

Coastal sea level rise with warming above 2 °C

Svetlana Jevrejeva^{a,1}, Luke P. Jackson^{a,b}, Riccardo E. M. Riva^{c,d}, Aslak Grinsted^e, and John C. Moore^{f,g,1}

^aNational Oceanography Centre, Liverpool L3 5DA, United Kingdom; ^bProgramme for Economic Modelling, Nuffield College, University of Oxford, Oxford OX1 1NF, United Kingdom; ^cDepartment Geoscience and Remote Sensing, Delft University of Technology, 2628CN Delft, The Netherlands; ^dClimate Institute, Delft University of Technology, 2628CN Delft, The Netherlands; ^eCentre for Ice and Climate, Niels Bohr Institute, University of Copenhagen, DK-2100 Copenhagen, Denmark; ^fJoint Center for Global Change Studies, College of Global Change and Earth System Science, Beijing Normal University, Beijing 100875, China; and ^gArctic Centre, University of Lapland, FI-96101 Rovaniemi, Finland

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Two degrees of global warming above the preindustrial level is widely suggested as an appropriate threshold beyond which climate change risks become unacceptably high. This “2 °C” threshold is likely to be reached between 2040 and 2050 for both Representative Concentration Pathway (RCP) 8.5 and 4.5. Resulting sea level rises will not be globally uniform, due to ocean dynamical processes and changes in gravity associated with water mass redistribution. Here we provide probabilistic sea level rise projections for the global coastline with warming above the 2 °C goal. By 2100, with a 2 °C warming under the RCP8.5 scenario, more than 90% of coastal areas will experience sea level rise exceeding the global estimate of 0.2 m, with up to 0.4 m expected along the Atlantic coast of North America and Norway. With a 5 °C rise by 2100, sea level will rise rapidly, reaching 0.9 m (median), and 80% of the coastline will exceed the global sea level rise at the 95th percentile upper limit of 1.8 m. Under RCP8.5, by 2100, New York may expect rises of 1.09 m, Guangzhou may expect rises of 0.91 m, and Lagos may expect rises of 0.90 m, with the 95th percentile upper limit of 2.24 m, 1.93 m, and 1.92 m, respectively. The coastal communities of rapidly expanding cities in the developing world, and vulnerable tropical coastal ecosystems, will have a very limited time after midcentury to adapt to sea level rises unprecedented since the dawn of the Bronze Age.

2° warming | coastal sea level rise | probabilistic sea level projections | regional sea level rise

The threshold for dangerous climate change is widely reported to be about 2 °C above preindustrial temperature; therefore, international efforts have been generally aimed at keeping average global temperatures below this (1, 2). Fragile coastal ecosystems (3) and increasing concentrations of population and economic activity in maritime cities (4) are reasons why future sea level rise is one of the most damaging aspects of the warming climate (5). Furthermore, sea level is set to continue to rise for centuries after greenhouse gas emissions concentrations are stabilized due to system inertia and feedback time scales (5–7). Impact, risk, adaptation policies, and long-term decision-making in coastal areas depend on regional and local sea level rise projections, and local projections can differ substantially from the global one (6, 8–11). Coastal sea level projections should also take into account the local vertical land movement that is caused both by glacial isostatic adjustments (GIAs) due to redistribution of masses subsequent to the end of the last ice age (12–14), and subsidence due to groundwater extraction, urbanization, tectonics, and river delta sedimentation rates (15).

Global sea level is an integrated climate system response to changes in radiative forcing that alters the dynamics and thermodynamics of the atmosphere, ocean, and cryosphere. In a warming climate, global sea level will rise due to melting of land-based glaciers and ice sheets and from the thermal expansion of ocean waters. Sea level rise along coastlines displays complex spatial patterns (8–10) due to the dynamic redistribution of ocean mass (11–14) and the gravitational effects of ice sheets and glaciers melting into the ocean, so-called “fingerprints” (12), associated with specific geographical distributions of ice loss from mountain glaciers, Greenland, and Antarctica ice sheets and due to changes in man-made reservoirs and groundwater extraction (6).

