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Viewpoint

Expert assessment of sea-level rise by AD 2100 and AD 2300

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ABSTRACT

Large uncertainty surrounds projections of global sea-level rise, resulting from uncertainty about future warming and an incomplete understanding of the complex processes and feedback mechanisms that cause sea level to rise. Consequently, existing models produce widely differing predictions of sea-level rise even for the same temperature scenario. Here we present results of a broad survey of 90 experts who were amongst the most active scientific publishers on the topic of sea level in recent years. They provided a probabilistic assessment of sea-level rise by AD 2100 and AD 2300 under two contrasting temperature scenarios. For the low scenario, which limits warming to <2 °C above pre-industrial temperature and has slowly falling temperature after AD 2050, the median 'likely' range provided by the experts is 0.4–0.6 m by AD 2100 and 0.6–1.0 m by AD 2300, suggesting a good chance to limit future sea-level rise to <1.0 m if climate mitigation measures are successfully implemented. In contrast, for the high warming scenario (4.5 °C by AD 2100 and 8 °C in AD 2300) the median likely ranges are 0.7–1.2 m by AD 2100 and 2.0–3.0 m by AD 2300, calling into question the future survival of some coastal cities and low-lying island nations.

1. Introduction

Beginning in the late 19th or early 20th century, the rate of global sea-level rise increased sharply above the relatively stable background rates of the previous ~2000 years (e.g. Church and White, 2006; Engelhart et al., 2009; Church and White, 2011; Gehrels and Woodworth, 2012; IPCC, 2013). This onset of modern sea-level rise coincided with increasing global temperature (e.g. Kemp et al., 2011). While there is widespread agreement that the rate of sea-level rise will continue to increase during the 21st century, great uncertainty surrounds its future magnitude. The Intergovernmental Panel on Climate Change's (IPCC) Fifth Assessment Report (AR5) projected global sea-level rise to AD 2100 forced by different emission scenarios (IPCC, 2013). Projected sea-level rise under each scenario is the sum of individual contributions from steric changes and melting of glaciers and ice caps, the Greenland Ice Sheet, the Antarctic Ice Sheet, and land water storage. These projections are derived from process-based models and assessment of glacier and ice sheet contributions. The IPCC AR5 projected a 'likely' (i.e. 66% likelihood range) global-average sea-level rise of 28–61 cm for a scenario of drastic emissions reductions (RCP 2.6) and 52–98 cm in case of unmitigated growth of emissions (RCP 8.5) by AD 2100 (relative to AD 1986–2005). This marks a substantial upward revision (~60%) compared to the IPCC 4th assessment report published in 2007. The process-based models used in the 4th report substantially underestimated the observed past sea-level rise (Rahmstorf et al., 2007, 2012a).

Process-based predictions of sea-level rise are limited by uncertainties surrounding the response of the Greenland and West Antarctic ice sheets (Pfeffer et al., 2008; Rignot et al., 2011; Pritchard et al., 2012), steric changes (Domingues et al., 2008; Marcelja, 2010), contributions from mountain glaciers (Raper and Braithwaite, 2009), as well as from groundwater pumping for irrigation purposes and storage of water in reservoirs (Konikow, 2011; Pokhrel et al., 2012; Wada et al., 2012). In large part because of the limitations of physical process-based models, IPCC AR5 does not offer "very likely" (90% likelihood range) sea-level projections, but concluded that "*there is currently insufficient evidence to evaluate the probability of specific levels above the assessed likely range*" (Summary for Policy Makers, p. 18).

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Semi-empirical models linking global temperature and sea level provide a complementary approach for estimating future sea-level rise (e.g. Rahmstorf, 2007; Grinsted et al., 2009; Vermeer and Rahmstorf, 2009). Semi-empirical models are calibrated with data from the past to constrain how sea level responded to changing temperatures. Projections are made by driving the model with a scenario of future warming. They are robust to the choice of input data and statistical technique (Rahmstorf et al., 2012b) and successfully predicted the out-of-sample 20th century sea-level rise when calibrated with data up to AD 1900 (Bittermann et al., 2013). However, it is unknown if the historic relationship between sea-level rise and temperature will continue to hold in the future (Rahmstorf, 2010). Semi-empirical models predict a larger sea-level rise than the IPCC AR5 by AD 2100 under the same scenario of future temperature rise.

