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Key Points:

- We present the first comprehensive database of 21st century global sea level rise projections
- Upper estimates of sea level rise in 2100 are often higher than upper bounds found in Intergovernmental Panel on Climate Change reports
- A comparison of recent global sea level rise projections reveals far greater agreement among studies in 2050 compared to 2100

Supporting Information:

- Supporting Information S1
- Table S1

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Evolution of 21st Century Sea Level Rise Projections

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Abstract The modern era of scientific global-mean sea level rise (SLR) projections began in the early 1980s. In subsequent decades, understanding of driving processes has improved, and new methodologies have been developed. Nonetheless, despite more than 70 studies, future SLR remains deeply uncertain. To facilitate understanding of the historical development of SLR projections and contextualize current projections, we have compiled a comprehensive database of 21st century global SLR projections. Although central estimates of 21st century global-mean SLR have been relatively consistent, the range of projected SLR has varied greatly over time. Among studies providing multiple estimates, the range of upper projections shrank from 1.3–1.8 m during the 1980s to 0.6–0.9 m in 2007, before expanding again to 0.5–2.5 m since 2013. Upper projections of SLR from individual studies are generally higher than upper projections from the Intergovernmental Panel on Climate Change, potentially due to differing percentile bounds or a predisposition of consensus-based approaches toward relatively conservative outcomes.

Plain Language Summary In spite of more than 35 years of research, and over 70 individual studies, the upper bound of future global-mean sea level rise (SLR) remains deeply uncertain. In an effort to improve understanding of the history of the science behind projected SLR, we present and analyze the first comprehensive database of 21st century global-mean SLR projections. Results show a reduction in the range of SLR projections from the first studies through the mid-2000s that has since reversed. In addition, results from this work indicate a tendency for Intergovernmental Panel on Climate Change reports to *err on the side of least drama*—a conservative bias that could potentially impede risk management.

1. Introduction

Coastal populations and associated economic assets have increased steadily in recent decades (Neumann et al., 2015); by 2100, the population within 10-m elevation of mean sea level could exceed 830 million (Merkens et al., 2016). As coastal populations expand, the risks associated with sea-level rise (SLR) are also continuing to grow (P. U. Clark et al., 2016). Consequently, there is rapidly expanding demand for SLR projections at both global and local scales, but care is needed to ensure that these projections and their estimated uncertainties accurately reflect scientific knowledge (e.g., Sweet et al., 2017). An understanding of the historical evolution of sea-level projections provides crucial context for interpreting the current state of the art.

In the late 1970s and early 1980s, a growing awareness of the potential instability of the West Antarctic Ice Sheet (WAIS; e.g., J. A. Clark & Lingle, 1977) and the potential impact of global warming on sea level led to the development of the first modern projections of the 21st century global-mean SLR (Gornitz et al., 1982; Hoffman et al., 1983). These projections began with simple statistical models of the relationship between global mean sea level and temperature (Gornitz et al., 1982) but soon became dominated by approaches that aimed to assess likely future SLR by integrating model- and literature-based projections for individual processes (e.g., Hoffman et al., 1983). Policymakers recognized the need to incorporate these emerging projections into decision processes, leading to a National Research Council (U.S.) study (National Research Council, 1987) that developed a discrete set of scenarios, eventually adapted by the U.S. Army Corps of Engineers

(U.S. Army Corps of Engineers, 1989). In subsequent years, understanding of processes driving SLR improved, and new scientific and analytic tools were developed. Thus, methods of projecting future SLR expanded to include process-based models (e.g., Raper et al., 1996), semiempirical models (e.g., Rahmstorf, 2007), unstructured expert judgments (e.g., B. P. Horton et al., 2014), and probabilistic assessments (e.g., Kopp et al., 2014).

Despite methodological advances, the upper bound of sea level projections remains deeply uncertain, with no single agreed-upon probability distribution, and no generally accepted *best* estimation method (Kopp et al., 2017). Although there have been attempts to summarize both the difficulties associated with projecting future SLR and the inevitable differences among SLR projections (Oppenheimer & Alley, 2016), to date there has been no attempt to develop a comprehensive database to examine the historical development of global-mean SLR projections.

Here, we have compiled a comprehensive database of studies from 1983 to 2018 that project future global-mean SLR at the end of the 21st century. It should be noted that there are a variety of factors that lead to differences in projected global-mean SLR across studies, including approaches to characterizing risk, specific SLR components included and analyzed in any given study, relative reliance upon global climate models compared to other sources of information, and assumptions about emission scenarios and future climate forcing. Because of the diverse sets of assumptions and goals used by individual studies, it is often not possible to make direct comparisons between separate studies; however, we nonetheless attempt to illuminate and contextualize the varied sources of differences across SLR projections as a whole. As the number of publications on this topic continues to expand, this database may provide context for researchers and decision makers as they grapple with challenges from methodological choices to deep uncertainty.

2. Database of SLR Projections

The database (Table S1 in the supporting information) includes SLR projections from 74 different studies (Figure 1a), which are subdivided into eight methodological categories (Table 1 and Figure S1). The 21st century SLR projections in the database are also categorized by low, middle, and high emission scenarios. Table S2 shows the categorization of emission scenarios used in Intergovernmental Panel on Climate Change (IPCC) reports for this database (Church et al., 2001, 2013; Hartmann et al., 2013; Meehl et al., 2007; Rogelj et al., 2012; Warrick et al., 1996; Warrick & Oerlemans, 1990). SLR projections made under geoengineering scenarios are not included.