Projections of each sea level component are characterized by uncertainties (6, 16), the largest due to limitations of process-based models to simulate the dynamics of ice mass loss from the Greenland and Antarctica ice sheets (6, 17, 18). This lack of precise knowledge can be accommodated in a probabilistic approach (9, 10, 16) where the sea level rise for each component is represented by continuous probability density functions (pdfs). Future sea level has been previously expressed in terms of levels at specific dates under a climate scenario accounting for uncertainties in the response of the sea level contributors for Northern Europe by 2100 (10) and for individual tide gauge stations through to 2200 (9). However, here we introduce pdfs for each individual component of sea level rise and global sea level rise under warming of 2 °C, 4 °C, or 5 °C (Fig. 1 C–H and *Materials and Methods*). We calculated spatial patterns of dynamic changes in sea surface height and global average steric sea level change from 33 models involving 83 realizations, in the Coupled Model Intercomparison Project Phase 5 (CMIP5) (Table S1 and Fig. S1 A–C). Spatial patterns of ice loss from glaciers and ice sheets (Fig. S1 D–F) are derived from present-day spatial attribution of terrestrial ice loss (14) and scaled using the pdfs of contributions from glaciers and ice sheets with warming of 2 °C, 4 °C, or 5 °C (Fig. 1 C, E, and G). The land water fingerprint is calculated using projected changes in land water storage (19). At each point on the global ocean, a putative sea level can be generated by random sampling of the component pdfs and summing. Repeating this process 5,000 times provides enough realizations of sea level to create the pdf for sea level rise at each point on the globe. Finally, to account for the redistribution of ocean mass due to GIA, we add the time-integrated global sea level field from the ICE-6G C (VM5a) model (13) to the sum of sea level components. Here we do not take into account the local vertical land movement caused by subsidence due to groundwater

Significance

Warming of 2 °C will lead to an average global ocean rise of 20 cm, but more than 90% of coastal areas will experience greater rises. If warming continues above 2 °C, then, by 2100, sea level will be rising faster than at any time during human civilization, and 80% of the global coastline is expected to exceed the 95th percentile upper limit of 1.8 m for mean global ocean sea level rise. Coastal communities, notably rapidly expanding cities in the developing world; small island states; United Nations Educational, Scientific and Cultural Organization Cultural World Heritage sites; and vulnerable tropical coastal ecosystems will have a very limited time after midcentury to adapt to these rises.

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¹To whom correspondence may be addressed. Email: sveta@noc.ac.uk or john.moore.bnu@gmail.com.

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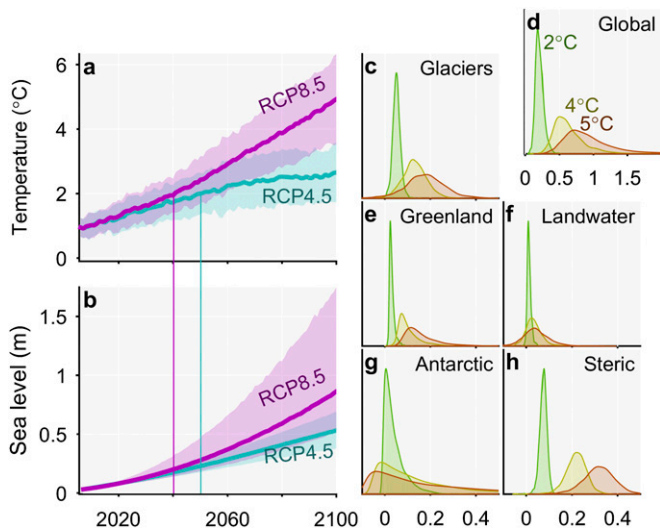


Fig. 1. Projections (5%, 50%, and 95% quantiles) of (A) global average surface temperature and (B) global sea level rise since 2005, with dates when expected global mean temperature rises 2 °C. (C–H) The sea level pdfs for the individual components, and for combined global sea level rise for warmings of 2 (green), 4 (yellow) and 5 °C (brown): (C) glaciers, (D) global, (E) Greenland, (F) land water, (G) Antarctic, and (H) steric. The x axis is sea level (meters) and y axis is probability density.

extraction, urbanization, and river delta sedimentation due to the general lack of long-term projections for global coastlines and individual cities (15). However, for some cities, including Manila, Jakarta, Bangkok, Ho Chi Minh City, and New Orleans, subsidence estimates do exist (15), and we discuss their sea level projections and the large uncertainties associated with local vertical land movement.

Results

With the Representative Concentration Pathway 8.5 (RCP8.5) emission scenario, a 2 °C warming relative to the preindustrial period is expected by 2041 (Fig. 1A), reaching 4 °C by 2083, continuing to a median projected warming of almost 5 °C by 2100 (6, 20), with consequent global mean sea level rises (Fig. 1B). By 2040, the median rate of sea level rise is expected to be 6 mm·y⁻¹, 3 times larger than the rate of sea level rise during the 20th century. If RCP8.5 is followed, then, in contrast to the almost 200-y (1850–2040) period taken to raise mean global temperatures by 2 °C, a further rise of 2 °C occurs in the following 43 y to 2083 (Table 1). This rate of change would probably be unprecedented over the Holocene, and certainly within the period of large human settlements; sea level will continue to rise, with 0.9 m expected by 2100, with 95th percentile upper limit of 1.8 m (10, 16).