The wide range of sea-level projections from process-based and semi-empirical models is reflected in recent assessments of sea-level rise. By AD 2100 the 2009 Antarctic Science Report anticipated up to 1.4 m (Turner et al., 2009), the 2011 Arctic Monitoring and Assessment Program 0.9–1.6 m (AMAP, 2012), the 2012 U.S. National Research Council report 0.5–1.4 m (NRC, 2012), and the 2012 World Bank Climate Report 0.27–1.23 m (World Bank, 2012), although there are some differences in the underlying scenario assumptions and exact time intervals used. Most recently, sea-level scenarios prepared by the National Oceanic and Atmospheric Administration (NOAA) for the U.S. National Climate Assessment projected a mid-range of 0.5–1.2 m, with plausible lower and upper limits of 0.2 m and 2.0 m (Parris et al., 2012). Assessments like the ones cited may be affected by cultural and institutional processes (Oppenheimer et al., 2007; O'Reilly et al., 2012; Brysse et al., 2013).

As our modeling capacity is immature and different modeling approaches yield conflicting results (an issue known as structural model uncertainty; O'Reilly et al., 2011), expert elicitation is a useful approach to gauge the range of views held in the scientific community (Cooke, 1991; National Research Council, 1994; Arkes et al., 1997; USEPA, 2011). Expert elicitations yield no new scientific results, but they make the views of scientists transparent to a wider public, which is important in situations where policy decisions (e.g. coastal planning and hazard mitigation) must be taken based on the limited (and sometimes conflicting) scientific information available (Dewispelare et al., 1995). Such elicitations are also a valuable tool for quantifying uncertainty (Arkes et al., 1997; USEPA, 2011). The Inter Academy Council (2010), in its review for the United Nations on the process and procedures of the IPCC, therefore recommended that "*Where practical, formal expert elicitation procedures should be used to obtain subjective probabilities for key results*" (p. 41). Whereas the IPCC did not include an expert elicitation on sea-level rise in AR5, we present one here.

Expert elicitations can be divided into "deep" and "broad" types (National Research Council, 1994). A "deep" elicitation compiles the views of a small number of experts in considerable detail (e.g. Morgan and Keith, 1995; Cooke and Goossens, 2004; Zickfeld et al., 2007; Bamber and Aspinall, 2013). In contrast, a "broad" elicitation asks a large number of experts a small number of questions, aiming for wide participation by minimizing the required time investment for participation (e.g. Keeney and von Winterfeldt, 1991; Hoffmann et al., 2006; Wardekker et al., 2010). Broad elicitations are appropriate for interdisciplinary problems that involve large uncertainties (Hoffmann et al., 2006) like sea-level prediction. Such an elicitation asks carefully phrased questions that prompt a subjective (Bayesian) probability assessment from the respondent, since statements about uncertain issues cannot by definition be made with certainty (USEPA, 2011; Knol et al., 2010). Therefore, responses reflect the degree of uncertainty perceived by the experts (Clemen and Winkler, 1999). Here, we report the results from an anonymous, broad elicitation to determine the professional judgments from members of the scientific community about global sea-level rise for the periods AD 2000–2100 and AD 2000–2300.

2. Materials and methods

A key element of an expert elicitation is the choice of experts (e.g. USEPA, 2011; Knol et al., 2010). We objectively selected sea-level experts identified from the peer-reviewed literature using the scientific publication database Web of Science of Thompson Reuters. We searched (on the 19th September 2012) for all papers in peer-reviewed journals on the index term "sea level" published since AD 2007 to identify the 500 scientists who (co-)authored the greatest number of these papers. Thus, we obtained a sample of 500 experts that arguably includes the most active scientific publishers on the subject of sea level and all of whom had published at least six peer-reviewed on "sea level" since AD 2007. We found e-mail addresses for 360 of these experts and accordingly sent out invitations to participate in the survey on 16th November 2012, with a unique identifier to ensure anonymity and avoid duplicate responses. Of those invited, 36% (131) participated, which is typical for this type of internet-based survey (e.g. Wardekker et al., 2010). The main reason given for declining to participate was a (perceived) lack of expertise in predicting future sea-level rise. We could not analyze 41 responses from participants because they either left all boxes blank or filled with a question mark, or the responses were logically inconsistent (e.g. gave a higher probability for exceeding a 1.0 m sea-level rise than a 0.8 m rise). Not all survey respondents completed every percentile box.

