

## RESEARCH ARTICLE

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## Key Points:

- Rates of local sea-level rise differs from rate of global sea-level rise
- Differences arise from land motion, ocean dynamics, and Antarctic mass balance
- Local sea-level rise can dramatically increase flood probabilities

## Supporting Information:

- EFT2\_37 Supp Info.pdf
- EFT2\_37 Table S06.tsv
- EFT2\_37 Table S05.tsv
- EFT2\_37 Table S09.tsv
- EFT2\_37 Table S08.tsv
- EFT2\_37 Table S07.tsv
- EFT2\_37 Project Code.zip
- README.txt

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# Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites

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**Abstract** Sea-level rise due to both climate change and non-climatic factors threatens coastal settlements, infrastructure, and ecosystems. Projections of mean global sea-level (GSL) rise provide insufficient information to plan adaptive responses; local decisions require local projections that accommodate different risk tolerances and time frames and that can be linked to storm surge projections. Here we present a global set of local sea-level (LSL) projections to inform decisions on timescales ranging from the coming decades through the 22nd century. We provide complete probability distributions, informed by a combination of expert community assessment, expert elicitation, and process modeling. Between the years 2000 and 2100, we project a *very likely* (90% probability) GSL rise of 0.5–1.2 m under representative concentration pathway (RCP) 8.5, 0.4–0.9 m under RCP 4.5, and 0.3–0.8 m under RCP 2.6. Site-to-site differences in LSL projections are due to varying non-climatic background uplift or subsidence, oceanographic effects, and spatially variable responses of the geoid and the lithosphere to shrinking land ice. The Antarctic ice sheet (AIS) constitutes a growing share of variance in GSL and LSL projections. In the global average and at many locations, it is the dominant source of variance in late 21st century projections, though at some sites oceanographic processes contribute the largest share throughout the century. LSL rise dramatically reshapes flood risk, greatly increasing the expected number of “1-in-10” and “1-in-100” year events.

## 1. Introduction

Sea-level rise figures prominently among the consequences of climate change. It impacts settlements and ecosystems both through permanent inundation of the lowest-lying areas and by increasing the frequency and/or severity of storm surge over a much larger region. In Miami-Dade County, Florida, for example, a uniform 90-cm sea-level rise would permanently inundate the residences of about 5% of the county's population, about the same fraction currently threatened by the storm tide of a 1-in-100 year flood event [Tebaldi *et al.*, 2012]. A 1-in-100 year flood on top of such a sea-level rise would, assuming geographically uniform flooding, expose an additional 35% of the population (Climate Central, Surging Seas, 2013, retrieved from SurgingSeas.org, updated November 2013).

The future rate of mean global sea-level (GSL) rise will be controlled primarily by the thermal expansion of ocean water and by mass loss from glaciers, ice caps, and ice sheets [Church *et al.*, 2013]. Changes in land water storage, through groundwater depletion and reservoir impoundment, may have influenced twentieth-century sea-level change [Gregory *et al.*, 2013] but are expected to be relatively minor contributors compared to other factors in the current century [Church *et al.*, 2013].

Local sea-level (LSL) change can differ significantly from GSL rise [Milne *et al.*, 2009; Stammer *et al.*, 2013], so for adaptation planning and risk management, localized assessments are critical. The spatial variability of LSL change arises from: (1) non-uniform changes in ocean dynamics, heat content, and salinity [Lev-ermann *et al.*, 2005; Yin *et al.*, 2009], (2) perturbations in the Earth's gravitational field and crustal height (together known as static-equilibrium effects) associated with the redistribution of mass between the

cryosphere and the ocean [Kopp *et al.*, 2010; Mitrovica *et al.*, 2011], (3) glacial isostatic adjustment (GIA) [Farrell and Clark, 1976], and (4) vertical land motion due to tectonics, local groundwater, and hydrocarbon withdrawal, and natural sediment compaction and transport [e.g., Miller *et al.*, 2013].

Most past assessments of LSL change have focused on specific regions, such as the Netherlands [Katsman *et al.*, 2011], the U.S. Pacific coast [National Research Council, 2012], New York City [Horton *et al.*, 2011; New York City Panel on Climate Change, 2013], and New Jersey [Miller *et al.*, 2013]. Slangen *et al.* [2012], Slangen *et al.* [2014], Perrette *et al.* [2013], and Church *et al.* [2013] [AR5] have produced global projections of LSL using Coupled Model Intercomparison Project (CMIP) projections [Taylor *et al.*, 2012] for thermal expansion and ocean dynamics, along with estimates of net land ice changes, their associated static-equilibrium effects and GIA.

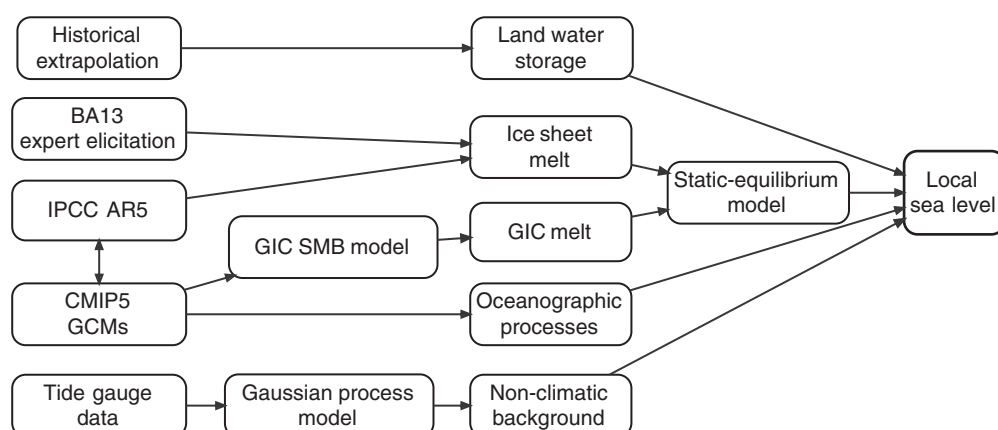
Here we expand upon past efforts to project LSL globally. First, we present a complete probability distribution. This is critical for planning purposes; the *likely* (67% probability) ranges presented in AR5 and many other previous efforts provide no information about the highest 17% of outcomes, which may well be key to risk management. Second, we indicatively extend our projections to 2200, in order to inform both decision-making regarding long-term infrastructure investment decisions and their longer term land use consequences, and also greenhouse gas mitigation decisions in the context of long-term sea-level rise commitments [Levermann *et al.*, 2013]. Finally, using a Gaussian process model [Kopp, 2013] of historical tide-gauge data [Holgate *et al.*, 2013], we include probabilistic estimates of local non-climatic factors.

We first present our framework and projections for selected locations (projections for all tide-gauge locations are included in the Supporting Information), then assess the effects of sea-level rise on coastal flooding risk at these locations. Throughout, we seek to employ transparent assumptions and an easily replicable methodology that is useful for risk assessment and can be readily updated with new information.

## 2. Methods

LSL projections require the projection and aggregation of the individual components of sea-level change [e.g., Milne *et al.*, 2009] at each site of interest. Here, we project three ice sheet components (the Greenland Ice Sheet, GIS; the West Antarctic ice sheet, WAIS; and the East Antarctic ice sheet, EAIS); glacier and ice cap (GIC) surface mass balance (SMB); global mean thermal expansion and regional ocean steric and ocean dynamic effects (which we collectively call oceanographic processes); land water storage; and long-term, local, non-climatic sea-level change due to factors such as GIA, sediment compaction, and tectonics. In our base case, we allow correlations, derived from the SMB model, between different mountain glaciers but otherwise assume that, conditional upon a global radiative forcing pathway, the components are independent of one another. To calculate GSL and LSL probability distributions, we employ 10,000 Latin hypercube samples from time-dependent probability distributions of cumulative sea-level rise contributions for each of the individual components. The sources of information used to develop these distributions are described below and summarized in Figure 1.

We construct separate projections for three representative concentration pathways (RCPs): RCP 2.6, RCP 4.5, and RCP 8.5 [Meinshausen *et al.*, 2011], which correspond respectively to *likely* global mean temperature increases in 2081–2100 of 1.9–2.3 C, 2.0–3.6 C, and 3.2–5.4 C above 1850–1900 levels [Intergovernmental Panel on Climate Change, 2013]. We do not consider RCP 6.0, as 21st-century sea-level rise projections for this pathway are nearly identical to those for RCP 4.5, and few CMIP Phase 5 (CMIP5) model runs for RCP 6.0 extend beyond 2100 [Taylor *et al.*, 2012]. The RCPs do not represent socioeconomic scenarios but can be compared to emissions in no-policy socioeconomic projections such as the Shared Socioeconomic Pathways (SSPs) [O'Neill *et al.*, 2014]. Radiative forcing in RCP 6.0 in the second half of the century is comparable to that in the lowest emissions SSP (SSP 1), while RCP 8.5 is above four of the SSPs but below the highest-emission SSP [Riahi, 2013]. Thus, RCP 8.5 can be viewed as corresponding to high-end business-as-usual emissions and RCP 4.5 as a moderate mitigation policy scenario. RCP 2.6 requires net-negative global emissions in the last quarter of the 21st century, implying a combination of intensive greenhouse gas mitigation and at least modest active carbon dioxide removal.



**Figure 1.** Logical flow of sources of information used in local sea-level projections. GCMs, global climate models; GIC, glaciers and ice caps; SMB: surface mass balance.

## 2.1. Ice Sheets

Our projections of 21st-century changes in mass balance of GIS and the Antarctic ice sheet (AIS) are generated by combining the projections of AR5 and the expert elicitation of *Bamber and Aspinall* [2013] [BA13]. AR5 is used to characterize median and *likely* ranges of sea-level change, while BA13 is used to calibrate the shape of the tails (Supporting Information Figure S1 and Table S1).

AR5 separately assesses AIS and GIS mass balance changes driven by SMB and ice sheet dynamics. For ice sheet dynamics, AR5 determined that there was insufficient knowledge to differentiate between RCP 2.6 and 4.5 (and 8.5 for AIS). Projections of total ice sheet mass loss—given as a *likely* cumulative sea-level rise contribution—are thus partially scenario-independent. BA13 probed more deeply into the tail of ice sheet mass loss projections, inquiring into the 5th–95th percentile ranges of GIS, EGIS, and WAIS. However, BA13 does not differentiate between SMB and ice sheet dynamics or between RCPs.

We reconcile the projections as described in the Supporting Information. For AIS, the reconciled RCP 8.5 projections (median/*likely*/*very likely* [90% probability] of 4/–8 to 15/–11 to 33 cm) are significantly reduced in range relative to BA13 (median/*likely*/*very likely* of 13/2 to 41/–2 to 83 cm); for GIS, the reconciled projections are almost identical to those based directly on AR5 and have a *likely* range (8–25 cm) close to the *very likely* range estimated from BA13 (9–29 cm) (Supporting Information Table S1).

Ice sheet mass balance changes do not cause globally uniform sea-level rise. To account for the differing patterns of static-equilibrium sea-level rise caused by land ice mass loss, we apply sea-level fingerprints, calculated after *Mitrovica et al.* [2011] (Supporting Information Figure S2). These fingerprints assume mass loss from each ice sheet is uniform; in most regions, the error introduced by this assumption is minimal [*Mitrovica et al.*, 2011].

## 2.2. Glacier and Ice Caps

For each RCP, we generate mass balance projections for 17 different source regions of glaciers and ice caps (described in the Supporting Information). For each source region, we employ a multivariate *t*-distribution of ice mass change with a mean and covariance estimated from the process model results of *Marzeion et al.* [2012]. Each source region has a distinct static-equilibrium sea-level fingerprint, calculated in the same fashion as for ice sheet mass loss (Supporting Information Figure S2).

The projections based on *Marzeion et al.* [2012] are modestly narrower and have a slightly higher median than those of AR5: a *likely* range of 9–15 cm from non-Antarctic glaciers by 2100 for RCP 2.6 (vs. 4–16 cm for AR5) and 14–21 cm for RCP 8.5 (vs. 9–23 cm for AR5). We opt for the *Marzeion et al.* [2012] projections because of the availability of disaggregated output representing projections based on a suite of global climate models (GCMs) for each source region.