Where possible, the 5th, 50th, and 95th percentile estimates from the original studies are used as lower, central, and upper estimates for each study-by-scenario in the database. However, this is not always possible, because (1) some studies use different definitions of lower, central, and upper estimates (for example, 10th, 50th, and 90th percentiles or a mean ± one standard deviation) and (2) not all studies provide a range of estimates but instead report a single value. This is particularly true for many of the early studies; in such cases, the values provided are considered central estimates. We also note that the 5th to 95th percentile range used in this analysis differs from the ranges used in some of the IPCC assessment reports. The first (FAR), second (SAR), and third (TAR) assessment reports provide extreme ranges of SLR across scenarios, the fourth assessment report (AR4) provides a span of the 5–95% range across scenarios, and the fifth assessment report (AR5) focuses on a central or *likely* (at least 66% probability) range of SLR across scenarios (Church et al., 2001, 2013; Meehl et al., 2007; Warrick et al., 1996; Warrick & Oerlemans, 1990; Table S3). The evolution of emission scenarios, coupled with methodological choices, inevitably limits direct comparisons of how and why SLR projections have evolved over time.

The number of projections for each study in the database is often related to the number of different climate scenarios used. However, some studies (particularly probabilistic studies) have single projections composed of thousands of additional SLR samples. For example, the database includes three projections from Kopp et al. (2014)—one each for Representative Concentration Pathways (RCPs)2.6, 4.5, and 8.5—but each of these projections was based upon 10,000 Monte Carlo samples of SLR (Kopp et al., 2014).

Each study in the database includes the following fields: (1) year in which the study was published, (2) lead author of the study, (3) methodological approach, (4) base year(s) for the projections, (5) end year(s) for the projections, (6) emission scenario used, (7) emission scenario category (low, middle, or high), (8) lower estimate of sea level change, (9) lower rate of sea level change, (10) definition of lower estimate of sea

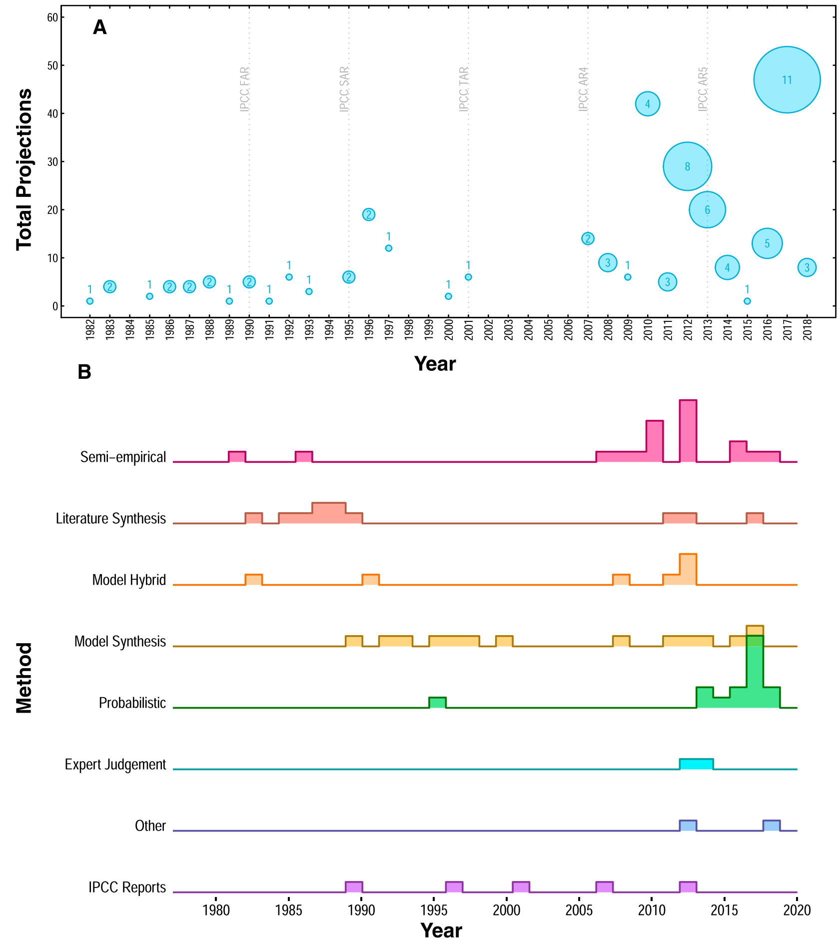

Figure 1. Total projections and methodology time series of 21st century SLR projections. (a) Total number of 21st century SLR projections per study year, where the number of individual studies producing projections each year is indicated by size and numbers in blue for each point. Many studies produce multiple projections, including different projections for different emission scenarios. The year in which the study was published is shown on the *x* axis. Gray dashed lines indicate years of IPCC reports. (b) Density time series of relative number of studies for each methodology category published from 1982 to the present. SLR = sea level rise; IPCC = Intergovernmental Panel on Climate Change; FAR = first assessment report; SAR = second assessment report; TAR = third assessment report; AR4 = fourth assessment report; AR5 = fifth assessment report.

level change, (11) central estimate of sea level change, (12) central rate of sea level change, (13) definition of central estimate of sea level change, (14) upper estimate of sea level change, (15) upper rate of sea level change, and (16) definition of upper estimate of sea level change. Not all of these fields are available for each SLR projection; for example, some studies include only a central estimate, rather than lower, central, and upper estimates of SLR. Note that lower, central, and upper estimates should not be confused with low, middle, and high emission scenarios. For example, a study that provides a single estimate of SLR based on a high emission scenario would be classified as a central estimate with a scenario type classified as *High*.

The database does not include studies that looked at just one or two components of global SLR but rather includes only studies that have at least in some way incorporated (1) thermal expansion, (2) polar ice sheets, and (3) glaciers and ice caps. Although we have attempted to include all projections of 21st century SLR, it is perhaps inevitable that we have missed a small number of projections that should have been included.

