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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

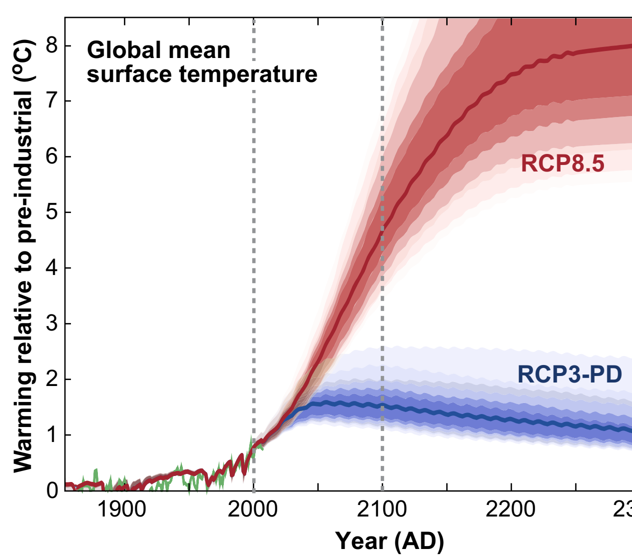

Fig. 1. Scenarios of global temperature changes up to AD 2300. The two scenarios are reproduced from Meinshausen et al. (2011) and were presented to survey participants as basis for their assessment of future sea-level rise. These temperature projections correspond to the lower (RCP3-PD; blue) and upper (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.