### 2.3. Oceanographic Processes

Projections of changes in GSL due to thermal expansion and in LSL due to regional steric and dynamic effects are based upon the CMIP5 GCMs. In particular, we employ a  $t$ -distribution with the mean and covariance of a multi-model ensemble constructed from the CMIP5 archive (Supporting Information Figures S3 and S4, Table S2). Values used are 19-year running averages. For each model, we use a single realization. The sea-level change at each tide-gauge location is assumed to be represented by the nearest ocean grid cell value of each GCM.

The horizontal resolution of the CMIP5 ocean models is  $\sim 1$  degree. In these coarse-resolution models, sea level at the coast may differ from the open ocean due to local biases driven by unresolved processes (e.g., coastal currents) and bathymetry [Holt *et al.*, 2009] or via the influence of small-scale processes (e.g., eddies) on larger-scale steric and dynamic changes [Penduff *et al.*, 2010, 2011]. Although there is some evidence that climate-forced trends in sea level are not sensitive to resolution [Penduff *et al.*, 2011; Suzuki *et al.*, 2005], higher-resolution coastal modeling is required to determine whether the probabilities estimated at the GCM grid scale are significantly changed by sub-grid processes.

GCM projections exhibit a range of late nineteenth-century sea-level behavior largely attributable to model drift. Uncorrected GCM-based estimates of the rate of mean global sea-level change from 1861 to 1900 range from  $-0.4$  to  $+1.1$  mm/yr. To correct for global-mean model drift, we apply a linear correction term to each model. The linear correction adjusts the rate of GSL rise over 1861–1900 to match a rate of thermal expansion estimated by removing the multi-model average of GIC mass loss from Marzeion *et al.* [2012] from the GSL curve of Church and White [2011]. After correction, the rate of thermal expansion over 1861–1900 is  $0.3 \pm 0.9$  ( $2\sigma$ ) mm/yr (Supporting Information Figure S3).

Consistent with AR5's judgment that the 5th–95th percentile of CMIP5 output represents a *likely* (67% probability) range for global mean thermal expansion, we multiply the standard deviation of the  $t$ -distribution for oceanographic processes by 1.7.

### 2.4. Land Water Storage

Following the approach of Rahmstorf *et al.* [2012], we estimate GSL change due to changes in water storage on land based upon the relationship between such changes and population (Supporting Information Figure S5). For changes in reservoir storage, we use the historical cumulative impoundment estimate of Chao *et al.* [2008]. We assume that reservoir construction is a sigmoidal function of population:

$$I = a \times \text{erf}((P(t) - b)/c) + I_0 \quad (1)$$

where  $I$  is impoundment expressed in mm equivalent sea level (esl),  $P(t)$  is world population as a function of time, and the remaining variables are constants. The results imply a maximum additional impoundment of 6 mm (esl) on top of the current 30 mm; based on the discrepancy between the “nominal” and “actual” impoundment estimated by Chao *et al.* [2008], we conservatively allow a  $2\sigma$  error in this estimate of  $\pm 50$  %.

For the rate of groundwater depletion, we fit the estimates of Wada *et al.* [2012] and Konikow [2011] as linear functions of population, forced through the origin. The estimate of Wada *et al.* [2012] is based on fluxes estimated from a global hydrological model of groundwater recharge and a global database of groundwater abstraction, while that of Konikow [2011] uses a range of approaches depending on the data available for each aquifer. We take the mean and standard deviation of the two slopes estimated ( $0.06 \pm 0.02$  mm/yr/billion people) and allow an additional  $2\sigma$  error of  $\pm 50$  %, a level based upon the errors estimated by the authors of the two impoundment studies. In our main calculation, we do not include the water resource assessment model-based estimate of Pokhrel *et al.* [2012], which is about a factor of three higher than the other two estimates; we include this estimate in a sensitivity case.

We employ population projections derived from United Nations Department of Economics and Social Affairs [2014]. We treat population as distributed following a triangular distribution, with the median, minimum, and maximum values corresponding to the middle, low, and high U.N. scenarios (10.9, 6.8, and 16.6 billion people in 2100, respectively). For scenarios in which population declines, we allow

some reduction in impoundment, but do not allow impoundment to decrease below its year 2000 level.

### 2.5. Glacial Isostatic Adjustment, Tectonics, and Other Non-Climatic Local Effects

GIA, tectonics, and other non-climatic local effects that can be approximated as linear trends over the twentieth century are assumed to continue unchanged in the 21st and 22nd centuries. This is a good assumption for GIA, but imperfect for other processes. Tectonic processes can operate unsteadily, and a linear trend estimated from the historical record may be inaccurate. LSL rise related to fluid withdrawal is subject to engineering, resource depletion, market factors and policy controls, and might either increase or decrease in the future relative to historical levels. In addition, the trend estimates can encompass slow ocean dynamic changes that are close to constant over the historical record but could change in the future. Nonetheless, for a global analysis, assuming the continuation of observed historical changes offers the best currently feasible approach.

We estimate historical rates using a spatiotemporal Gaussian process model akin to that employed by Kopp [2013]. Sea level as recorded in the tide-gauge records (Permanent Service for Mean Sea Level, Tide-gauge data, retrieved from <http://www.psmsl.org/data/obtaining/>, accessed January 2014) is represented as the sum of three Gaussian processes: (1) a globally uniform process, (2) a regionally varying, temporally linear process, and (3) a regionally varying, temporally autocorrelated non-linear process. We allow for spatial non-stationarity in the Gaussian process prior by optimizing the hyperparameters separately for each of 15 regions (Supporting Information Table S4 and Figure S6). The posterior estimate of the second (linear) process at each site is used for forward projections. Mathematical details are provided in the Supporting Information.

### 2.6. Post-2100 Projections

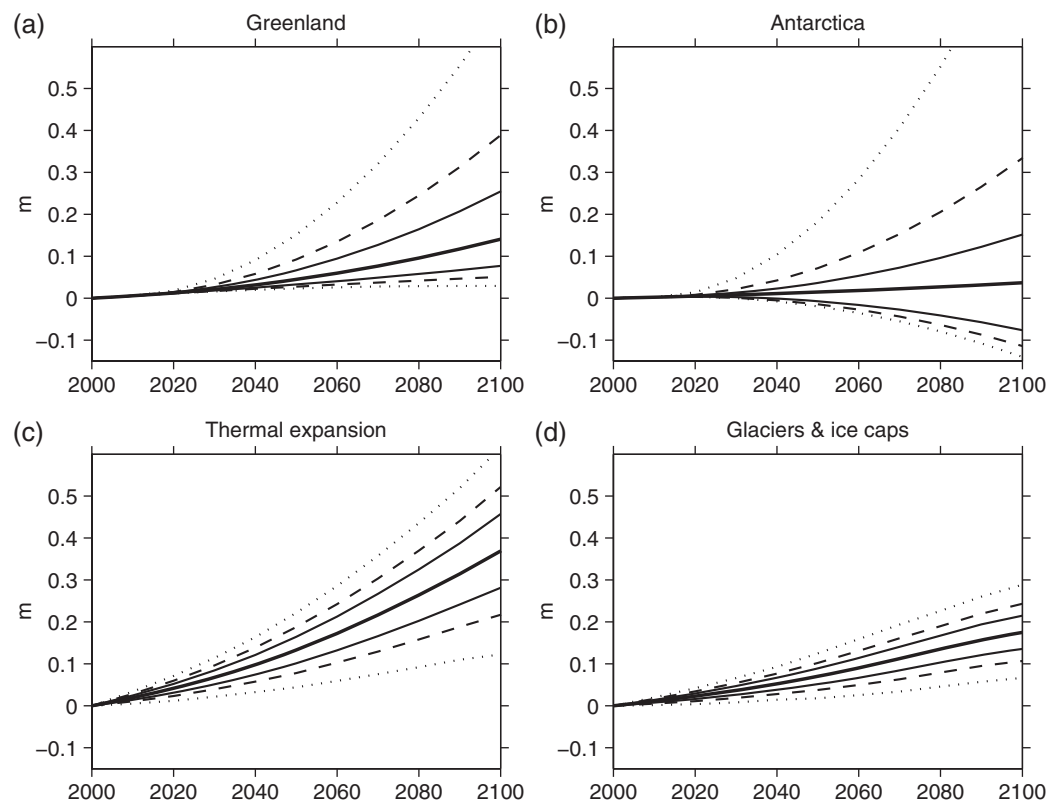
Indicative post-2100 projections are developed according to the methods described in the previous sections. For ice sheet mass balance, we continue the constant 21st century acceleration. For non-climatic factors that are approximated as linear in the 21st century, we continue the constant 21st century rate. For land water storage, we extend the population projections using the 22nd century growth rates of *United Nations Department of Economics and Social Affairs* [2004] and use the same relationships of impoundment and groundwater depletion to population as in the 21st century (Supporting Information Figure S5). The number of GCM-based model results for GIC and oceanographic processes drops significantly beyond 2100 (Supporting Information Table S2), leading in these terms to a modest discontinuity and a reduction in variance in these terms at the start of the 22nd century (Supporting Information Figure S7). Acknowledging the limitations of these assumptions, we present post-2100 projections in tables rounded to the nearest decimeter.

### 2.7. Flood Probabilities

To examine the implications of our projections for coastal flooding, we combine Latin hypercube samples from the sea-level distribution for an illustrative subset of sites with maximum-likelihood generalized Pareto distributions (GPDs) estimated from observed storm tides after Tebaldi *et al.* [2012], updated to use the full historic record of hourly water levels available at each location. Hourly data for non-U.S. sites are from the University of Hawaii Sea Level Center (retrieved from [uhslc.soest.hawaii.edu](http://uhslc.soest.hawaii.edu), May 2014). The estimated GPDs do not take into account any future changes in storm frequency, intensity, or track [e.g., Knutson *et al.*, 2010], so projected future flood probabilities should be viewed primarily as an illustration.

Using the maximum-likelihood GPDs, we compute return levels corresponding to a set of representative return periods (e.g., the 1-in-10 or 1-in-100 year flood events). For each decade of each realization of LSL change, we then add the projected sea-level change and re-estimate a GPD. The result for each realization is a trajectory of probabilities over time for each of the original return levels. For example, for the 10-year event, the initial probability at 2000 is 10% per year and increases over time as sea-level rises. Cumulatively summing each decade's expectation through the century, we compute the expected number of the original events by 2100. Under stationary sea levels, there would be one expected 1-in-100 year event and ten expected 1-in-10 year events between 2001 and 2100.





**Figure 2.** Projections of cumulative contributions of (a) the Greenland ice sheet, (b) the Antarctic ice sheet, (c) thermal expansion, and (d) glaciers to sea-level rise in RCP 8.5. Heavy = median, light = 67% range, dashed = 5th–95th percentile; dotted = 0.5th–99.5th percentiles.

### 3. Sea-Level Projections

#### 3.1. Mean Global Sea-Level Projections

The cumulative 21st century GSL contribution of each component is shown in Figure 2 (for RCP 8.5) and in Table 1 and Supporting Information Figure S7 (for all RCPs). In the 21st century, thermal expansion and GIC provide the largest contributions to the median outcome and have narrower uncertainty ranges than the ice sheet contributions. AIS has the broadest uncertainty range, extending from a small negative contribution to sea level (presumably due to warming-induced increased snow accumulation) to a large positive contribution (requiring a substantial and/or widespread dynamic change).