The ninety international sea-level experts provided their probabilistic assessment of global sea-level rise, given two temperature scenarios derived from the upper and lower extremes of the Representative Concentration Pathways (RCPs) scenarios (Meinshausen et al., 2011; Fig. 1). This conditional approach separates uncertainty about future temperature from that about sea-level rise (for the exact phrasing of the questions see Supplementary Note S1). In the RCP 3-PD greenhouse gas scenario there is warming of ∼1 °C from AD 2000 to AD 2060 followed by a

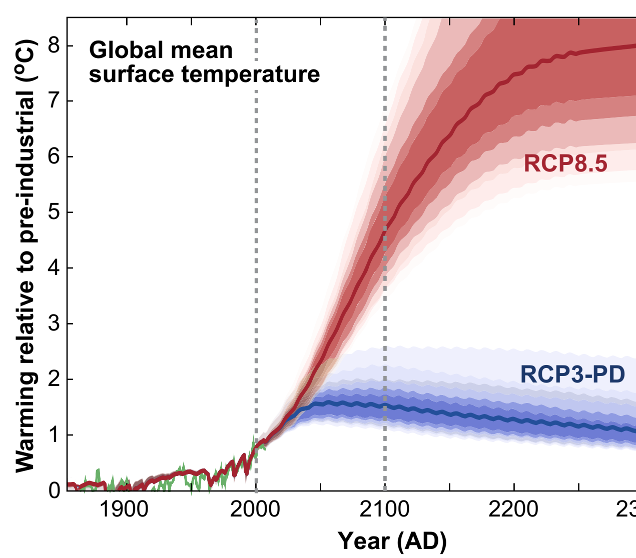

Fig. 1. Scenarios of global temperature changes up to AD 2300. The two scenarios are reproduced from Meinshausen et al. (2011) and were presented to survey participants as basis for their assessment of future sea-level rise. These temperature projections correspond to the lower (RCP3-PD; blue) and upper (RCP8.5; red) greenhouse gas scenarios included in the Representative Concentration Pathways (RCP) and their extension to AD 2300 (Moss et al., 2010; Meinshausen et al., 2011). The thin green line shows observed global temperature.

slow cooling up to AD 2300, with high probability the global temperature stays below the international policy limit of 2 °C above the pre-industrial level throughout. In the RCP 8.5 emission scenario there is warming of 4.5 °C by AD 2100 and a further 3.5 °C during the years AD 2100 to AD 2300.

3. Results and discussion

The experts provided two probability ranges for each case. By definition, sea-level rise is assessed to have a 66% probability to be within the inner range (17th to 83rd percentiles), which thus corresponds to the IPCC's definition of a 'likely' range. With an assessed probability of 90%, sea-level rise will be within the outer range (5th to 95th percentiles), corresponding to the IPCC's definition of a 'very likely' range. Fig. 2 presents box plots of the survey results, and the median 'likely' ranges and 'very likely' ranges across all experts are provided in Table 1. The mean ranges are moderately higher (typically by ~10%) than the median ranges because the distribution is slightly skewed towards higher values. The AD 2100 ranges given by the experts are higher than those projected by the IPCC AR5. IPCC AR5 predicted a 'likely range' of 0.28–0.61 m under RCP 2.6 (numbers for RCP 3.0 are not provided by IPCC, but would be similar) and 0.52–0.98 m under RCP 8.5 by AD 2100. The IPCC AR5 did not provide 'very likely' predictions.