2.1. Projection Windows

Projection windows for the SLR projections included in the database are determined by the base year(s) and end year(s) used by each individual study and are not uniform across different studies. Base years for entries

Table 1
Method Categories of SLR Projections Published Since 1982

Method	Definition	Total studies[a]
Semiempirical models	Calculations are based on a historical statistical relationship between global-mean sea level and some other driving factor, such as temperature	19
Literature syntheses	Previously published projections are used to estimate contributions from every individual component of SLR considered and generate a new future SLR projection	10
Model hybrid studies	A combination of physical and statistical modeling techniques is used to produce estimates for some, but not all, individual SLR components; other methods, such as literature syntheses, are used to estimate contributions from remaining SLR components	6
Model syntheses	Some combination of physical and statistical modeling is used to estimate contributions from every individual component of SLR considered and generate a new future SLR projection	14
Probabilistic projections	Different submodels or lines of evidence are combined in a fashion intended to produce comprehensive probability distributions of future sea level change	15
Expert judgment studies	Projections based on responses to broad surveys of experts active in the field of sea level	2
Other methods	A small number of studies such as those that employed a combination of tide gauge data, satellite altimeter data, and data about the equilibrium sea level response to a warming climate	2
IPCC reports	Projections provided in the IPCC assessment reports	5

[a]Note that here, as in Figure 1, we focus on the broad patterns of study methodologies over the course of the history of the science and include all published SLR projections rather than limiting the total studies column to only the 21st century projections that are included in the SLR database. SLR = sea level rise; IPCC = Intergovernmental Panel on Climate Change.

tend to vary with the time at which each projection was made, but, when analyzing 21st century SLR estimates, we have required that end years for studies extend to at least the final decade of the 21st century. So, for example, a study with an end year of 2080 would not be included in such analysis, but a study with an end year window spanning 2070–2099 would be included. We have not used these same requirements in analyzing evolving methodologies for SLR studies (e.g., Figure 1b); instead, we have included all relevant unique SLR projections as we consider how this aspect of the history of the science has evolved over time.

In order to generate consistency across studies and create a common framework in which to compare different SLR projections, we have normalized the sea level estimates by using the base and end years to calculate average rates of SLR for each projection in the database, as follows:

$$SLR_{Adj} = SLR\left(\frac{100}{(Y - Y_0)}\right), \quad (1)$$

where SLR_{Adj} is the normalized SLR projection (the rate of sea level change), SLR is the SLR reported in the original study, Y is the study end year, and Y_0 is the study baseline year. In cases where a range of years is used for either the study end point, or for the study baseline, we use the central year from the range for equation (1) above. This normalization process results in little change to the overall values of SLR at the end of the 21st century that we report here compared to values given in the original studies, given that most projection windows are already close to 100 years. We do note that because of interannual and decadal variations in SLR and because of the acceleration of most projections, this normalization process may slightly bias some results compared to others; however, this approach is nonetheless useful in allowing us to standardize the different projections for easier comparison across studies.

3. Evolution of SLR Estimates and Ranges

SLR projections prior to the first IPCC report (between 1982 and 1990) included the first semiempirical study, which projected global-mean sea level at 2050 (Gornitz et al., 1982), as well as the first model hybrid study (Hoffman et al., 1983). However, most of the projections from this time period used a literature synthesis approach to estimate future SLR (e.g., Thomas, 1987; Figures 1b, 2, and S2). In total, there were only 16 published projections from 1982 to 1989 (Figure 1a). SLR projections from this time period have the greatest range of any time period across the 36 years which the database spans (Figure 2, S3). Projections of 2100 sea level range from −1.0 m for a scenario of drastically reduced greenhouse gas emissions relative to

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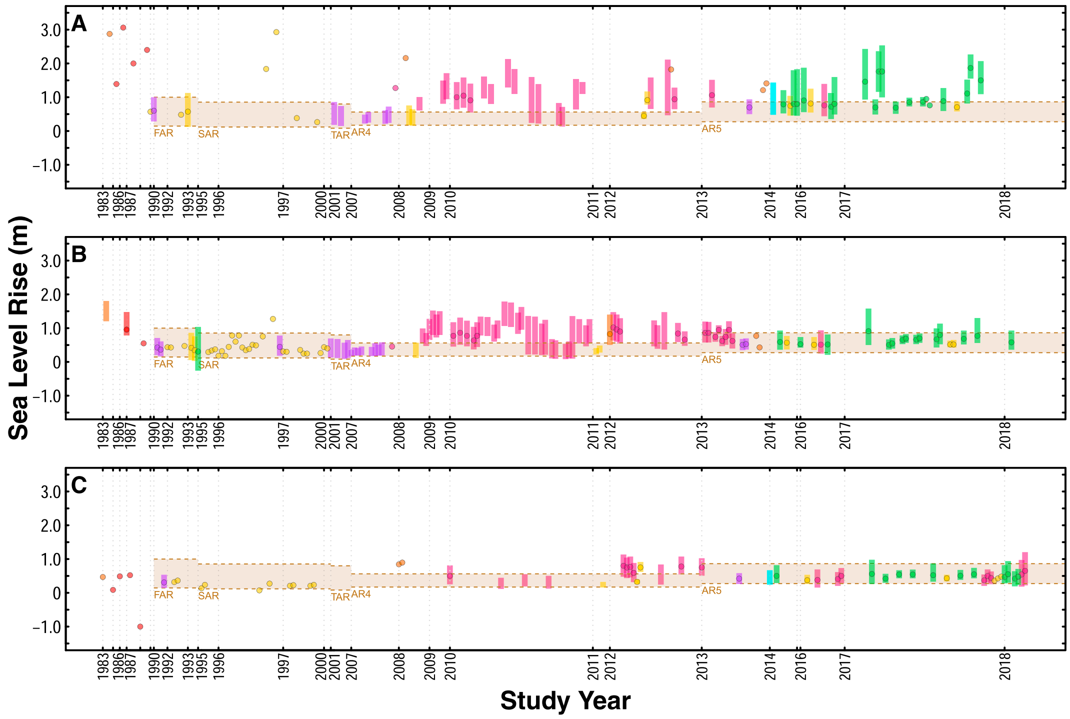