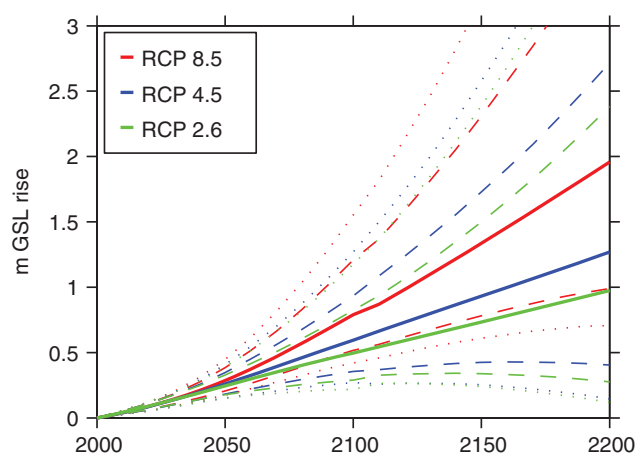
Adding samples from the component distributions together indicates a *likely* GSL rise (Figure 3 and Table 1) in RCP 8.5 of 0.6–1.0 m by 2100, with a *very likely* range of 0.5–1.2 m and a *virtually certain* (99% probability) range of 0.4–1.8 m. The right-skewed “fat tail” of the projections arises from the ice sheet components. Even in the low-emissions RCP 2.6 pathway, sea-level rise by 2100 *very likely* exceeds the 32 cm that would be projected from a simple linear continuation of the 1993–2009 rate [Church and White, 2011].

Through the middle of the current century, GSL rise is nearly indistinguishable between the three forcing pathways (Figure 3 and Table 1). Only in the second half of the century do differences of >6 cm begin to emerge in either the median or the tails of the projections. By 2100, median projections reach 0.8 m for RCP 8.5, 0.6 m for RCP 4.5 and 0.5 m for RCP 2.6. By 2200, upper tail outcomes are clearly higher in the high-forcing pathway, yet there remains significant overlap in the ranges of all three pathways, with *likely* GSL rise by 2200 of 1.3–2.8 m in RCP 8.5 and 0.5–1.6 m in RCP 2.6. The overlap between RCPs is due in significant part to the large and scenario-independent uncertainty of AIS dynamics, even as the thermal expansion, GIC and, to a lesser extent, GIS contributions begin to differentiate (Supporting Information Figure S7).

**Table 1.** GSL Projections<sup>a</sup>

cm	RCP 8.5					RCP 4.5					RCP 2.6				
	50	17–83	5–95	0.5–99.5	99.9	50	17–83	5–95	0.5–99.5	99.9	50	17–83	5–95	0.5–99.5	99.9
<b>2100—Components</b>															
GIC	18	14–21	11–24	7–29	<30	13	10–17	7–19	3–23	<25	12	9–15	7–17	3–20	<25
GIS	14	8–25	5–39	3–70	<95	9	4–15	2–23	0–40	<55	6	4–12	3–17	2–31	<45
AIS	4	–8 to 15	–11 to 33	–14 to 91	<155	5	–5 to 16	–9 to 33	–11 to 88	<150	6	–4 to 17	–8 to 35	–10 to 93	<155
TE	37	28–46	22–52	12–62	<65	26	18–34	13–40	4–48	<55	19	13–26	8–31	1–38	<40
LWS	5	3–7	2–8	–0 to 11	<11	5	3–7	2–8	–0 to 11	<11	5	3–7	2–8	–0 to 11	<11
Total	79	62–100	52–121	39–176	<245	59	45–77	36–93	24–147	<215	50	37–65	29–82	19–141	<210
<b>Projections by year</b>															
2030	14	12–17	11–18	8–21	<25	14	12–16	10–18	8–20	<20	14	12–16	10–18	8–20	<20
2050	29	24–34	21–38	16–49	<60	26	21–31	18–35	14–44	<55	25	21–29	18–33	14–43	<55
2100	79	62–100	52–121	39–176	<245	59	45–77	36–93	24–147	<215	50	37–65	29–82	19–141	<210
2150	130	100–180	80–230	60–370	<540	90	60–130	40–170	20–310	<480	70	50–110	30–150	20–290	<460
2200	200	130–280	100–370	60–630	<950	130	70–200	40–270	10–520	<830	100	50–160	30–240	10–500	<810
<b>Other projections for 2100</b>															
AR5	73	53–97				52	35–70				43	28–60			
H14		70–120	50–150									40–60	25–70		
J12	110		81–165			75		52–110			57		36–83		
S12						90		64–121			75		52–96		

<sup>a</sup>TE: Thermal expansion, LWS: Land water storage, H14: Horton *et al.* [2014], J12: Jevrejeva *et al.* [2012], S12: Schaeffer *et al.* [2012]. All values are cm above 2000 CE baseline except for AR5, which is above a 1986–2005 baseline.



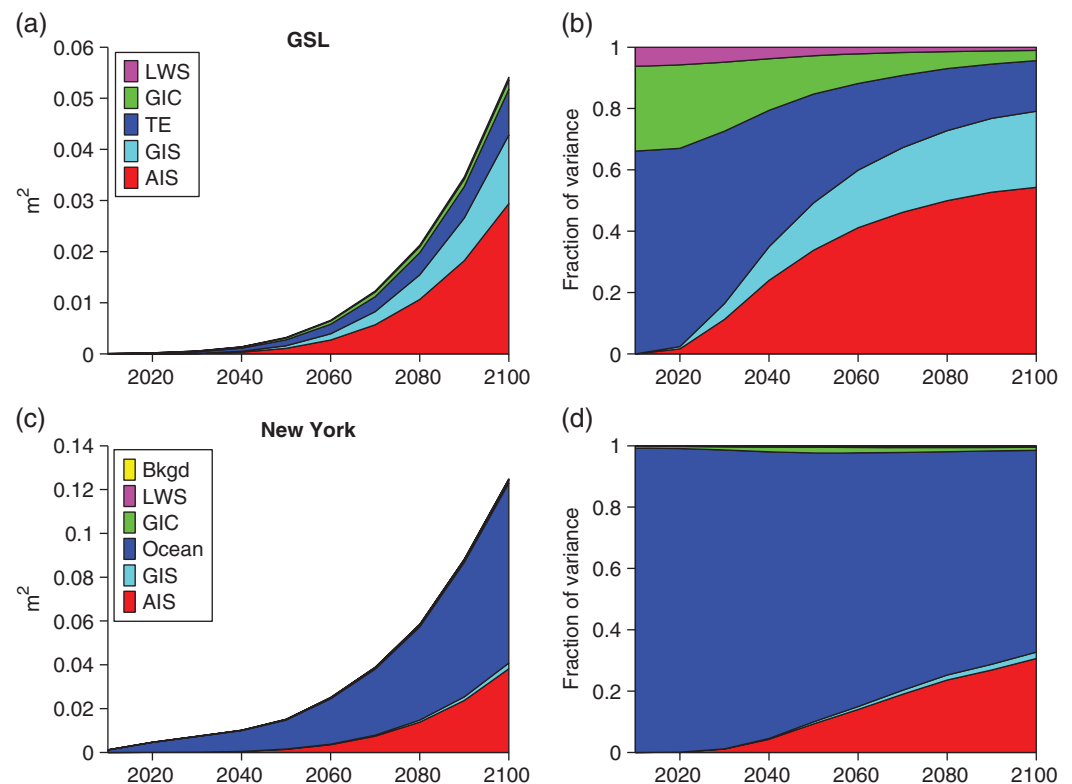
**Figure 3.** Projections of GSL rise for the three RCPs. Heavy = median, dashed = 5th–95th percentile, dotted = 0.5th–99.5th percentiles.

The importance of different components to the GSL uncertainty varies with time. While in 2020 about two-thirds of the total variance in GSL is due to uncertainty in projections of thermal expansion, by 2050 in RCP 8.5 changes in ice sheet volume are responsible for more than half the variance and changes in thermal expansion for only about one-third. By 2100, AIS alone is responsible for half the variance, with an additional 30% due to GIS uncertainty and only 15% due to uncertainty in thermal expansion (Figure 4). Because the uncertainty in AIS mass loss is largely scenario-independent, its dominant contribution to variance holds across RCPs; indeed, it is even

more dominant in lower emissions pathways where the contributions from other sources are smaller and more strongly constrained (Supporting Information Figure S8).

### 3.2. Comparison With Other Global Projections

By construction, our *likely* projections of GSL in 2100 are close to those of AR5 (Table 1), though differ slightly (e.g., in RCP 8.5 in 2100, 0.6–1.0 m vs. AR5's 0.5–1.0 m) due to: (1) the drift correction to a possibly non-zero ( $0.3 \pm 0.9$  mm/yr) background thermal expansion, (2) the use of *Marzeion et al.* [2012] for GIC, and (3) the use of a year 2000 as opposed to 1985–2005 baseline. AR5 projections of GSL rise are lower



**Figure 4.** Sources of variance in raw (a, c) and fractional terms (b, d), globally (a–b) and at New York City (c–d) in RCP 8.5. AIS: Antarctic ice sheet, GIS: Greenland ice sheet, TE: thermal expansion, Ocean: oceanographic processes, GIC: glaciers and ice caps, LWS: land water storage, Bkgd: local background effects.

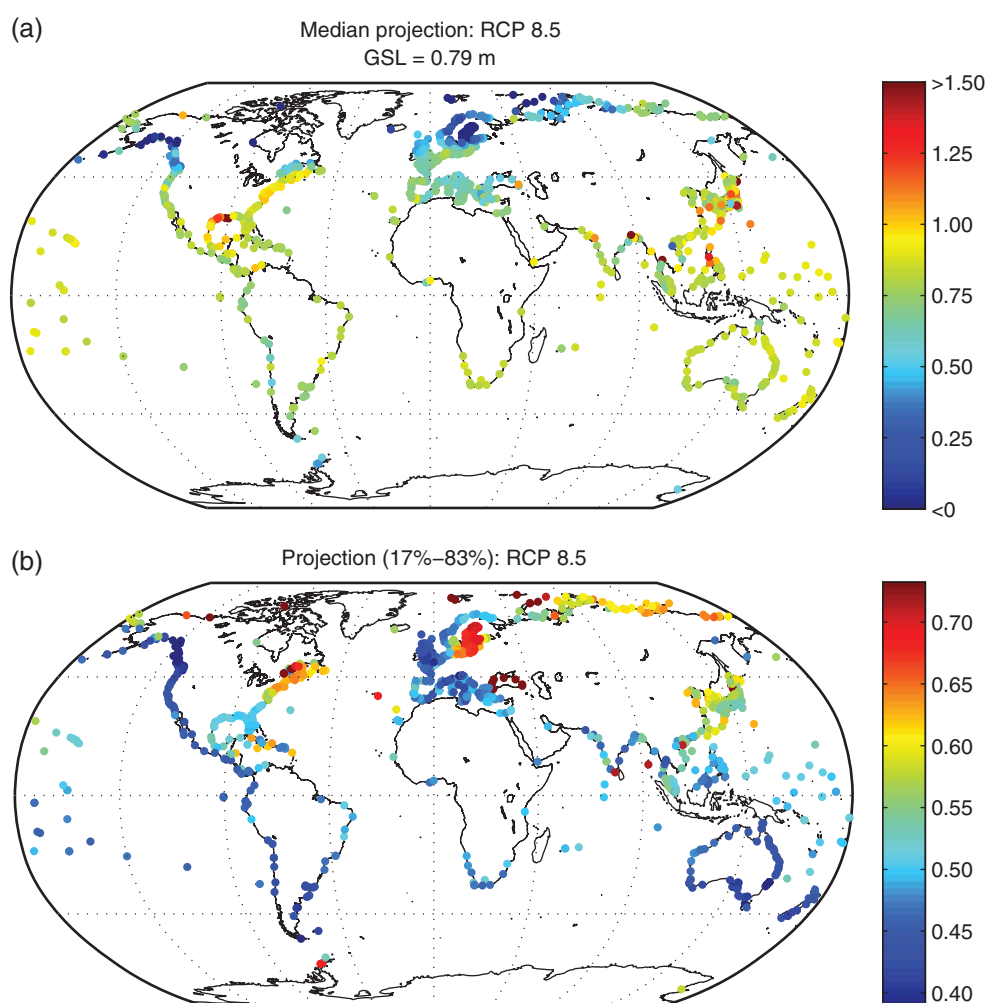
than those from other sources, such as semi-empirical models [Rahmstorf, 2007; Schaeffer et al., 2012; Vermeer and Rahmstorf, 2009] and expert surveys [Horton et al., 2014]. However, AR5 only projects *likely* ranges; higher magnitudes of ice loss are implied if less likely outcomes are considered [Little et al., 2013a].