We found no significant correlation between the sea-level ranges given by the experts and their self-reported Hirsch (H) Index (Hirsch, 2005) (a common ranking measure of the scientific publication record; Fig. 3). This is an important test for broad expert surveys, because it can reveal differences among the views of experts with different degrees of expertise, experience, or scientific standing. That we found no correlation is perhaps expected, given that we only invited experts with a strong publication record on sea level. We also looked for a possible effect of the country or region where the experts are based (Fig. 3). The respondents, working in 18 countries, were equally split between North America and Europe (46% each), with only 8% from the rest of the world (Brazil, China, Japan, and Australia). Given the small number of experts from outside North America and Europe, only a comparison between these two regions was justified. North American experts returned slightly greater sea-level rise estimates than their European colleagues in all instances, but the difference was not statistically significant.

Table 1
The median 'likely' ranges and 'very likely' ranges of sea-level rise for AD 2100 and AD 2300 from the expert elicitation.

Year	Scenario	Likely range (m) (17th–83rd percentiles)	Very likely range (m) (5th–95th percentiles)
AD 2100	Lower (RCP 3)	0.4–0.6	0.25–0.7
	Upper (RCP 8.5)	0.7–1.2	0.5–1.5
AD 2300	Lower (RCP 3)	0.6–1.0	0.5–1.2
	Upper (RCP 8.5)	2.0–3.0	1.3–4.0

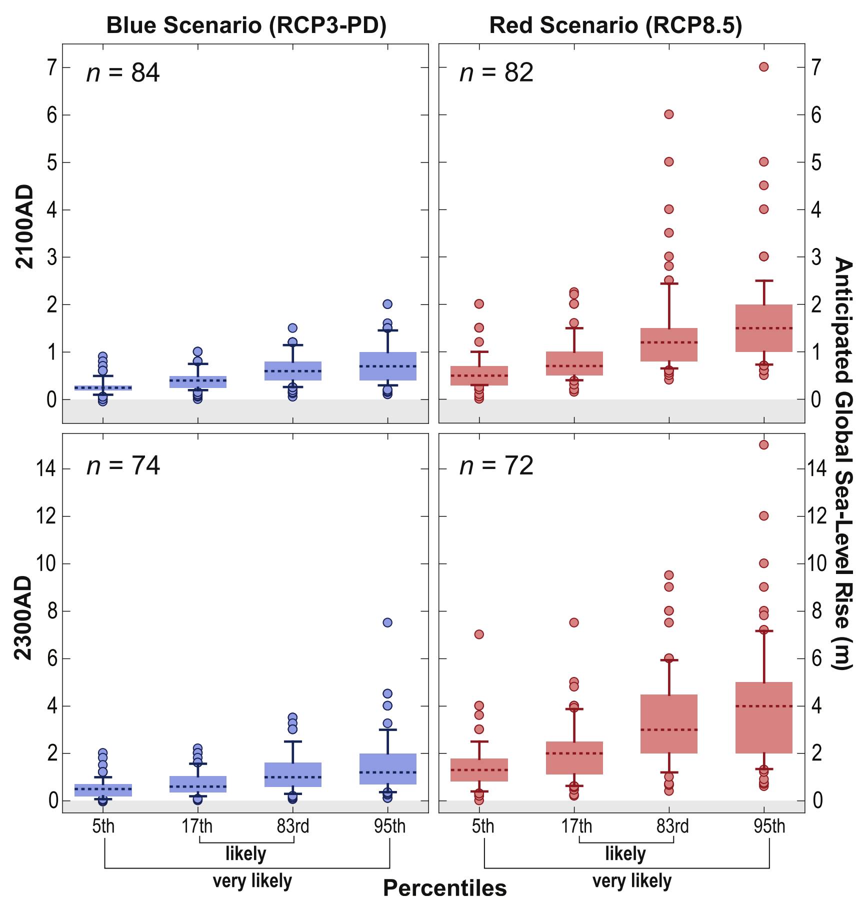

Fig. 2. Box plots of survey results from all experts who provided at least partial responses to questions. The number of respondents for each of the four questions is shown in the top left corner; it is lower than the total of 90 participants since not all answered each question. Participants were asked to estimate likely (17th–83rd percentiles) and very likely (5th–95th percentiles) sea-level rise under two temperature scenarios and at two time points (AD 2100 and AD 2300), resulting in four sets of responses. Shaded boxes represent the range between the first and third quartiles of responses. Dashed horizontal line within the box is the median response. Whiskers (solid lines) represent two standard deviations of the responses. Filled circles show individual responses that are beyond two standard deviations of the median.