Figure 2. Evolution of the ranges of SLR projections from 1983 to 2018. Circular points represent central SLR projections; bars extend from the lower SLR projection to the upper SLR projection for (a) high emission scenarios, (b) middle emission scenarios, and (c) low emission scenarios. Where possible, bars show the 5th to 95th percentile range of individual projections. Bar and point colors correspond to the methodology used by each study and are as in Figure 1b: semiempirical (pink), literature synthesis (red), model hybrid (orange), model synthesis (yellow), probabilistic (green), expert judgment (cyan), other (blue), and IPCC reports (purple). Tan-shaded regions and dashed lines represent the ranges of SLR from the IPCC reports, as in Table S3: the extreme range of projections for IPCC FAR and SAR, the range of all AOGCMs and SRES scenarios for TAR, the 5–95% range across SRES scenarios for AR4 (which do not include dynamic ice sheet response), and the *likely* (17th to 83rd percentiles) range from process-based models for AR5 (potential rise above this range as specified in AR5 is not included in the shaded region). Note that (1) time steps are nonuniform, in order to clearly show all projections, (2) a small number of projections in the database have no specified emission scenario and are left off of this figure, and (3) projections have been normalized using equation (1) as specified in section 2.1. SLR = sea level rise; IPCC = Intergovernmental Panel on Climate Change; FAR = first assessment report; SAR = second assessment report; TAR = third assessment report; AR4 = fourth assessment report; AR5 = fifth assessment report.

1985 and low climate sensitivity (W. C. Clark et al., 1988) to 3.1 m for a scenario that included 4.0 °C warming in response to a doubling of CO_2 concentrations (Hoffman et al., 1986).

The range of these projections may reflect gaps in scientific knowledge about the processes that contribute to SLR, reflected in assumptions used to produce projections. For example, Hoffman et al. (1983) noted the problem of determining population and productivity growth, atmospheric and climatic change, and oceanic and glacial response. They also remarked that differences in estimates of SLR were due to insufficient scientific understanding and deficiencies in the methods used for constructing estimates, before stating that these shortcomings could be overcome with future research (Hoffman et al., 1983).

IPCC FAR, published in 1990, noted the difficulty in comparing future SLR values from different studies with varying time periods (end years between 2025 and 2100) and differing assumptions. FAR generated global SLR projections of 0.31 to 1.1 m (extreme range of all four IPCC scenarios), based on IPCC FAR greenhouse gas forcing scenarios (Warrick & Oerlemans, 1990; Table S3). The major contributions to SLR in FAR projections were thermal expansion and glaciers and small ice caps (Warrick & Oerlemans, 1990). It was assumed that the major ice sheets would remain stable throughout the 21st century, with only small contributions to SLR associated with changes in surface mass balance (Warrick & Oerlemans, 1990). FAR SLR projections included a minor positive contribution from the Greenland Ice Sheet and a minor negative contribution from ice mass gains in Antarctica (Warrick & Oerlemans, 1990).

SLR projections made between IPCC FAR and SAR reports (1991 and 1995) included model synthesis studies (e.g., Wigley & Raper, 1993), as well as the first probabilistic study in the database (Titus & Narayanan, 1995). Projections of the 21st century SLR ranged from −0.26 m (the 2.5th percentile from a probability distribution based on the IS92A-F scenarios; Titus & Narayanan, 1995) to 1.13 m (for the IPCC BAU scenario; Wigley & Raper, 1993).

SAR was published in 1996 and drew upon projections published in FAR (Warrick & Oerlemans, 1990), as well as the new projections. However, as with FAR, SAR noted the difficulty of comparing previous studies due to their varying assumptions related to emission scenarios, greenhouse gas concentrations, radiative forcing, and climate sensitivity. As a synthesis of the published studies to date, SAR provided a set of projections using the IPCC emission scenarios that were slightly lower than those from FAR, ranging from 0.13 to 0.94 m (Table S3), mainly due to lower global temperature projections (Warrick et al., 1996).

SLR projections between SAR and TAR reports of the IPCC (1996 and 2001) included a number of projections from model synthesis studies (e.g., de Wolde et al., 1997). Projections of SLR at the end of the 21st century from studies during this time period ranged from 0.07 m for a low scenario, where CO_2 concentration stabilizes at 450 ppmv and low ice melt parameter values are used, to 2.9 m for a high scenario where CO_2 concentration stabilizes at 650 ppmv and high ice melt parameter values are used (Raper et al., 1996).

TAR drew upon some of the projections that are found in the database between 1996 and 2001 (de Wolde et al., 1997; Raper et al., 1996) but primarily focused on new model synthesis projections using Atmosphere-Ocean Global Climate Models (AOGCMs). The range of these 21st century global SLR projections extended from 0.09 to 0.88 m (Church et al., 2001) across the 35 Special Report on Emissions Scenarios (SRES) scenarios (Table S3). Projections for thermal expansion were based on a simple climate model (Raper et al., 1996), ice sheet mass balance sensitivities were derived from AOGCMs, and ice-dynamical changes in the WAIS were not included, as it was generally believed that major contributions to SLR due to loss of grounded ice from the WAIS were very unlikely during the 21st century (Church et al., 2001).