By using plausible information to complement the AR5 analysis, we project a *very likely* GSL rise in 2100 of 0.4–0.9 m for RCP 4.5, which compares to the 90% probability semi-empirical projections of 0.5–1.1 m [Jevrejeva et al., 2012] and 0.6–1.2 m [Schaeffer et al., 2012]. The widths of the semi-empirical *very likely* ranges are similar to those of our projections, with the entire distribution shifted to higher values. The 95th percentiles of these two semi-empirical projections resemble the 98th and 99th percentiles of our projection, respectively.

Horton et al. [2014] conducted a survey of 90 experts with a substantial published record in sea-level research. Their survey found *likely/very likely* sea-level rise by 2100 of 0.7–1.2/0.5–1.5 m under RCP 8.5 and 0.4–0.6/0.3–0.7 m under RCP 2.6. Our projections for RCP 2.6 are similar to those of the surveyed experts, with a slightly fatter upper tail, while the experts' responses for RCP 8.5 are considerably fatter-tailed than our projections. The surveyed experts' 83rd and 95th percentiles correspond to our 95th and 99th percentiles, respectively. Although Horton et al. [2014] did not probe the reasons why their surveyed experts differed from AR5, we suggest it may be related to expectations about the behavior of Antarctica. As noted previously, high-end estimates of Antarctic mass loss from the expert elicitation of BA13 are higher than would be expected from the *likely* range of AR5 projections; our reconciled ice sheet projections significantly lower this contribution. (See also the sensitivity tests in section 4 for comparison.)

Our 99.9th percentile estimate for 2100 under RCP 8.5, 2.5 m, is consistent with other estimates of the maximum physically possible rate of sea-level rise in the 21st century [e.g., Miller et al., 2013]. It is higher than the 2.0 m estimate of Pfeffer et al. [2008], which corresponds to our 99.7th percentile. Comparing the individual contribution to Pfeffer et al.'s high-end projection shows that their projected GIC mass loss (55 cm) exceeds our highest projected value (32 cm), while their projections of GIS and AIS mass loss





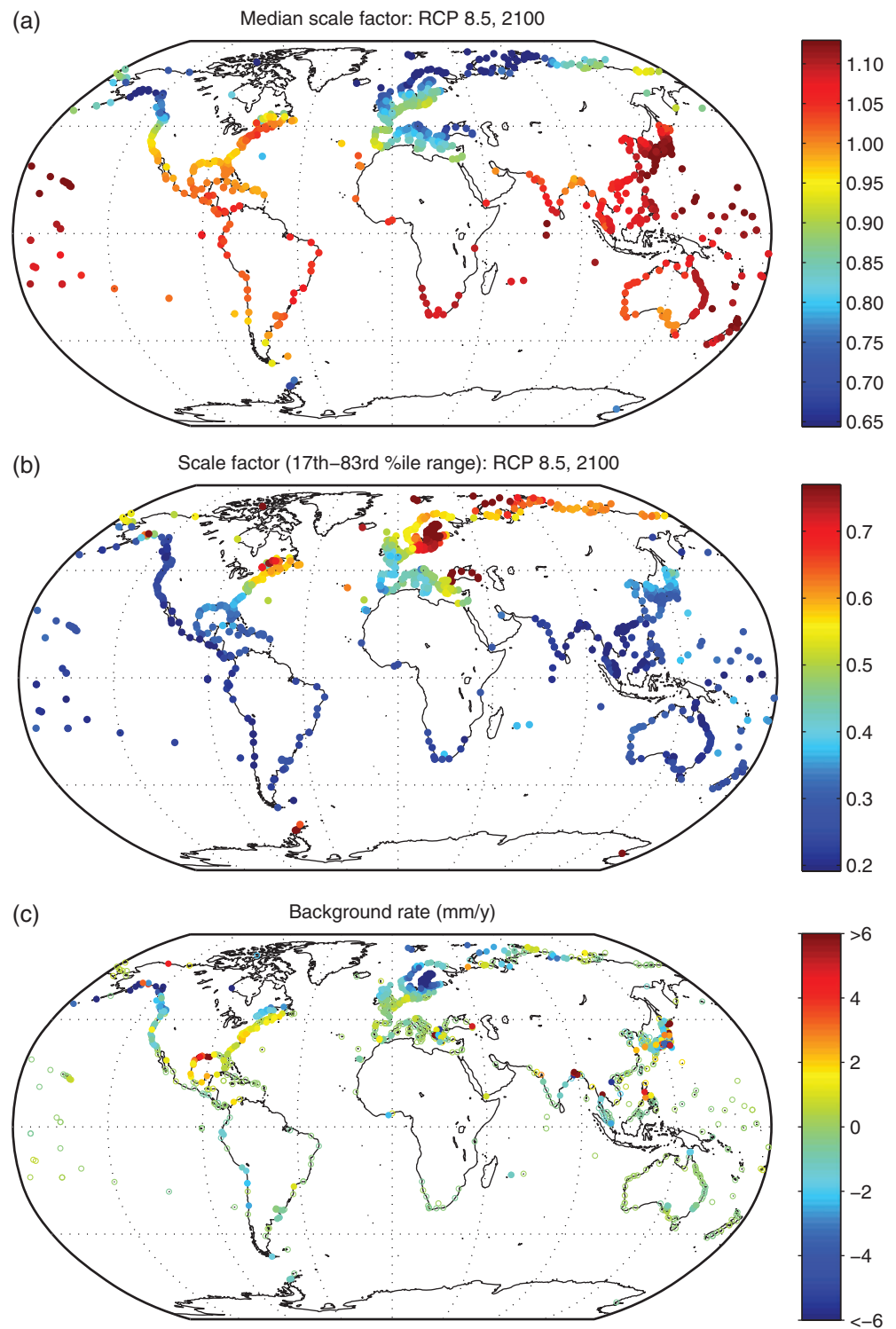
**Figure 5.** (a) Median projection and (b) width of likely range of local sea-level rise (m) in 2100 under RCP 8.5.

(53 and 62 cm, respectively) correspond to our 98th and 99th percentiles. Their projection of thermal expansion (30 cm) includes no uncertainty and corresponds to our 22nd percentile [cf., *Sliver et al.*, 2012]. They do not include changes in sea-level rise resulting from changes in land water storage. As noted previously, the tail of the sea-level rise projections is dominated by the uncertainty in AIS mass loss, which is lower in *Pfeffer et al.* [2008] than in either our projections or BA13.

### 3.3. Local Sea-Level Projections: Patterns

Figure 5 displays the median LSL projections for RCP 8.5 in 2100 and the projection uncertainty, as reflected by the difference between the 17th and 83rd percentile levels. In Figure 6, we illustrate the relationship between LSL and GSL using three indices: (1) the median value of  $R$ , which we define as the ratio of LSL change driven by land ice and oceanographic components to GSL change driven by those same components (Figure 6a), (2) the uncertainty in  $R$ , reflected in Figure 6b by the difference between its 17th and 83rd percentile levels, and (3) the magnitude and uncertainty of background, non-climatic LSL change (Figure 6c). For sites where  $R$  is close to 1 and exhibits little uncertainty, GSL projections with adjustment for local land motion provide a reasonable estimate of LSL; for other sites, more detailed projections, such as those in this article, are necessary.

The median value of  $R$  (Figure 6a) is within 5 % of unity at about a quarter of tide-gauge sites, with higher values in much of Oceania, the Indian Ocean, and southern Africa resulting from the static-equilibrium effects of land ice mass loss.  $R$  generally declines toward higher latitudes due to static-equilibrium effects,



**Figure 6.** (a) Median ratio  $R$  of climatically driven LSL change to climatically driven GSL exchange (i.e., excluding land water storage and local land motion) in RCP 8.5 in 2100; (b) width of the 17th–83rd percentile range of  $R$ ; (c) mean estimates of background rate of sea-level rise due to GIA, tectonics, and other local factors (mm/yr). Open circles in bottom indicate sites where  $2\sigma$  range spans zero.

but with values elevated in northeastern North America and to a lesser extent the North and Baltic Seas by oceanographic processes. This pattern—with sea-level rise dampened near land ice and enhanced far from it and in the northwestern North Atlantic—resembles that found by previous studies [Kopp *et al.*, 2010; Perrette *et al.*, 2013; Slangen *et al.*, 2012, 2014]. Uncertainty in  $R$  (Figure 6b) is also relatively small (*likely* range width of  $< 30\%$ ) in the inhabited southern hemisphere and low-latitude northern hemisphere, with the range increasing northwards due to both the sensitivity of static-equilibrium effects to the particular distribution of shrinking land ice reservoirs and—especially in northeastern North America, the Baltic Sea, and the Russian Arctic—uncertainty in oceanographic processes (Supporting Information Figure S4).

Added on top of the climatically driven factors reflected in  $R$  are the global effects of land water storage (not shown in Figure 6) and the effects of local land motion (Figure 6c). Moderately high rates of land subsidence can be associated with GIA, as in the northeastern United States (e.g.,  $1.3 \pm 0.2$  mm/yr at New York City), while more extreme rates generally include contributions from fluid withdrawal, delta processes, and/or tectonics. Subsidence driven by fluid withdrawal and delta processes is high at sites such as Bangkok, Thailand (background rate of  $11.9 \pm 1.1$  mm/yr at the Fort Phracula Chomklao tide gauge), Grand Isle, Louisiana ( $7.2 \pm 0.5$  mm/yr), Manila, the Philippines (background rate of  $4.9 \pm 0.6$  mm/yr), and Kolkata, India ( $5.1 \pm 1.0$  mm/yr). Episodic tectonic factors play an important role in both subsidence and uplift in Japan, where average background rates can range from  $-5.2 \pm 0.7$  mm/yr at Onahama to  $18.0 \pm 1.6$  mm/yr at Toba. At high latitudes, GIA-related uplift gives rise to high background rates of sea-level fall, as can be seen in places like Juneau, Alaska, ( $-14.9 \pm 0.5$  mm/yr), and Ratan, Sweden ( $-9.3 \pm 0.2$  mm/yr). While some previous global projections have used physical models to incorporate GIA [e.g., Slangen *et al.*, 2012, 2014], the current projections are to our knowledge the first to employ observationally based rates.

### 3.4. Local Sea-Level Projections: Examples

To illustrate the importance of local factors for sea-level rise projections, we consider several sites along the coasts of the United States where different factors dominate LSL change (Tables 2 and 3). While we focus on projections for RCP 8.5 as a way of highlighting the differences between GSL and LSL, similar considerations apply to other RCPs, which are shown in the tables.

New York City experiences greater-than-global sea-level rise under almost all plausible projections, with a *likely* range of 0.7–1.3 m by 2100 under RCP 8.5. Three factors enhance sea-level rise at New York. First, due to its location on the subsiding peripheral bulge of the former Laurentide Ice Sheet, the site experiences GIA-related sea-level rise of  $1.3 \pm 0.2$  mm/yr. Second, the rotational effects of WAIS mass loss increase the region's sea-level response to WAIS mass loss by about 20% [Mitrovica *et al.*, 2009]. Third, as noted in earlier papers [Kopp *et al.*, 2010; Yin *et al.*, 2009; Yin and Goddard, 2013], changes in the Gulf Stream may result in dynamic sea-level rise in the mid-Atlantic United States. This enhancement can be seen by examining the difference between oceanographic sea-level rise at New York and the global average, which has a median of 14 cm and a *likely* range of  $-6$  to  $+35$  cm. These three effects are partially counteracted by the  $\sim 55\%$  reduction in the sea-level response due to GIS mass loss, associated with the gravitationally induced migration of water away from of this relatively proximal ice mass. Indeed, the climatic factors that amplify and reduce LSL rise relative to GSL rise are nearly balanced in the median projection ( $R = 1.03$ , with a *likely* range of 0.73–1.30), with GIA effects pushing local rise to levels that exceed the global rise.