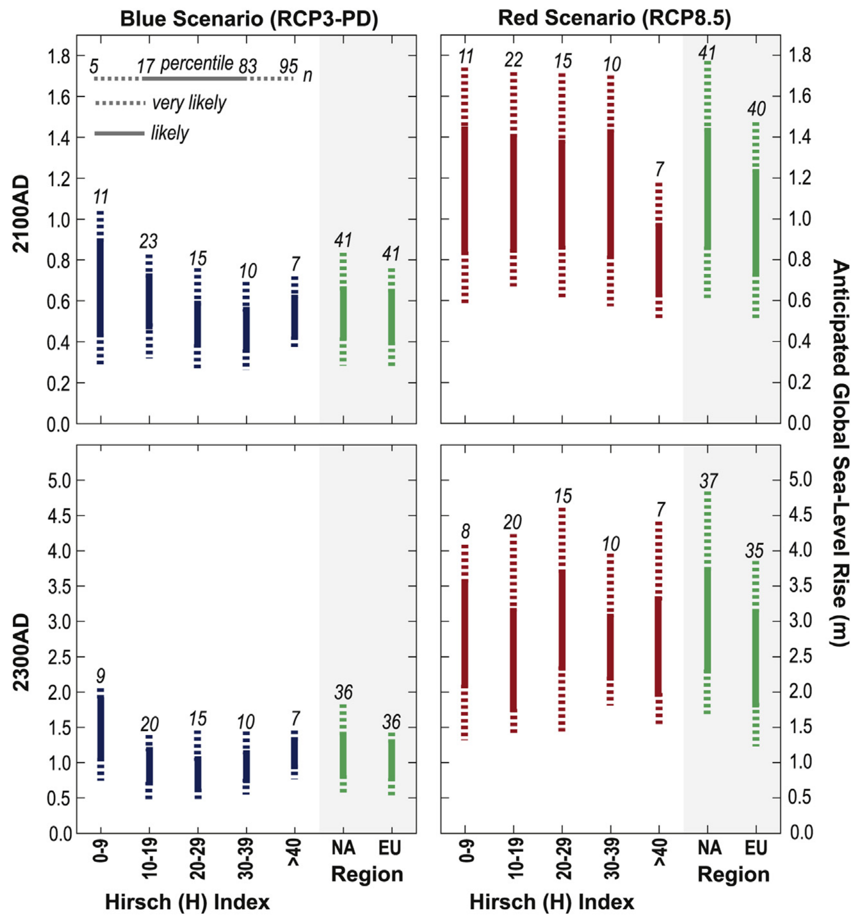

Fig. 3. Survey results from experts who provided at least partial responses to questions stratified by their self-reported Hirsch (H) Index and location (North America; NA or Europe; EU). Dashed lines represent the mean range of values respondents provided for the 5th–95th percentiles (very likely sea-level rise). Solid lines represent the mean range of values provided for the 17th–83rd percentiles (likely sea-level rise). The number of respondents is presented for each case.

We compared sea-level scenarios obtained from this expert elicitation with the recent NOAA scenarios (Parris et al., 2012) and those of the IPCC AR5 (Fig. 4). To add an exemplary time evolution we fitted a quadratic time dependence as was used in the NOAA scenarios. Our survey results are consistent with these scenarios; there is no systematic high or low bias of one relative to the other. NOAA's intermediate-low and intermediate-high scenarios (0.5 m and 1.2 m) are near the mean values of the expert survey for the low and high temperature scenarios. The highest and lowest predictions from NOAA (0.2 m and 2.0 m) are outside of the mean 'very likely' ranges provided by our experts, but within the full range of predictions returned by our experts (Figs. 2 and 4).