Between the publication of TAR in 2001 and AR4 in 2007, there were no new projections of global SLR, although there were numerous publications exploring the mechanisms that drive SLR (e.g., Gregory et al., 2001; Levermann et al., 2005; Oerlemans, 2001; Suzuki et al., 2005). These included studies related to thermal expansion (Gregory et al., 2001), ocean density and circulation changes (Gregory et al., 2001; Levermann et al., 2005), glaciers (Oerlemans, 2001), and the Greenland and Antarctic Ice Sheets (Suzuki et al., 2005). AR4 authors drew upon this literature in the development of their projections, which ranged from 0.18 to 0.59 m (Meehl et al., 2007). This range was notably lower than the TAR range, primarily because it did not account for contributions from Greenland glaciers and West Antarctic ice streams (Meehl et al., 2007). AR4 projections included a large contribution from thermal expansion, with additional positive contributions from glaciers, ice caps, and Greenland via surface mass balance, though negative contributions from a snowier Antarctic Ice Sheet. AR4 authors noted that much uncertainty remained about ice flow in Greenland glaciers and West Antarctica and that although the primary AR4 projections did not account for such contributions, increased ice discharge from these processes could greatly increase future SLR (Meehl et al., 2007). The discussion of future SLR in AR4 indicated a need for more research on the subject of future polar ice sheet response to continued global warming.

Dissatisfaction with physical models of SLR (Rahmstorf, 2007), along with growing observational evidence of ice sheet loss (e.g., Rignot et al., 2011), helped spur a significant increase in the number of SLR projections (20 new studies) between the publication of AR4 in 2007 and the publication of AR5 in 2013. New projections were dominated by the renaissance of semiempirical models (Rahmstorf, 2007; Figures 1b, 2, and S2). Rahmstorf (2007) suggested that the historical relationship between global-mean surface temperature and rate of sea level change, combined with projections of global-mean surface temperature, could yield improved SLR projections relative to those based on physical modeling. Between 2007 and 2013, the range of SLR for 2100 from semiempirical models was 0.17 to 2.05 m. These projections are, however, limited by the structural uncertainty regarding whether empirical connections observed during the instrumental or proxy time periods will remain unchanged in the future and are also sensitive to the choice of data used for calibration (Rahmstorf et al., 2012).

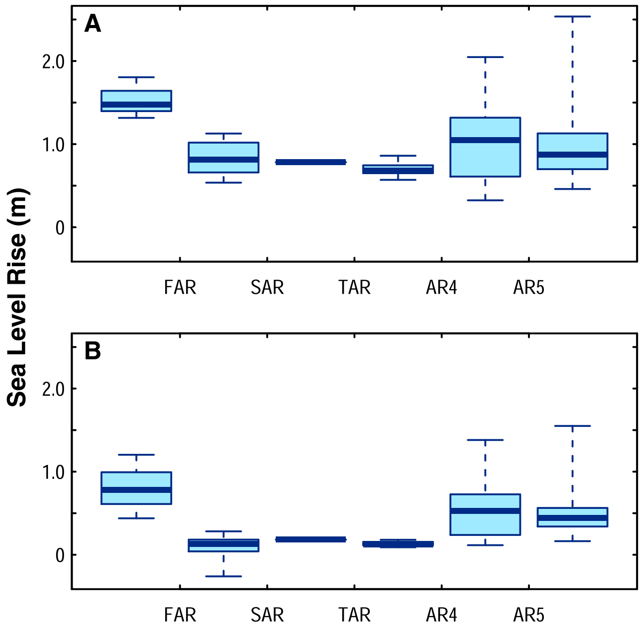

Figure 3. Box and whisker plots showing SLR ranges over time. Shown are the varying ranges of (a) upper SLR projections and (b) lower SLR projections. Box edges extend from the 25th to 75th percentiles; the solid line in each box shows the 50th percentile. Whiskers extend to data extremes, essentially ranging from 0 to 100th percentiles to show the full range of SLR projections in each case. The horizontal axis uses the Intergovernmental Panel on Climate Change assessment reports to divide the literature based on publication date. SLR = sea level rise; FAR = first assessment report; SAR = second assessment report; TAR = third assessment report; AR4 = fourth assessment report; AR5 = fifth assessment report.

AR5 authors drew upon results from semiempirical models (e.g., R. Horton et al., 2008; Rahmstorf, 2007) but assigned these projections low confidence, while also drawing upon various model synthesis and model hybrid studies, to which they assigned greater confidence (e.g., Sriver et al., 2012). AR5 provided their own projections of the 21st century SLR from process-based models, with a *likely* (at least 66% probability) range of 0.26–0.82 m (Table S3). This range, although comparable to the range given in TAR, represented a significant upward revision from the values reported in AR4, primarily due to the inclusion of more rapid changes in Greenland and Antarctic Ice Sheets. However, AR5 also noted that additional SLR up to several tenths of a meter was possible due to Marine Ice Sheet Instability, a process that was not included in the estimate of Antarctic Ice Sheet rapid dynamics due to imprecise estimates of the likelihood of such a contribution.

Twenty-eight studies and more than 90 projections (>30% of the total number of SLR projections in the database) have been published from 2013 to the present. This time period has also seen a proliferation of national and subnational sea level assessment documents (Hall et al., 2019). The range of 2100 SLR across these projections is 0.16 to 2.54 m, which is both broader and higher compared to projections made between TAR and AR5 (Figures 2, S3, and 3). The change in range reflects increased uncertainty about maximum contributions of the Greenland and Antarctic Ice Sheets to SLR (DeConto & Pollard, 2016; Levermann et al., 2013).