Sewell's Point in Norfolk, VA, is projected to experience higher-than-global mean sea-level rise due to the same factors as New York City: subsidence due to GIA, enhanced influence of WAIS mass loss, and exposure to changes in the Gulf Stream. Being located farther south along the U.S. East Coast, Norfolk experiences somewhat smaller ocean dynamic changes (median and *likely* ocean dynamic sea-level rise increment of 9 cm and  $-8$  to 26 cm) but greater sea-level rise due to GIS mass loss (experiencing about  $\sim 45\%$  less sea-level rise than the global mean). Its  $R$  value (1.00, *likely* range of 0.75–1.22) is similar to New York City. However, whereas New York City sits upon bedrock, Norfolk is located on the soft sediments of the Coastal Plain [Miller *et al.*, 2013]. As a consequence, it is exposed to sea-level rise due to both natural sediment compaction and compaction caused by groundwater withdrawal, which increases the background non-climatic rate of sea-level rise to  $2.5 \pm 0.3$  mm/yr. Accordingly, the *likely* range of LSL rise for RCP 8.5 in 2100 is 0.8–1.3 m.

**Table 2.** LSL Projections

		RCP 8.5				RCP 4.5				RCP 2.6					
cm	50	17–83	5–95	0.5–99.5	99.9	50	17–83	5–95	0.5–99.5	99.9	50	17–83	5–95	0.5–99.5	99.9
New York, NY, USA (Bkgd: 1.31 ± 0.18 mm/yr)															
2030	21	13–29	7–35	–1 to 44	<50	20	15–25	11–29	6–34	<40	20	14–26	9–31	2–38	<40
2050	38	27–50	19–59	8–73	<85	36	26–45	19–53	10–66	<75	35	24–45	16–53	6–67	<75
2100	96	65–129	44–154	15–212	<305	75	51–101	35–123	11–183	<255	62	41–85	27–106	7–170	<245
2150	150	110–200	90–250	60–420	<610	110	70–160	40–200	10–360	<520	90	60–120	40–170	30–340	<520
2200	210	150–290	120–370	70–690	<1020	140	80–220	50–300	–0 to 600	<890	110	60–180	40–260	20–580	<890
Sewell's Point, VA, USA (Bkgd: 2.45 ± 0.29 mm/yr)															
2030	24	18–29	14–34	8–40	<45	23	19–28	15–31	11–36	<40	23	18–28	15–32	9–38	<40
2050	43	34–53	27–60	18–73	<85	41	32–49	26–56	19–68	<80	40	31–48	24–55	16–68	<80
2100	105	77–134	59–158	33–218	<305	86	64–109	50–129	31–189	<260	74	55–96	42–116	23–183	<255
2150	170	130–210	110–260	80–430	<630	130	90–170	70–220	40–380	<540	110	80–140	60–190	50–360	<540
2200	230	170–310	140–400	100–710	<1050	170	110–240	80–320	30–620	<930	140	90–200	70–290	40–610	<920
Key West, FL, USA (Bkgd: 0.46 ± 0.41 mm/yr)															
2030	17	13–21	10–25	6–29	<30	16	12–21	9–24	5–28	<30	17	13–20	10–23	6–27	<30
2050	33	25–40	21–46	14–58	<75	30	23–36	19–42	12–53	<65	29	23–35	19–40	14–51	<65
2100	84	61–111	46–134	25–200	<290	65	47–86	35–105	19–172	<250	55	39–75	29–94	16–166	<240
2150	140	100–190	80–250	40–410	<620	100	60–140	40–190	20–350	<540	80	50–120	40–170	20–340	<530
2200	200	140–290	100–390	60–690	<1060	140	80–210	40–300	0–590	<940	110	50–180	30–270	10–590	<920
Galveston, TX, USA (Bkgd: 4.56 ± 0.27 mm/yr)															
2030	29	25–34	22–37	17–42	<45	28	24–33	21–36	17–40	<40	29	24–34	20–38	15–43	<45
2050	52	45–60	40–66	33–78	<95	49	43–56	38–61	32–71	<85	49	42–56	37–62	31–73	<90
2100	123	99–150	83–173	61–233	<325	105	86–125	75–144	58–208	<280	95	77–115	66–135	50–203	<275
2150	200	160–250	140–300	110–460	<660	160	120–200	100–250	70–400	<580	140	110–180	100–230	80–400	<570
2200	280	220–360	180–460	150–760	<1100	210	160–290	120–370	80–660	<990	190	140–250	110–340	90–650	<970
San Francisco, CA, USA (Bkgd: –0.08 ± 0.18 mm/yr)															
2030	13	10–16	8–18	6–21	<25	13	9–16	7–19	3–23	<25	13	10–16	8–18	5–22	<25
2050	27	20–33	16–39	10–50	<70	25	19–31	14–36	8–47	<65	24	18–30	13–35	7–46	<65
2100	75	55–99	43–122	26–190	<275	58	40–78	29–98	14–165	<240	50	35–69	25–88	12–159	<235
2150	130	90–170	70–230	50–390	<590	90	60–130	40–180	10–340	<530	70	40–110	30–160	20–330	<520
2200	180	120–270	80–370	50–680	<1030	130	70–200	30–280	–0 to 580	<920	100	40–170	20–260	–0 to 580	<910
Juneau, AK, USA (Bkgd: –14.91 ± 0.53 mm/yr)															
2030	–35	–37 to –32	–39 to –30	–42 to –27	<–25	–35	–38 to –33	–40 to –31	–42 to –28	<–25	–35	–38 to –33	–40 to –31	–42 to –27	<–25
2050	–54	–59 to –49	–63 to –44	–67 to –33	<–15	–56	–60 to –51	–64 to –47	–68 to –36	<–20	–57	–62 to –51	–66 to –47	–71 to –36	<–20
2100	–92	–108 to –72	–118 to –52	–131–18	<95	–104	–118 to –87	–127 to –68	–139 to –3	<70	–110	–124 to –93	–133 to –74	–144 to –6	<65
2150	–120	–160 to –80	–180 to –30	–210 to 130	<330	–150	–180 to –110	–200 to –70	–220 to 90	<260	–170	–190 to –130	–210 to –80	–220 to 90	<260
2200	–150	–210 to –70	–250 to 20	–290 to 310	<670	–200	–250 to –130	–280 to –50	–320 to 250	<560	–220	–270 to –160	–290 to –70	–310 to 250	<560

**Table 2.** (continued)

cm	RCP 8.5					RCP 4.5					RCP 2.6				
	50	17–83	5–95	0.5–99.5	99.9	50	17–83	5–95	0.5–99.5	99.9	50	17–83	5–95	0.5–99.5	99.9
Honolulu, HI, USA (Bkgd: $-0.20 \pm 0.39$ mm/yr)															
2030	15	12–18	9–21	6–25	<30	15	11–18	8–21	5–25	<30	15	12–18	9–20	6–24	<25
2050	30	23–38	18–44	12–57	<75	28	21–35	17–40	11–51	<70	26	20–33	15–39	8–51	<70
2100	87	63–114	48–141	28–209	<305	65	46–86	34–107	19–177	<265	55	37–76	26–97	11–170	<260
2150	140	100–200	70–260	40–440	<660	100	60–150	40–200	10–370	<580	80	50–120	30–180	10–360	<570
2200	210	130–320	90–430	40–760	<1150	140	70–220	40–320	–10 to 630	<1010	110	50–180	20–280	–0 to 610	<1000
Cuxhaven, Germany (Bkgd: $1.00 \pm 0.17$ mm/yr)															
2030	17	11–22	7–26	2–32	<35	16	10–22	6–27	–0 to 33	<35	16	9–23	4–28	–4 to 36	<40
2050	33	23–43	15–50	6–63	<75	29	21–37	15–43	6–54	<65	28	19–37	12–45	2–57	<70
2100	81	57–106	41–128	19–184	<260	61	45–80	34–98	19–156	<225	49	33–67	23–85	9–148	<220
2150	130	90–170	70–220	40–370	<550	90	60–130	40–170	10–320	<480	80	50–110	30–150	20–310	<480
2200	180	120–250	90–330	50–610	<940	120	60–180	40–260	0–530	<830	100	50–160	30–240	0–530	<840
Stockholm, Sweden (Bkgd: $-5.01 \pm 0.12$ mm/yr)															
2030	–4	–16 to 9	–25 to 18	–38 to 31	<40	–3	–11 to 6	–17 to 11	–25 to 20	<25	–5	–19 to 9	–29 to 20	–45 to 36	<45
2050	–2	–24 to 19	–39 to 36	–61 to 59	<70	–2	–13 to 9	–21 to 18	–33 to 31	<40	–7	–29 to 15	–45 to 31	–69 to 55	<70
2100	17	–17 to 52	–41 to 80	–74 to 132	<210	–1	–21 to 21	–35 to 41	–55 to 94	<165	–19	–56 to 19	–84 to 49	–125 to 107	<175
2150	30	–10 to 80	–40 to 130	–80 to 270	<450	0	–40 to 40	–60 to 80	–90 to 220	<390	–40	–150 to 60	–220 to 140	–330 to 290	<440
2200	50	–20 to 120	–60 to 200	–110 to 480	<810	–10	–60 to 60	–90 to 140	–130 to 400	<710	–60	–200 to 80	–290 to 200	–430 to 440	<760
Kushimoto, Japan (Bkgd: $1.46 \pm 0.80$ mm/yr)															
2030	20	15–25	12–28	8–33	<35	19	15–24	11–27	7–32	<35	20	15–24	11–28	7–33	<35
2050	40	30–49	24–57	15–68	<85	36	28–44	22–51	15–61	<75	35	26–43	20–50	12–61	<75
2100	104	79–133	63–159	41–219	<310	80	59–103	45–124	28–180	<265	70	51–91	39–112	23–172	<255
2150	170	120–220	100–280	60–440	<650	120	80–170	60–220	30–370	<570	100	70–140	50–190	40–350	<540
2200	240	170–350	120–450	70–740	<1140	170	100–250	60–340	20–620	<1000	130	80–210	50–290	30–590	<950
Valparaíso, Chile (Bkgd: $-2.47 \pm 0.79$ mm/yr)															
2030	6	3–9	1–11	–1 to 13	<15	5	2–8	0–11	–3 to 14	<15	6	3–8	1–10	–1 to 12	<15
2050	15	9–21	5–26	0–36	<45	13	7–19	3–23	–3 to 32	<40	12	6–17	2–22	–3 to 30	<40
2100	54	35–77	23–99	8–149	<210	36	18–55	8–72	–7 to 115	<170	27	12–44	3–61	–6 to 107	<165
2150	100	60–150	40–200	20–330	<470	60	30–100	0–140	–20 to 250	<390	40	10–70	–0 to 110	–20 to 230	<370
2200	150	90–250	50–340	10–580	<910	80	20–150	–10 to 230	–50 to 440	<740	50	–0 to 110	–20 to 180	–50 to 410	<740



