how much ice will be lost from the Greenland and Antarctic ice sheets as a result of rapid accelerations in ice dynamics. Huge progress has been made in understanding of ice dynamics (Moore *et al* 2013, Church *et al* 2013a), ice stream flow (Bougamont *et al* 2011), grounding line migration (Schoof 2011, Docquier *et al* 2012, *Drouet et al* 2012) and integration of ice sheet models with high-resolution climate models (Cornford *et al* 2013). However, currently there is only limited number of model simulations of ice sheet contributions with RCP-like scenarios (Bindschadler *et al* 2013, Nick *et al* 2013). The role of ice-sheet ocean interaction is one the main challenges for the ice sheet modelling community. Lack of scenario dependent ice sheet model runs impose difficulties in exploring the ranges of uncertainties in potential contributions from ice sheets and the alternative approach suggested by Bamber and Aspinall (2013) illustrates the magnitude of uncertainties in ice sheet mass loss projections by 2100. In fact, ice sheet experts suggest possible contributions from both ice sheets exceeding 84 cm at 5% probability by 2100 (Bamber and Aspinall 2013). This number is consistent with our estimate of highest contribution from ice sheets (table 1).

3.3. Use of SEMs to explore the range of uncertainties

SEMs have been developed to make projections of sea level rise since 2007. Instead of projecting individual components of sea level separately SEMs consider changes in global sea level as an integrated response of the entire climate system to changes in temperature (Rahmstorf 2007, Vermeer and Rahmstorf 2009, Grinsted *et al* 2010) or radiative forcing (Jevrejeva *et al* 2010). Projections by SEMs are based on the assumption that sea level in the next 100 years will respond as it has in the past 100–300 years (Vermeer and Rahmstorf 2009, Grinsted *et al* 2010, Jevrejeva *et al* 2010) or even 1000 years (Rahmstorf *et al* 2012), to imposed climate forcing. This may not hold in the future if potentially nonlinear physical processes, such as marine ice-sheet instability or thermal expansion do not scale in the future as they have in the past. However, SEMs by design generate millions of potential sea level projections with model parameters selected randomly from amongst their distributions, exploring a wide range of sea level projections and generating 5–95% confidence intervals from the millions possible realizations. For example, the response time parameter varies from 10–5000 years in sea level simulations by 2100 (Jevrejeva *et al* 2012a). This range of response times spans the typical time constants of the main sea level reservoirs, representing the responses of small glaciers, thermal expansion of the ocean, and ice-sheet response to changes in radiative forcing given by the RCP scenarios which can be used to provide upper and low limits for sea level projections at the year 2100. The most sensitive SEMs give upper bound of 160 cm (Church *et al* 2013a, Rahmstorf *et al* 2012, Grinsted *et al* 2010), providing good agreement with the probabilistic upper limit of 180 cm (section 2.1) and 190 cm from process based model outputs (section 2.2).

4. Conclusion

We constructed the probability density function for global sea level rise at 2100 and calculate that a rise of 180 cm has only a 5% probability of being exceeded. This estimate is supported by the 190 cm of sea level rise calculated using the high end estimates from process based models for individual sea level components forced by the RCP8.5 scenario (table 1). Large contributions from the Antarctic (41 cm) and Greenland (46 cm) ice sheets simulated by process based models (Bindschadler *et al* 2013, Hinkel *et al* 2014) and published after the expert elicitation study of Bamber and Aspinall (2013) are consistent with the expert opinion of an 84 cm contribution from ice sheets. The largest uncertainties in sea level projections are due to the limited number of ice sheet models able to drive changes in ice sheet dynamics with climate forcing (Moore *et al* 2013, Church *et al* 2013a, Bindschadler *et al* 2013, Nick *et al* 2013, Hinkel *et al* 2014). Nevertheless, there is evidence that ice shelves in West Antarctica are not stable but are thinning rapidly (Pritchard *et al* 2012), and that the large outlet glaciers that drain the West Antarctic ice sheet have been accelerating in recent decades, most likely as a result of increased melting of their ice-shelf termini by warm Circumpolar Deep Water (Steig *et al* 2012).

In this paper we suggest that there is a 95% chance that mean sea levels will not exceed 180 cm above those at present. This will vary regionally due to various factors such as: (1) groundwater depletion causing local subsidence (an acute problem in some cities such as Bangkok); (2) glacial isostatic rebound leading to some cities rising above mean sea level (such as Stockholm); (3) regional sea level disparity due to preferential melt of Greenland or Antarctic ice sheets and the self-gravitational effect (Church *et al* 2013a). Assessing how to deal with the impact and costs of sea level rise poses serious structural issues in economic cost-benefit analysis (Weitzman 2009), but widely used assumption is of a quadratic function for climate change impacts (Nordhaus 2008, Weitzman 2010). The annual damage costs for the European Union with sea level rise of 1.4 m by 2100 are projected to be six times greater than for the rise of 0.6 m with A1B climate scenario (Brown *et al* 2011). However, Weitzman (2009), in his ‘Dismal theorem’ shows that if the rate of decay of the probability tail of the climate impact function is polynomial while the cost of damage rises exponentially, then the cost-benefit function does not converge and no cost of mitigation is too high to justify. As financial infrastructure is being concentrated at faster rates in urban areas than in countries as a whole (Anthoff *et al* 2009), and since the majority of large cities are located along coastlines, the implications for planning of the Dismal theorem should be considered in addition to the 5% high end estimate we provide. Sea level rise also damages agricultural land and taints sweet water supplies, both of which are essential to maintain quality of city life, and the net economic impact from high end sea level rise results from all these damage functions. Large scale human migration is tending to create dense coastal urban settlements, especially in the developing world. Potential over-concentration of people and resources in coastal zones at risk from flooding may reverse this trend, or at least cause planners to consider relocating infrastructure to higher, inland, regions. In countries where this is not possible, increased cross-border migration pressure will be inevitable.

The upper limit of 180 cm reflects our view of the present understanding of the uncertainties in Greenland and Antarctica ice loss. This is a very active field, and the focus on ice sheet dynamics is increasing, although the size and number of modelling groups are still tiny compared with Earth System Model centres. Ice dynamics uncertainty is likely to be reduced if a broader and more diverse group prioritizes the research. For example, a key issue is that the calving of icebergs into the sea and the collapse of ice shelves are intrinsically discrete events with timescales on the order of seconds and fractures propagate near the speed of sound, while typical ice flow is of the order of metres per year. These problems require novel approaches such as statistical parameterizations based on ideas from quantum physics (Bassis 2011) or numerical models adapted from studies of brittle media (Åström *et al* 2013). While these, and other approaches mature, better flood risk and adaptation planning may come from using expert elicitation to map the full uncertainty distribution.

It is clear from the wide range of nationally and locally-adopted maximum rises that engineers and planners find it difficult to choose appropriate extremes for sea level rise, and we hope that our approach in this paper can help towards a methodology in this regard. Although uncertainties are large now, they will be revised (higher or lower) in future as models develop. It is however certain that sea level rise will continue beyond 2100, and this timescale is of importance in coastal adaptation and mitigation planning. The speed of rise and the absolute rise at any given date are related views of the same phenomenon. A sea level rise with only a 5% probability at the year 2100 is far more likely to have occurred by the year 2200 because of the centennial-scale response times of the ice-ocean system.

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