Although all of the categories of SLR projections have been represented during this recent time period (Figure 1b), a major new development since AR5 has been the spread of probabilistic methodologies (e.g., Kopp et al., 2014, 2017) and the introduction of projections derived from expert judgment methodologies (Bamber & Aspinall, 2013; B. P. Horton et al., 2014). The development of probabilistic methodologies and utilization of structured expert judgment methodologies (Figure 1b) support exploration of extreme SLR possibilities, which can generate the greatest risks, and thus play an important role in coastal risk management and planning (Kopp et al., 2014). Although a few earlier assessments involving decision makers attempted to provide upper bound SLR projections for risk-based decision contexts (R. Horton et al., 2010), structured expert judgment and probabilistic approaches hold promise for mainstreaming consideration of high-end outcomes via decision-maker engagement and coproduction of knowledge (R. Horton et al., 2015; Sweet et al., 2017). Such projections address the inadequacy of presenting only central ranges for SLR projections, as the *likely* (at least 66% probability) ranges provide no information about the highest 17% of outcomes (Kopp et al., 2014). However, while probabilistic methodologies represent an important addition to SLR projection methods, large uncertainties remain about key processes influencing individual SLR components, how different components may interact in a changing climate, and future concentrations of radiatively important agents and associated climate sensitivity.

4. IPCC SLR Projections: Erring on the Side of Least Drama?

AR5 projected a *likely* (i.e., at least 66% probability) global-mean SLR of 0.52–0.98 m in the case of unmitigated growth of emissions (RCP8.5) by 2100, relative to 1986–2005 (Church et al., 2013). However, many projections for high emission scenarios from individual studies (Figures 2a, S2a, and 4) are much greater than 1 m. This trend has been particularly true for upper estimates of SLR from high-emission scenarios (Figures 2 and 4), with the majority of these projections exceeding the upper estimates provided by the IPCC assessment reports. This result aligns with the findings of Horton et al. (2014), in which the authors noted that most experts predicted greater amounts of SLR by 2100 than the likely range of the 21st century SLR given in AR5 (Church et al., 2013).

Although the IPCC acknowledges its limitations in projecting future SLR (Church et al., 2001, 2013; Meehl et al., 2007; Warrick et al., 1996; Warrick & Oerlemans, 1990), caveat language included in the reports

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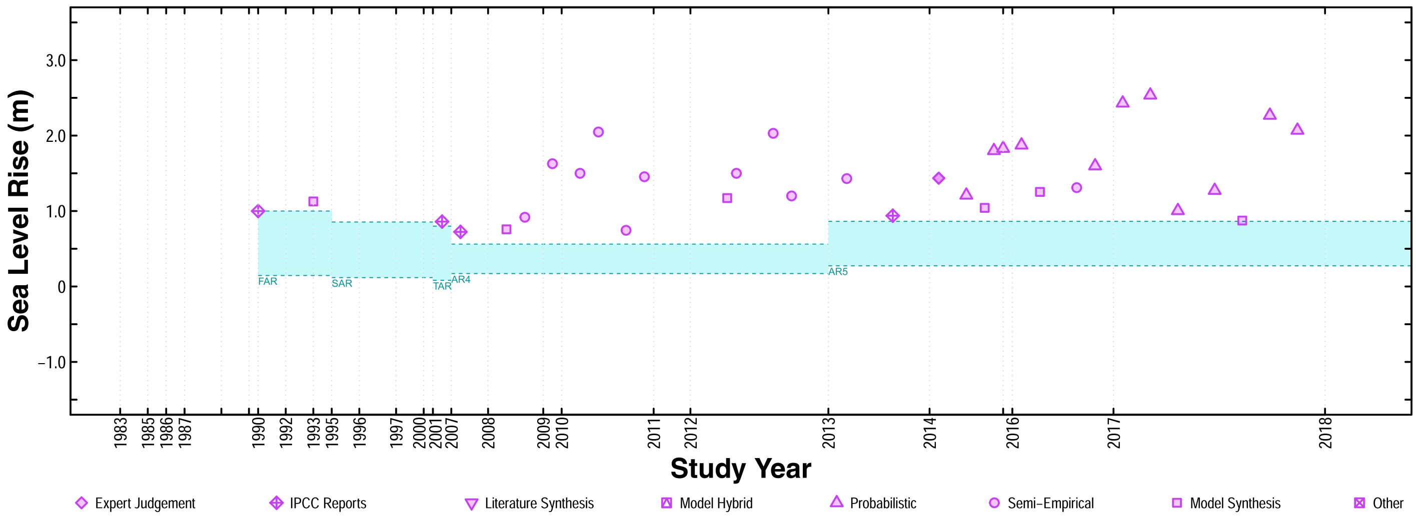

Figure 4. Comparison of upper estimates for high emission scenarios from individual studies to IPCC projected ranges of SLR. Shown are the upper estimates of SLR for high emission scenarios from 1983–2018 (purple), and the IPCC projected SLR ranges (blue). Where possible, upper estimates from high emission scenarios show the 95th percentile estimate; ranges for IPCC reports are as shown in Table S3: the extreme range of projections for IPCC FAR and SAR, the range of all AOGCMs and SRES scenarios for TAR, the 5–95% range across SRES scenarios for AR4 (which do not include dynamic ice sheet response), and the *likely* (17th to 83rd percentiles) range from process-based models for AR5 (potential rise above this range as specified in AR5 is not included in the shaded region). Note that time steps are nonuniform, in order to clearly show all projections, and projections have been normalized using equation (1) as specified in section 2.1. IPCC = Intergovernmental Panel on Climate Change; SLR = sea level rise; AOGCMs = Atmosphere-Ocean Global Climate Models; FAR = first assessment report; SAR = second assessment report; TAR = third assessment report; AR4 = fourth assessment report; AR5 = fifth assessment report.