**Table 3.** Components of LSL Rise in 2100

		RCP 8.5				RCP 4.5				RCP 2.6					
cm	50	17–83	5–95	0.5–99.5	99.9	50	17–83	5–95	0.5–99.5	99.9	50	17–83	5–95	0.5–99.5	99.9
New York, NY, USA															
GIC	14	11–17	9–19	6–22	<25	11	8–13	6–15	3–18	<20	9	7–12	5–13	3–16	<20
GIS	6	3–11	2–17	1–31	<40	4	2–7	1–10	0–18	<25	3	2–5	1–8	1–14	<20
AIS	4	–8 to 17	–12 to 38	–15 to 108	<180	6	–5 to 19	–9 to 38	–12 to 104	<170	7	–4 to 20	–8 to 40	–11 to 110	<180
Oce.	51	24–78	5–98	–24 to 125	<140	35	15–55	1–70	–23 to 92	<100	23	6–41	–6 to 53	–25 to 71	<80
LWS	5	3–7	2–8	–0 to 11	<10	5	3–7	2–8	–0 to 11	<10	5	3–7	2–8	–0 to 11	<10
GIA/Tect.	13	12–14	12–15	11–15	<15	13	12–14	12–15	11–15	<15	13	12–14	12–15	11–15	<15
Total	96	65–129	44–154	15–212	<305	75	51–101	35–123	11–183	<255	62	41–85	27–106	7–170	<245
Sewell's Point, VA, USA															
GIC	15	12–18	9–21	6–24	<25	11	9–14	6–16	3–20	<20	10	8–13	6–14	3–17	<20
GIS	8	4–14	3–22	2–39	<55	5	2–9	1–13	0–22	<30	4	2–6	2–10	1–17	<25
AIS	4	–8 to 17	–12 to 38	–15 to 108	<180	6	–5 to 19	–9 to 38	–12 to 105	<170	7	–4 to 20	–8 to 40	–11 to 110	<180
Oce.	46	23–69	7–85	–17 to 108	<120	32	16–49	4–62	–15 to 79	<90	22	8–38	–3 to 48	–19 to 64	<70
LWS	5	3–7	2–8	–0 to 11	<10	5	3–7	2–8	–0 to 11	<10	5	3–7	2–8	–0 to 11	<10
GIA/Tect.	25	23–26	22–27	21–28	<30	25	23–26	22–27	21–28	<30	25	23–26	22–27	21–28	<30
Total	105	77–134	59–158	33–218	<305	86	64–109	50–129	31–189	<260	74	55–96	42–116	23–183	<255
Key West, FL, USA															
GIC	18	14–22	11–24	7–29	<30	13	10–17	7–19	4–23	<25	12	9–15	7–17	3–20	<25
GIS	12	6–21	4–32	2–58	<80	8	3–13	2–19	0–33	<45	5	3–10	2–15	2–26	<35
AIS	4	–8 to 18	–13 to 39	–16 to 110	<185	6	–6 to 19	–10 to 39	–13 to 106	<175	7	–5 to 20	–8 to 41	–11 to 112	<185
Oce.	39	22–56	10–68	–8 to 85	<95	28	15–40	6–49	–8 to 62	<70	20	10–31	3–38	–8 to 49	<55
LWS	5	3–7	2–8	–0 to 11	<10	5	3–7	2–8	–0 to 11	<10	5	3–7	2–8	–0 to 11	<10
GIA/Tect.	5	3–7	1–8	–1 to 10	<10	5	3–7	1–8	–1 to 10	<10	5	3–7	1–8	–1 to 10	<10
Total	84	61–111	46–134	25–200	<290	65	47–86	35–105	19–172	<250	55	39–75	29–94	16–166	<240
Galveston, TX, USA															
GIC	16	13–20	10–23	6–27	<30	13	9–16	7–18	3–22	<25	11	8–14	6–16	3–19	<20
GIS	11	6–21	4–31	2–56	<75	7	3–12	1–18	0–32	<45	5	3–9	2–14	2–25	<35
AIS	4	–8 to 17	–12 to 38	–15 to 107	<180	6	–5 to 19	–9 to 38	–12 to 103	<170	7	–4 to 20	–8 to 40	–11 to 109	<180
Oce.	38	20–57	7–70	–13 to 89	<100	27	15–40	6–49	–9 to 62	<70	20	7–32	–2 to 42	–16 to 55	<60
LWS	5	3–7	2–8	–0 to 11	<10	5	3–7	2–8	–0 to 11	<10	5	3–7	2–8	–0 to 11	<10
GIA/Tect.	46	44–47	43–48	42–49	<50	46	44–47	43–48	42–49	<50	46	44–47	43–48	42–49	<50
Total	123	99–150	83–173	61–233	<325	105	86–125	75–144	58–208	<280	95	77–115	66–135	50–203	<275

**Table 3.** (continued)

cm	RCP 8.5			RCP 4.5			RCP 2.6		
	50	17–83	5–95	50	17–83	5–95	50	17–83	5–95
<b>San Francisco, CA, USA</b>									
GIC	15	12–18	9–21	6–24	<25	<25	11	8–14	6–17
GIS	12	7–23	5–35	3–62	<85	<85	8	3–14	2–20
AIS	4	–8 to 18	–13 to 39	–16 to 111	<185	<185	6	–6 to 19	–10 to 39
Oce.	37	25–50	16–60	2–72	<80	<80	27	16–39	8–47
LWS	5	3–7	2–8	–0 to 11	<10	<10	5	3–7	2–8
GIA/Tect.	–1	–2 to 0	–2 to 1	–3 to 2	<0	<0	–1	–2 to 0	–2 to 1
Total	75	55–99	43–122	26–190	<275	<275	58	40–78	29–98
<b>Juneau, AK, USA</b>									
GIC	3	1–4	0–5	–1 to 6	<5	<5	2	1–3	0–4
GIS	8	5–15	3–23	2–42	<55	<55	5	2–9	1–14
AIS	4	–8 to 17	–12 to 37	–15 to 106	<180	<180	6	–6 to 19	–9 to 38
Oce.	36	27–46	20–53	9–62	<65	<65	26	18–35	13–41
LWS	5	3–7	2–8	–0 to 11	<10	<10	5	3–7	2–8
GIA/Tect.	149	–152 to –147	–153 to –145	–156 to –142	<–140	<–140	–149	–152 to –147	–153 to –145
Total	–92	–108 to –72	–118 to –52	–131 to 18	<95	<95	–104	–118 to –87	–127 to –68
<b>Honolulu, HI, USA</b>									
GIC	20	15–24	12–27	7–32	<35	<35	15	11–19	8–22
GIS	17	9–31	6–47	4–85	<115	<115	11	5–19	2–28
AIS	5	–9 to 19	–14 to 41	–17 to 115	<195	<195	7	–6 to 20	–11 to 42
Oce.	40	24–55	14–66	–3 to 81	<90	<90	28	17–39	10–47
LWS	5	3–7	2–8	–0 to 11	<10	<10	5	3–7	2–8
GIA/Tect.	–2	–4 to 0	–5 to 1	–7 to 3	<5	<5	–2	–4 to 0	–5 to 1
Total	87	63–114	48–141	28–209	<305	<305	65	46–86	34–107
<b>Cuxhaven, Germany</b>									
GIC	8	7–10	5–12	3–14	<15	<15	6	5–8	4–9
GIS	2	1–4	1–7	0–12	<15	<15	2	1–3	0–4
AIS	4	–8 to 16	–12 to 36	–15 to 97	<165	<165	6	–6 to 17	–10 to 36
Oce.	51	30–70	16–85	–5 to 106	<115	<115	33	21–45	12–54
LWS	5	3–7	2–8	–0 to 11	<10	<10	5	3–7	2–8
GIA/Tect.	10	9–11	9–11	8–12	<15	<15	10	9–11	9–11
Total	81	57–106	41–128	19–184	<260	<260	61	45–80	34–98

**Table 3.** (continued)

Table 3. (continued)															
		RCP 8.5				RCP 4.5				RCP 2.6					
cm	50	17–83	5–95	0.5–99.5	99.9	50	17–83	5–95	0.5–99.5	99.9	50	17–83	5–95	0.5–99.5	99.9
Stockholm, Sweden															
GIC	6	4–7	3–8	2–9	<10	4	3–5	3–6	1–7	<10	4	3–4	2–5	2–6	<5
GIS	1	1–2	0–4	0–7	<10	1	0–2	0–2	0–4	<5	1	0–1	0–2	0–3	<5
AIS	4	–8 to 16	–12 to 35	–15 to 97	<160	6	–6 to 17	–10 to 35	–12 to 94	<155	6	–5 to 18	–8 to 37	–11 to 99	<165
Oce.	50	18–82	–4 to 104	–37 to 137	<155	33	17–50	4–63	–15 to 82	<90	14	–21 to 48	–47 to 75	–89 to 114	<140
LWS	5	3–7	2–8	–0 to 11	<10	5	3–7	2–8	–0 to 11	<10	5	3–7	2–8	–0 to 11	<10
GIA/Tect.	–50	–51 to –50	–51 to –49	–52 to –49	<–50	–50	–51 to –50	–51 to –49	–52 to –49	<–50	–50	–51 to –50	–51 to –49	–52 to –49	<–50
Total	17	–17 to 52	–41 to 80	–74 to 132	<210	–1	–21 to 21	–35 to 41	–55 to 94	<165	–19	–56 to 19	–84 to 49	–125 to 107	<175
Kushimoto, Japan															
GIC	18	13–22	10–24	6–29	<30	13	10–17	7–19	3–24	<25	12	9–15	6–17	3–21	<25
GIS	17	9–31	6–47	4–84	<115	11	5–18	2–27	0–48	<65	8	5–14	3–21	2–38	<50
AIS	4	–9 to 17	–13 to 38	–16 to 105	<175	6	–6 to 18	–10 to 38	–13 to 102	<165	6	–5 to 19	–9 to 40	–12 to 107	<175
Oce.	43	26–61	14–73	–5 to 91	<100	29	15–43	5–54	–11 to 69	<75	22	10–35	1–44	–14 to 57	<65
LWS	5	3–7	2–8	–0 to 11	<10	5	3–7	2–8	–0 to 11	<10	5	3–7	2–8	–0 to 11	<10
GIA/Tect.	15	11–19	8–21	4–25	<25	15	11–19	8–21	4–25	<25	15	11–19	8–21	4–25	<25
Total	104	79–133	63–159	41–219	<310	80	59–103	45–124	28–180	<265	70	51–91	39–112	23–172	<255
Valparaiso, Chile															
GIC	18	14–22	10–26	6–31	<35	13	10–17	7–20	2–25	<25	12	9–15	6–18	3–22	<25
GIS	17	9–31	6–47	4–85	<115	11	5–19	2–28	0–49	<65	8	5–14	3–21	2–38	<50
AIS	3	–8 to 14	–12 to 30	–14 to 82	<130	4	–6 to 14	–10 to 30	–12 to 79	<125	4	–5 to 15	–8 to 31	–11 to 83	<135
Oce.	33	23–44	16–51	4–62	<70	25	15–36	8–43	–3 to 53	<60	21	12–29	7–35	–3 to 44	<50
LWS	5	3–7	2–8	–0 to 11	<10	5	3–7	2–8	–0 to 11	<10	5	3–7	2–8	–0 to 11	<10
GIA/Tect.	–25	–28 to –21	–31 to –18	–35 to –15	<–15	–25	–28 to –21	–31 to –18	–35 to –15	<–15	–25	–28 to –21	–31 to –18	–35 to –15	<–15
Total	54	35–77	23–99	8–149	<210	36	18–55	8–72	–7 to 115	<170	27	12–44	3–61	–9 to 107	<165

Sea-level rise at Key West, Florida, is closer to the global mean, with a *likely* range in RCP 8.5 by 2100 of 0.6–1.1 m (median  $R = 1.00$ , *likely* range of 0.83–1.15, background rise of  $0.5 \pm 0.4$  mm/yr). By contrast, the deltaic western Gulf of Mexico coastline experiences some of the fastest rates of sea-level rise in the world as a result of groundwater withdrawal and hydrocarbon production [Kolker et al., 2011; White and Tremblay, 1995]. At Galveston, Texas, a background subsidence rate of  $4.6 \pm 0.3$  mm/yr drives a *likely* range of sea-level rise by 2100 in RCP 8.5 of 1.0–1.5 m. Because the uncertainty in subsidence rate is small relative to other sources of uncertainty, this causes a shift in the range rather than a broadening of overall uncertainty, as occurs at New York City (reflected in a *likely*  $R$  of 0.78–1.13, which is narrower than at New York City).

The Pacific Coast of the contiguous United States is subject to considerable short length-scale sea-level rise variability due to tectonics, as can be seen by comparing the background non-climatic rate of sea-level rise at Los Angeles ( $-1.1 \pm 0.3$  mm/yr) and nearby Santa Monica ( $-0.6 \pm 0.3$  mm/yr). In general, sea-level rise on this coast is close to the global average, with a *likely* range in 2100 under RCP 8.5 at San Francisco of 0.6–1.0 m (median  $R = 0.96$ , *likely* 0.84–1.08, background rate of  $-0.1 \pm 0.2$  mm/yr). The slightly lower-than-global projection is a result of smaller Greenland and GIC contributions due to proximity to these land ice reservoirs, though counterbalanced by enhanced sea-level rise from AIS mass loss. Ocean dynamic factors are projected to play a minimal role.