The results of our survey are broadly consistent with those of a recent deep elicitation focused on ice sheets (Bamber and Aspinall, 2013) that projected sea-level rise of 0.33–1.32 m by AD 2100 under an intermediate emissions scenario (RCP 4.5). However, our experts estimated a much greater sea-level rise than a deep elicitation published in 1996 (Titus and Narayanan, 1996), which found only a 1% chance of exceeding 1.0 m of sea-level rise by AD 2100 with temperatures increases of up to 4.7 °C, which exceed the warming scenarios used here. This difference likely reflects an evolution of expert opinion over time in light of scientific advances, including new observational data for sea level and ice sheet mass loss, the further evolution of process-based models and development of semi-empirical models. A recent study analyzing the ranges of projected sea-level rise in the scientific literature from AD 1989 to

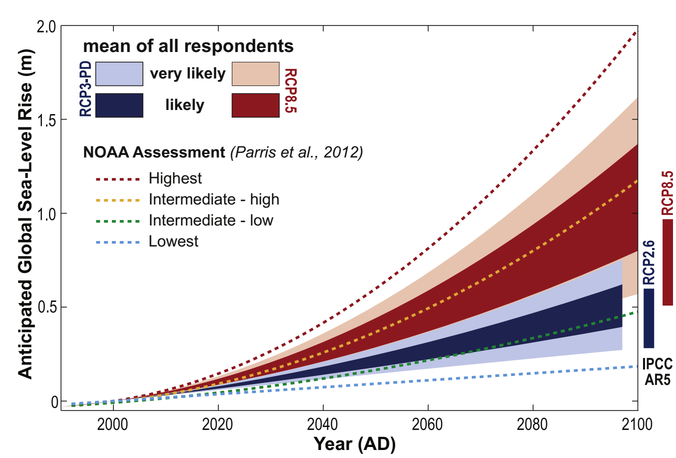

Fig. 4. Scenarios of future sea-level rise generated from survey results for two contrasting temperature scenarios (RCP3-PD; blue and RCP8; red). Shading represents mean likely and very likely ranges. The evolution of sea-level rise from AD 2000 to the respondent estimates for AD 2100 was described by a quadratic time dependence. The current NOAA sea-level scenarios (Parris et al., 2012), published after our survey was conducted, are shown for comparison as dashed lines. Likely projections from IPCC AR5 for AD 2100 (relative to AD 2000) are shown for RCP 2.6 and 8.5 as vertical bars on the right.

AD 2009 found that projections published in the scientific literature have increased substantially over that period (Rick et al., 2011).

4. Conclusions

Our survey reflects the substantial uncertainty that remains in predicting the magnitude of future sea-level rise. Most experts estimate a larger sea-level rise by AD 2100 than the IPCC AR5 projects. The body of expert opinion is more in line with the recent NOAA sea-level scenarios. We expect on average about 0.5 m of sea-level rise for the low and 1.0 m for the upper temperature scenario. Thirteen experts estimated a 17% probability of exceeding 2.0 m of sea-level rise by AD 2100 under the upper temperature scenario.

For the rise from AD 2000 to AD 2300, the median 'likely' range is 0.6–1.0 m for the low temperature scenario. This is significantly more optimistic than the semi-empirical model result of Schaeffer et al. (2012) that estimated 2.0 m of global rise for the same temperature scenario. The IPCC AR5 model spread for low emission scenarios (includes RCP 2.6) is 0.41–0.85 m by AD 2300. Our survey results and the IPCC AR5 assessment thus suggest that stringent mitigation measures could deliver a good chance to keep sea-level rise below the 1 m guardrail proposed by the German Advisory Council on Global Change (WBGU, 2006). For the high-temperature scenario, the median "likely" range given by the experts is 2.0–3.0 m, with some experts estimating a rise of up to 14.0 m (Fig. 2). The IPCC AR5 model spread for the high emission scenario (includes RCP 8.5) is 0.92 m–3.59 m by AD 2300. Overall the results for AD 2300 illustrate the risk that temperature increases from unmitigated emissions could commit coastal populations to a long-term, multi-meter sea-level rise that would have catastrophic impacts on many coastal cities and low-lying lands. However, they also illustrate the potential for escaping such large sea-level rise through successful reduction of emissions.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.quascirev.2013.11.002.

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