tends to get filtered out in headline numbers. There are several reasons that projected SLR from the IPCC reports may tend to be lower than upper estimates from other studies. First, the type of model-based studies on which AR5 placed the greatest emphasis may be relatively insensitive to potential changes in ice sheet behavior as temperatures rise (Church et al., 2013). Second, the IPCC percentile bounds may be narrower than other studies used to project ranges of SLR. For example, AR5 focused on a *likely* (approximately 17th to 83rd percentiles) range of projected SLR and did not attempt to provide quantitative information about less likely outcomes. Third, consensus-based approaches like the IPCC, with their large number of authors, may be predisposed to relatively conservative outcomes—both in the overall assessment of the literature and through communication choices, such as which percentiles to emphasize (Brysse et al., 2013). Finally, the IPCC knowledge development process only includes scientists. Without the inclusion of decision makers who manage coastal risk in the development of that knowledge, the utility of the IPCC for planning and managing coastal risk, especially at regional to local scales, is hard to gauge. Of the small number of SLR projections that have included participation and input from decisions makers, all have considered high-end estimates as useful for considering impacts and consequences of SLR, particularly examining assets for which we can tolerate only a low probability of hazard occurrence, due to large consequences should the hazard occur (e.g., nuclear power plants or other energy infrastructure).

Ultimately, the IPCC reports have tended to err on the side of providing intentionally cautious and conservative estimates of SLR, rather than focusing on less likely, extreme possibilities that would be of high consequence, should they occur. This bias toward such cautious estimates has been described previously as *erring on the side of least drama* (Brysse et al., 2013). Many individual studies, both globally and locally (R. M. Horton et al., 2011), have not constrained the ranges of their SLR projections in the same conservative manner as the IPCC reports. Rather than erring on the side of least drama (Brysse et al., 2013), such studies better encompass less likely, but more severe outcomes of future SLR that may be of greater interest to audiences concerned with risk-based perspectives (e.g., Rosenzweig et al., 2014).

This database documents the development of a 36-year-old body of scientific knowledge. Throughout this history, the IPCC remains a useful foil. Gradually, over the latter reports (TAR, AR4, and AR5), IPCC has become a judge of the standard of scientific practice, deeming certain methods (e.g., physical models) credible and

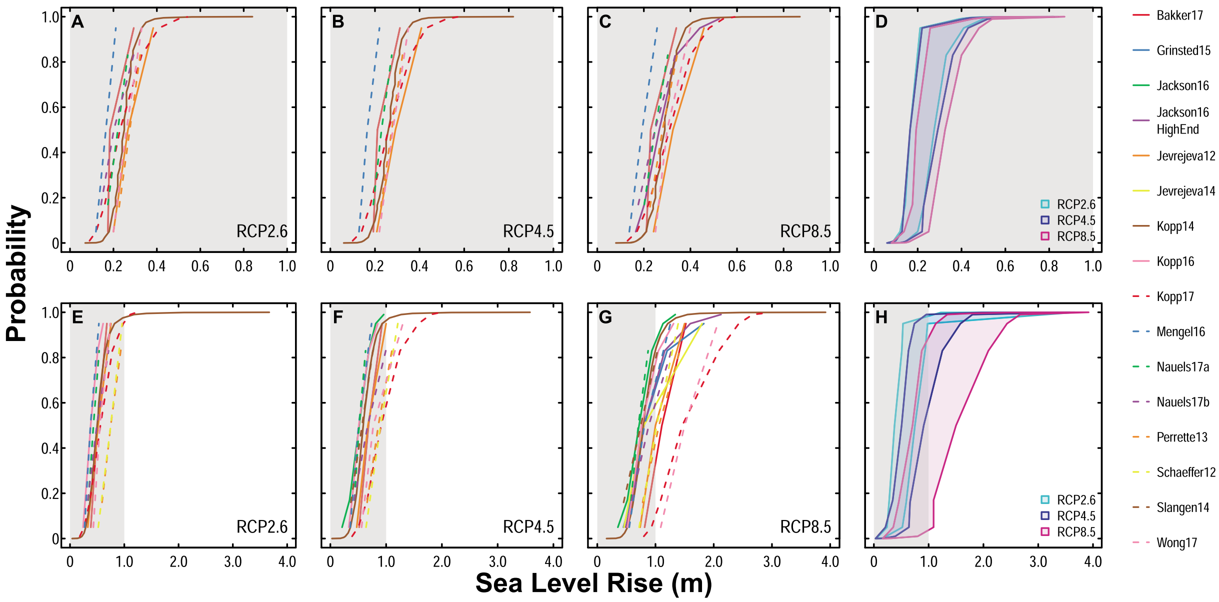

Figure 5. Cumulative distribution functions based on projections from semiempirical, probabilistic, and model synthesis studies produced since the fifth assessment report (AR5) for both 2050 (a–d) and 2100 (e–h). The rightmost panel in each row shows regions representing the upper and lower bounds of cumulative distribution functions s for RCP2.6, RCP4.5, and RCP8.5 emission scenarios.

others perhaps not yet so (e.g., semiempirical models; Figure 4). The conservative bias exhibited by IPCC analyses may in part be due to IPCC Working Group 1's development of knowledge solely within the epistemic domain of the natural sciences (e.g., McNie et al., 2016).