Farther north, the proximity of historic and modern glaciers controls LSL projections. At Juneau, predicted sea-level rise is dominated by a glacio-isostatic sea-level fall of  $14.9 \pm 0.5$  mm/yr, interpreted as resulting primarily from the ongoing response to post-Little Ice Age glacial mass loss, with a secondary contribution from post-Last Glacial Maximum GIA [Larsen et al., 2005]. Moreover, shrinking glaciers in Alaska and western Canada cause about 2.4 mm of LSL fall at Juneau for every mm of global sea-level rise, which reduces the overall magnitude of sea-level rise caused by projected glacial mass loss (median  $R = 0.71$ , *likely* 0.59–0.83). As a consequence, under RCP 8.5 Juneau is *likely* to experience a sea level fall of 0.7–1.1 m by 2100.

Hawai'i and other central Pacific islands experience significantly greater-than-average sea-level rise resulting from land ice mass loss (20% enhancement for GIS, EAIS, and the median combination of shrinking glaciers, and 30% for WAIS, giving rise to median  $R = 1.13$  and *likely* 0.98–1.26). The *likely* range of sea-level rise at Honolulu, Hawai'i, is slightly higher than the global mean (0.6–1.1 m in 2100 under RCP 8.5, with a background rate of  $-0.2 \pm 0.4$  mm/yr). The amplification relative to the global mean is more apparent in the tail of the projections, where ice sheet mass loss contributions constitute a larger proportion of the sea-level rise. As a consequence, the tail of sea-level rise is fatter at Hawai'i than globally, with a 95th percentile in RCP 8.5 of 1.4 m (compared to GSL of 1.2 m) and a 99.5th percentile of 2.1 m (compared to GSL of 1.8 m).

A similar range of behaviors is seen outside the United States. At Cuxhaven, on the German North Sea coast, a slightly higher-than-global *likely* range of 0.6–1.1 m arises from a background subsidence rate of  $1.0 \pm 0.2$  mm/yr. Because of its relative proximity to Greenland, Cuxhaven is less exposed to climatically driven sea-level rise than average (median  $R = 0.89$ , *likely* 0.62–1.15); unlike sites in eastern North America that are similarly close to Greenland, it does not experience a countervailing oceanographic sea-level rise. The city of Stockholm, Sweden, like Juneau, is experiencing a strong GIA-related uplift of  $-5.0 \pm 0.1$  mm/yr, leading to a *likely* sea-level rise of  $-0.4$  to  $+0.8$  m. Being farther from a large, actively shrinking glacier, however, Stockholm is in the median more exposed than Juneau to climatically driven sea-level change (median  $R = 0.83$ , *likely* 0.41–1.20).

Like Honolulu, the town of Kushimoto, in Wakayama Prefecture, Japan, is in the far-field of the major ice sheets and most major glaciers. It is also exposed to a *likely* ocean dynamic sea-level rise of  $-5$  to  $+18$  cm in 2100. Together, these factors lead to a median  $R = 1.14$ , *likely* 0.98–1.28. Kushimoto also is experiencing tectonic subsidence, leading to a *likely* sea-level rise in 2100 of 0.8–1.3 m.

The city of Valparaiso, on the Chilean Pacific coast, is experiencing tectonic uplift of  $2.5 \pm 0.8$  and exposed to a *likely* ocean dynamic sea-level fall of  $-2$  to  $9$  cm. Although it experiences about 30% less-than-global sea-level rise due to WAIS mass loss, it experiences a larger-than-average response to GIS, EAIS, and most glaciers; accordingly its overall sensitivity to sea-level rise is close to the global average (median  $R = 0.99$ , *likely* 0.90–1.08). All these factors together yield a *likely* 2100 sea-level rise 0.4–0.8 m.

#### 4. Variance and Sensitivity Assessment

As shown in the previous section, LSL rise is controlled by different factors—both climatic and non-climatic—at different locations and intervals over the next two centuries. The analysis also reveals that the adopted risk tolerance (choice of exceedance probability) influences the importance of different components. Median outcomes will vary regionally, driven strongly by varying levels of subsidence and, in certain regions, oceanographic processes. High-end (low-probability) outcomes are driven, globally and in most locations, by uncertainty in the ice sheet contribution, with the Antarctic signal becoming dominant in the highest end of the tail, particularly later in the century (Figure 4 and Supporting Information Figures S8 and S9). This contribution varies less by location.

To test the robustness of our results, we examine three alternate assumptions regarding ice sheet mass loss and two alternative assumptions regarding the robustness of GCM projections (Supporting Information Tables S1 and S3):

1. AR: using a lognormal fit to the AR5 median and *likely* ranges of ice sheet mass balance (GIS almost unchanged from reconciled projections; for AIS, *very likely* range of  $-15$  to  $23$  cm in RCP 8.5 by 2100)
2. BA: using a lognormal fit to the BA13 median and *very likely* projections of ice sheet mass balance (GIS: median  $14$  cm and *very likely*  $9$ – $29$  cm; AIS: median  $14$  cm, *very likely*  $-2$  to  $83$  cm)
3. Alt. Corr.: assuming positive correlations of  $0.7$  between WAIS and GIS and a negative correlation of  $-0.2$  between EAIS and the other two ice sheets, following the main projections of *Bamber and Aspinall* [2013]
4. High GCM Confidence: assuming the *very likely* ranges estimated by the GCMs for oceanographic changes are *very likely* rather than *likely* ranges
5. Reduced degrees of freedom (DOF): Assuming the GCMs collectively provide only six independent estimates of GIC and oceanographic change, due to non-independence of models
6. Higher groundwater depletion (GWD): The ratio of groundwater depletion to population is treated as a triangular distribution, with the minimum, median, and maximum estimated respectively from *Konikow* [2011], *Wada et al.* [2012] and *Pokhrel et al.* [2012].

At a global level and at most locations, the two alternative characterizations of ice sheet mass changes have the largest effects, with the median sea-level rise under RCP 8.5 in 2100 varying between  $79$  cm under default assumptions and case AR and  $91$  cm under case BA. The effect is larger in the tails, with 99.5th percentile projections of  $140$  cm under AR,  $176$  cm under default assumptions,  $187$  cm under Alt. Corr., and  $300$  cm under BA. Varying the confidence in GCMs, by contrast, has little global effect. Although the per-capita rate of groundwater depletion estimated from *Pokhrel et al.* [2012] is about three times that of the *Wada et al.* [2012], the overall effect of the Higher GWD assumption is small due to the magnitude of other uncertainties; this case experiences  $3$  cm extra GSL rise at the 5th percentile,  $4$  cm at the median, and  $6$  cm at the 99.5th percentile.

While all LSL projections are sensitive to assumptions about ice sheet behavior, some are sensitive to assumptions about confidence in GCM output. Due to the wide range of projections in the CMIP5 ensemble at New York City [Yin, 2012], the 99.5th percentile projections are  $212$  cm under default assumptions,  $205$  cm under High GCM Confidence, and  $232$  cm under Reduced DOF. Even at New York City, however, GCM uncertainty remains secondary to ice sheet uncertainty; the 99.5th percentile is  $178$  cm under AR,  $212$  cm under Alt. Corr., and  $359$  cm under BA. Moreover, the significance of GCM uncertainty can be quite small: at the sites discussed above, the difference between the 99.5th percentiles of the High GCM Confidence and Reduced DOF cases under RCP 8.5 in 2100 is  $27$  cm at New York,  $19$  cm at Sewell's Point,  $12$  cm at Cuxhaven,  $9$  cm at Galveston, and  $6$  cm or less at Honolulu, Juneau, Key West, Kushimoto, San Francisco, and Valparaiso. A large difference ( $55$  cm) at Stockholm may reflect differences between GCMs in the representation of the semi-closed Baltic Sea.

These sensitivity analyses are not exhaustive. There remains a need for improved ice sheet models to allow robust projections of the ice sheet component without heavy reliance upon expert elicitation. However, the development of such models is hindered by the limited consensus on the magnitude of positive and negative feedbacks on ice loss, such as those involving (a) temperature and snow albedo [Picard et al., 2012], (b) forest fires and snow albedo [Keegan et al., 2014], (c) snowfall and ice sheet discharge



[Winkelmann *et al.*, 2012], (d) grounding line retreat [Joughin *et al.*, 2014; Rignot *et al.*, 2014; Schoof, 2007], (e) static-equilibrium sea-level and grounding line retreat [Gomez *et al.*, 2010, 2012, 2013], (f) meltwater, ocean temperature, sea ice, and snowfall [Bintanja *et al.*, 2013], and (g) ice-cliff collapse [Bassis and Walker, 2012; Pollard and DeConto, 2013]. The wide range of projections and underlying uncertainties in continental-scale model projections pose challenges for interpreting the likelihood of their results [Bind-schadler *et al.*, 2013]. It is possible, however, that incomplete information could be better integrated in a probabilistic framework [Little *et al.*, 2013a, 2013b].

Furthermore, structural errors in models of other sea level components remain probable. These errors (e.g., a systematic bias caused by a missing process and/or feedback) may have a large impact on tails. Here, we do not attempt to perform a systematic analysis. However, we believe that this framework may be used to effectively allow for these possibilities to be considered. The subjective judgment applied in formulating these distributions is explicit and may be revisited over time.

## 5. Implications for Coastal Flooding

Since our projections provide full probability distributions, they can be combined with extreme value distributions to estimate the expected number of years in which flooding exceeds a given elevation, integrated over a given interval of time. Note that this is different from the expected number of flood events in a single year; the question here is not, “what is the probability of a flood of at least height  $X$ , given the projected sea-level change in 2050?” but, “in how many years between 2000 and 2050 do we expect floods of at least height  $X$ , given the projected pathway of sea level change?” Table 4 shows the expected number of years under each RCP with current “1-in-10 year” (10% probability per year) and “1-in-100 year” (1% probability per year) flood events for a selection of sites over 2001–2030, 2001–2050, and 2001–2100. Figure 7 shows the expected fraction of years with at least one event at the New York City, Key West, Cuxhaven, and Kushimoto tide gauges for a range of heights and the same periods of time under RCP 8.5; additional tide gauges and RCPs are shown in Supporting Information Figure S10.

At seven of the nine sites considered (New York, Sewell's Point, Key West, Galveston, San Francisco, Kushimoto, and Valparaiso, though not Cuxhaven or Stockholm), the expected number of years with current 1-in-10 year flood events, integrated over the 21st century, is under all RCPs at least five times larger than the 10 that would be predicted without sea-level rise. At the same seven sites, the expected number of years in the 21st century with current 1-in-100 year flood events is at least four times higher under RCP 2.6 and at least 8 times higher under RCP 8.5 than the 1 that would be expected without sea-level rise.

The increase in expected flood events is influenced both by the magnitude of projected LSL rise and by the range of past flood events. The latter is reflected in the difference between the 1-in-10 year and 1-in-100 year flood elevations, which will be larger at tide gauges that have experienced more extreme flood events. New York City and Cuxhaven are projected to experience fairly high sea-level rise (*likely* 0.7–1.3 m and 0.6–1.1 m by 2100 under RCP 8.5, respectively) but have also historically experienced large flood events, with the 1-in-100 year flood level about 70 cm higher than the 1-in-10 year flood level. Under RCP 8.5, these two sites respectively expect nine and four 1-in-100 year floods over the 21st century—the same as would be expected for 1-in-11 year and 1-in-25 year events without sea-level rise.

Stockholm has experienced fairly few large flood events, with the 1-in-100 year flood level only about 20 cm higher than the 1-in-10 year flood level, but also has a low projected sea-level rise (*likely* –0.2 to 0.5 m). As a consequence, it also expects nine 1-in-100 year floods over the 21st century under RCP 8.5. Key West, by contrast, has a projected sea-level rise similar to Cuxhaven but has not experienced as many large flood events. The 1-in-100 year flood level there is only about 23 cm higher than the 1-in-10 year flood level. Accordingly, it is expected to experience 48 years over the 21st century with a 1-in-100 year flood event, about the same as would be expected for a 1-in-2 year event without sea-level rise.

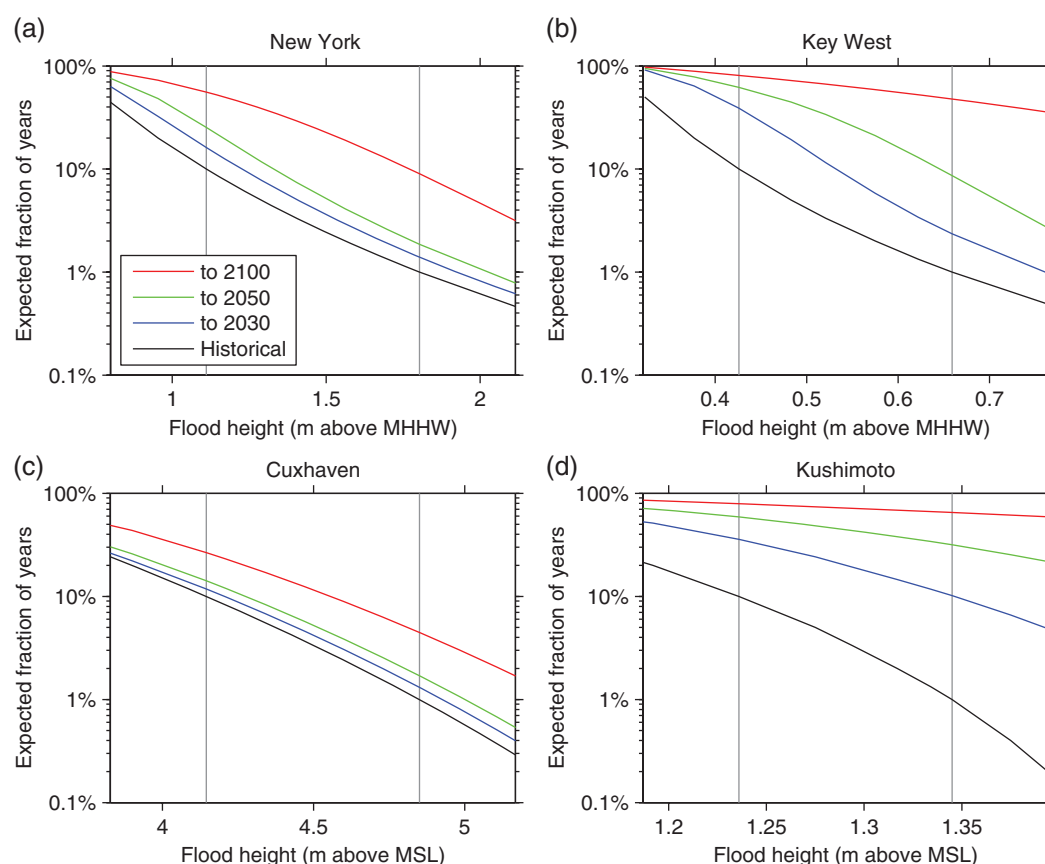
The most extreme case among the nine sites considered is Kushimoto, which both has a large projected sea-level rise (*likely* 0.8–1.3 m by 2100) and has experienced few large flood events, with the 1-in-100 year flood level just 10 cm higher than the 1-in-10 year flood level. Over the course of the 21st century, under

	1-in-10 Year Events					Height (m)	1-in-100 Year Events			
	Height (m)	No SLR	RCP 2.6	RCP 4.5	RCP 8.5		No SLR	RCP 2.6	RCP 4.5	RCP 8.5
2001–2030										
New York	1.11	3.0	4.8	4.7	4.9	1.80	0.3	0.4	0.4	0.4
Sewell's Point	1.12	3.0	6.0	5.9	6.0	1.66	0.3	0.6	0.6	0.6
Key West	0.43	3.0	11.7	11.5	11.7	0.66	0.3	0.7	0.7	0.7
Galveston	0.99	3.0	4.9	4.8	4.9	1.89	0.3	0.4	0.4	0.4
San Francisco	0.67	3.0	5.8	5.7	5.7	0.88	0.3	0.6	0.6	0.6
Cuxhaven	4.14	3.0	3.5	3.5	3.5	4.85	0.3	0.4	0.4	0.4
Stockholm	0.81	3.0	2.7	2.5	2.6	1.03	0.3	0.3	0.3	0.3
Kushimoto	1.24	3.0	10.7	10.5	10.7	1.34	0.3	3.0	2.9	3.1
Valparaíso	1.17	3.0	8.3	8.2	8.4	1.24	0.3	1.8	1.8	1.9
2001–2050										
New York	1.11	5.0	11.8	11.8	12.7	1.80	0.5	0.9	0.9	0.9
Sewell's Point	1.12	5.0	15.5	15.6	16.1	1.66	0.5	1.5	1.5	1.5
Key West	0.43	5.0	31.1	30.7	31.0	0.66	0.5	3.4	3.6	4.3
Galveston	0.99	5.0	14.4	14.2	14.9	1.89	0.5	0.8	0.8	0.8
San Francisco	0.67	5.0	17.5	17.4	17.8	0.88	0.5	2.1	2.2	2.3
Cuxhaven	4.14	5.0	6.9	6.9	7.1	4.85	0.5	0.8	0.8	0.8
Stockholm	0.81	5.0	5.6	4.5	5.6	1.03	0.5	0.8	0.5	0.8
Kushimoto	1.24	5.0	29.2	29.0	29.4	1.34	0.5	14.8	14.8	15.8
Valparaíso	1.17	5.0	22.1	22.0	23.3	1.24	0.5	7.6	7.9	8.9
2001–2100										
New York	1.11	10	50	53	56	1.80	1	4	6	9
Sewell's Point	1.12	10	61	62	64	1.66	1	11	14	19
Key West	0.43	10	81	81	81	0.66	1	40	43	48
Galveston	0.99	10	62	62	64	1.89	1	4	5	8
San Francisco	0.67	10	65	66	67	0.88	1	26	31	36
Cuxhaven	4.14	10	21	22	27	4.85	1	3	3	4
Stockholm	0.81	10	15	13	23	1.03	1	4	2	9
Kushimoto	1.24	10	79	79	79	1.34	1	63	64	65
Valparaíso	1.17	10	68	69	72	1.24	1	45	48	54

<sup>a</sup>Heights for U.S. sites are with respect to the local mean higher high water datum for the 1983–2001 epoch. Heights for non-U.S. sites are with respect to the local mean sea level datum for the 1983–2001 epoch.

all RCPs, Kushimoto is expected to experience more than 60 years with flooding exceeding the current 1-in-100 year flood level.

Sea-level rise allowances [Hunter *et al.*, 2013] quantify the amount by which a structure needs to be raised so that its current flood probability remains unchanged. For example, the U.S. National Flood Insurance Program's Special Flood Hazard Areas are defined as areas with a 1% per year flood probability [National Flood Insurance Program, 2013]. A corresponding sea-level rise allowance would indicate the height above the current 1-in-100 year flood zone that would maintain an average 1% per year flood probability over the period of interest. Note that, because the allowance is with respect to flood risk integrated over time, its magnitude is less than that of the sea-level change expected by the end of the period of interest. At New York City, a project with a 2001–2030 lifetime, such as a house with a 30-year mortgage, would need to be elevated by 17 cm above the no-sea-level-rise 1-in-100 year flood zone to maintain a 1% per year flood probability. An infrastructure project with a 2001–2050 lifetime would need to be raised 26 cm, while a project with a 2001–2100 life time would need to be elevated by 52–69 cm, depending on the emissions trajectory (Figure 7).



**Figure 7.** Expected fraction of years with flooding at tide gauges in excess of a given height under stationary sea level (black) and RCP 8.5 over 2001–2030 (blue), 2050 (green) and 2100 (red). Grey vertical lines indicate the current 1-in-10 and 1-in-100 year flood levels. Heights are relative to mean higher high water for U.S. sites and mean sea level for non-U.S. sites.

## 6. Cautions

In addition to highlighting the sensitivities and research needs noted in section 4, we raise several cautions in interpreting our projections.

First, in the near-term, internal variability in sea-level rise [e.g., Bromirski *et al.*, 2011] makes estimation of precise timing of LSL change difficult. Most sites experience interannual variability with a  $2\sigma$  range of about 4–10 cm [Hay *et al.*, 2013; Kopp *et al.*, 2010]. At the illustrative sites we consider, the difference between the 17th and 83rd percentile projections exceeds the decimeter level between 2030 and 2050. Until this threshold is reached, year-to-year variability will be comparable to the uncertainty in projections.

Second, as previously noted, historically estimated background rates of local, non-climatic processes may not continue unchanged. For example, while we project  $72 \pm 5$  cm of 21st century sea-level rise due to non-climatic factors at Grand Isle, Louisiana, changes in fluid withdrawal could reduce the projection [Blum and Roberts, 2012].

Third, our background rate estimates are the result of an algorithm applied to a global database of tide-gauge data, with different sites having been subjected to different degrees of quality control. Some tide-gauge sites may have experienced datum shifts or other local sources of errors not identified by the analysis. We recommend that users of projections for practical applications in specific regions scrutinize local tide-gauge records for such effects.

Fourth, our flood probability estimates should be viewed indicatively. They are based on hourly tide-gauge records that may be of insufficient length to capture accurately the statistics of rare flood events. They do not account for projected changes in tropical or extratropical cyclone climatology, such

as the expectation that Category 4 and 5 hurricanes may become more frequent in the North Atlantic [e.g., Bender *et al.*, 2010] and perhaps globally [Emanuel, 2013]. They are developed for specific tide-gauge locations where flood risk is likely indicative of, but not identical to, risk for the wider vicinity, due to variation in local topography and hydrodynamics. Nonetheless, they do highlight the inadequacy of flood risk assessments based on historic flood probabilities for guiding long-term decisions in the face of ongoing sea-level rise.

## 7. Conclusions

Assessments of climate change risk, whether in the context of evaluation of economic costs or the planning of resilient coastal communities and ecosystem reserves, require projections of sea-level changes that characterize not just *likely* sea-level changes but also tail risk. Moreover, these projections must estimate sea-level change at specific locations, not just at the global mean. They must also cover a range of timescales relevant for planning purposes, from the 30-year time scale of a typical U.S. mortgage, to the > 50 year lifetime of long-lived infrastructure projects, to the > 1 century lifetime of the development effects of infrastructure investments. In this article, we synthesize several lines of information, including model projections, formal expert elicitation, and expert assessment as embodied in the Intergovernmental Panel on Climate Change's Fifth Assessment Report, to generate projections that fulfill all three desiderata.

Under RCP 8.5, we project a *very likely* mean global sea-level rise of 0.5–1.2 m by 2100 and 1.0–3.7 m by 2200, which under the strong emissions mitigation of RCP 2.6 is lowered to 0.3–0.8 m by 2100 and 0.3–2.4 m by 2200. Local sea-level rise projections differ from the global mean due to differing background rates of non-climatic sea-level change, spatially variable responses to different land ice reservoirs due to static-equilibrium effects, and spatially variable ocean steric and dynamic changes. Static-equilibrium effects lead to a tendency for greater-than-global sea-level rise in the central and western Pacific Ocean. Mid-latitude and high-latitude sites in North America and Europe are generally less exposed to climatically driven sea-level change, with the exception of northeastern North America, which has potential for a high oceanographic sea-level contribution. At most sites, by the end of the century, uncertainty is due primarily to uncertainty in AIS mass loss, though oceanographic uncertainty is also a major term at sites where oceanographic processes may make a significant contribution to sea-level rise.

Probabilistic projections of future local sea-level rise pathways can be combined with statistical or hydrodynamic flood projections to estimate flood probabilities that more accurately assess the risks relevant to structures and populations. Projected sea-level rise can dramatically change estimated risks; at the Battery in New York City, for example, we project over the 21st century an expected nine years with “1-in-100 year” flood events under RCP 8.5 and four under RCP 2.6. Such projections, especially if improved or augmented by more detailed storm and flood models that include factors such as changes in tropical and extratropical cyclone climatology and by hydrodynamic models of overland flooding, can guide insurance, land use planning, and other forms of coastal climate change risk management.

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### Erratum

In the originally published version of this article, the file names in the supporting information readme did not match the file names of the supporting information files. The readme content has since been corrected and this version may be considered the authoritative version of record.