Scientists evaluating science can lead to *cracks of bias* in many fields (Sarewitz, 2012). The IPCC is designed to influence the United Nations Framework on Climate Change Convention, which is critically important for curbing global emissions and, by inference, SLR. However, if the bias toward a lower, central range is due to epistemic norms, it suggests that the science-policy interface between the IPCC and United Nations Framework on Climate Change Convention or other decision-making bodies may be too limited to allow for appropriate participation from decision makers and the development of useful knowledge for climate adaptation (e.g., Parris et al., 2015).

5. Uncertainty Characterization in Recent SLR Projections on Different Time Scales

The comparison of SLR projections has historically been challenging, due to projections' varying time scales, inconsistent assumptions about emissions, radiative forcing, and climate sensitivities, and ambiguously defined lower, central, and upper estimates of SLR. However, the broad use of RCP scenarios and the adoption of explicit Bayesian probabilities (not only in probabilistic projections but also in semiempirical projections and model syntheses) across many of the SLR projections made since AR5 has helped to eliminate ambiguity at least in how emission scenarios and lower and upper estimates of SLR are defined (e.g., Grinsted et al., 2015; Kopp et al., 2014, 2017).

As discussed in Kopp et al. (2017), upper bounds of future SLR projections remain deeply uncertain. Deep uncertainty has been defined as "the condition in which analysts do not know or the parties to a decision cannot agree upon 1) the appropriate models to describe interactions among a system's variables; 2) the probability distributions to represent uncertainty about key parameters in the models; and/or 3) how to value the desirability of alternative outcomes" (Lempert et al., 2003). The deeply uncertain nature of SLR projections is evident by the fact that there is no unique probability distribution of future sea level; thus, it is unlikely that there will be any particular method that is found to be best for estimating future sea level change anytime in the near future (Kopp et al., 2017). Therefore, it is useful to compare multiple possible SLR distributions (Figure 5).

While there is significant spread in SLR projections for the end of the 21st century, the same is not necessarily true of SLR projections on shorter time scales. We have compared the partial cumulative distribution functions based on the selected values reported in semiempirical and probabilistic studies since AR5 (Figure 5). There is far greater agreement among studies about SLR in 2050 compared to 2100, although methodology appears to be more important than RCP for 2050 projections, whereas 2100 projections appear to be strongly influenced by RCP (Figure 5). The overall spread of projections is far more constrained for 2050 projections (5th percentile of 0.12 to 0.25 m and 95th percentile of 0.21 to 0.48 m; Table S4) than for 2100 (5th percentile of 0.21 to 1.09 m and 95th percentile of 0.53 to 2.43 m; Table S4). These results emphasize the deep uncertainty that scientists face in trying to predict the contributions to SLR at 2100 from various components, especially ice sheets, compared to the more tangible contributions to SLR on shorter time scales.

The majority of studies seeking to project future SLR have focused on the year 2100. However, as the world moves closer to the year 2100, it is essential to understand SLR and the impacts of rising sea levels on longer time scales (Brown et al., 2018; P. U. Clark et al., 2016; Levermann et al., 2013). A few recent studies have sought to project SLR for 2300, with median estimates of global-mean SLR ranging from 1.00 m under RCP2.6 to 11.69 m under RCP8.5 (Brown et al., 2018; Kopp et al., 2014, 2017; Nauels et al., 2017; Schaeffer et al., 2012), while studies looking at multimillennial sea level commitments have suggested over 20 m of future global-mean SLR for emission scenarios similar to RCP4.5 (P. U. Clark et al., 2016; Levermann et al., 2013).

6. Conclusion

In 1983, Hoffman et al. (1983) issued a call for further investigation of the components that contribute SLR, suggesting that with further research, differences in estimates of future SLR due to inadequate scientific knowledge and shortcomings in the methods used to construct estimates could be overcome, allowing for more precise estimates of future changes in sea level. More than a generation later, future SLR remains deeply uncertain in nature, in spite of more than 70 unique studies projecting future SLR, and additional studies investigating individual components of SLR, as well as significant developments in methodological approaches.

This database illustrates the many ways in which methodologies of SLR have evolved over the last four decades. From projections made during the 1980s prior to FAR to the publication of AR4, there was ultimately a narrowing and a lowering of the range of the projected 21st century SLR (from 1.32–1.81 m to 0.57–0.86 m for upper projections and from 0.43–1.20 m to 0.09–0.18 m for lower projections; Figure 3) across the studies in the database (Figures 2, 3, S2, S3, and S4). Since AR4, however, the range of SLR projections among individual studies has increased, with a range of 0.46–2.54 m for upper projections and a range of 0.16 to 1.55 m for lower projections published since AR5 (Figure 3).

The narrowing of SLR projections from the 1980s to AR4, followed by the broadening of this range since AR4, may be an example of the phenomenon of *negative learning* or the departure over time of scientific beliefs from the prior answer due to the introduction of new technical information (Oppenheimer et al., 2008). For example, in the specific case of SLR projections, it is possible that the narrowing of projections prior to AR4 in the period immediately prior to observed changes in ice sheet behavior was somewhat premature, a trend that has now begun to be reversed. In climate science, this phenomenon can often lead to confusion for decision makers and policy makers, though waiting for positive learning (often characterized by observations leading the models) can result in costly consequences (Oppenheimer et al., 2008). As new rounds of SLR projections are developed, a better awareness and understanding of the history of the science could be beneficial—highlighting the importance of a database such as the one developed here. In the future, coordinated programs and agreement on standardized approaches could facilitate efforts to make comparisons that illuminate all the reasons why projections differ across studies, something that is not possible given the diverse methods and impossibility of modifying many of the studies to date. As awareness grows that other aspects of the climate system may be characterized by deep uncertainty as well (e.g., Lenton et al., 2008), examples of how the SLR and coastal risk communities have integrated different types of information and projection approaches over time may prove instructive.

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