Table 1. Probabilistic projections of global sea level rise with global average surface temperature of 2 °C and 4 °C and by the end of the 21st century under the RCP8.5 scenario

Global warming		Global sea level rise, m		Rate of global sea level rise, mm·y ⁻¹	
°C	Year	Median	5 to 95%	Median	5 to 95%
2	2041	0.22	0.15–0.33	6	4–8
4	2083	0.63	0.39–1.24	10	7–28
5*	2100	0.86	0.53–1.78	14	7–35

*Some models suggest warming of 5 °C by 2100 (20).

Fig. 2A shows that, with 2 °C warming, more than 70% of global coastlines will experience sea level rise exceeding the median global rise of 0.2 m, with ratio up to 1.5 of local sea level to global sea level rise along the Atlantic coast of North America and Norway (Fig. 3A). A 95th percentile upper limit exceeding 0.3 m is projected for most coastlines (Fig. 2B), including the extensive, low-lying coastal regions in South and Southeast Asia, which are often located along deltaic systems vulnerable to storm surges (3). By 2030, when coastal sea level rises of up to 0.3 m are expected under most RCP scenarios, there will be a population of 400 million living in 23 coastal megacities, including 370 million living on the coasts of Asia, Africa, and South America (21). Projected land subsidence rates in coastal cities, mainly due to excessive groundwater extraction, are comparable to, or exceed, expected rates of sea level rises, resulting in an additional 0.2 m sea level rise in Bangkok and Ho Chi Minh City and 1.8 m in Jakarta by 2025 (15, 19). Each of these cities will house more than 10 million inhabitants by 2030.

If global temperatures reach 4 °C (by 2083 under RCP8.5), then more than 80% of coastlines will exceed the global median sea level rise of 0.6 m (Fig. 2C), with a 95th percentile rise of 1.3 m (Fig. 2D). Under RCP8.5, by the end of 21st century, the expected mean sea level rise will be 0.9 m, with 95th percentile upper limit above 1.8 m (Fig. 2E and F). The highest sea level rises, exceeding 2.0 m (Fig. 2F), are projected for the small-island nations in the low-latitude to midlatitude Pacific (e.g., Micronesia) and Indian (e.g., Chagos islands) Oceans due to their susceptibility to sea level rises from ice mass loss from glaciers and both ice sheets (6) in combination with dynamical sea level changes (Fig. S1). These islands are often fronted by live reef and mangrove systems, which are particularly sensitive to changing environmental conditions, especially rapidly rising sea levels that exacerbate the damaging effects of the frequent tropical cyclone storm surges (3).

Almost all of the 136 largest coastal cities (4) have projected median sea level rises of at least 0.9 m by 2100, with 95th percentile upper limits close to 2 m for the megacities of Southeast and South Asia, and large cities along the Atlantic coast of North America (Table 2 and Table S2). Only a small number of cities in northern Europe, including Glasgow, London, and Dublin, have lower median probable rises of around 0.5 m to 0.7 m (Table 2 and Table S2). The gravitational response to ice loss from Greenland and Antarctic ice sheets (12, 14) and isostatic rebound from previous glaciations mean that the only coasts where sea level rises below the global mean are expected are around Greenland and Antarctica, parts of the Arctic, Pacific Alaska, and northern Europe (Fig. 3).

Discussion and Conclusion

Uncertainties in projected sea level rise vary spatially and temporally, although they increase considerably with warming above 2 °C and reach 1.2 m (5 to 95% range) north of 35°S (Fig. S2F and I) by 2100. Our estimate of the 95th percentile global sea level rise (1.8 m) is 0.6 m higher than the 1.2 m (95th percentile) published previously (9). This is mainly due to differences in defining the contribution from the ice sheets. The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (AR5 IPCC) (6) provides sea level projections spanning a likely range (66%) and with medium confidence only, largely due to difficulties in projecting ice mass loss from the Greenland and Antarctica ice sheets (10, 16). Both the present study and Kopp et al. (9) therefore used a formal expert elicitation (22) to derive uncertainties of the Antarctic contribution. Kopp et al. (9) reduced these ice dynamics estimates to match the IPCC AR5 central estimates (6), although Oppenheimer et al. (23) suggest that, in doing this, the central range may not be internally consistent with the appended tail. In contrast to Kopp et al. (9), we argue that there is no justification for diminishing the tail risk as perceived by experts (10, 16) and allow for the full range of expert uncertainties as estimated by

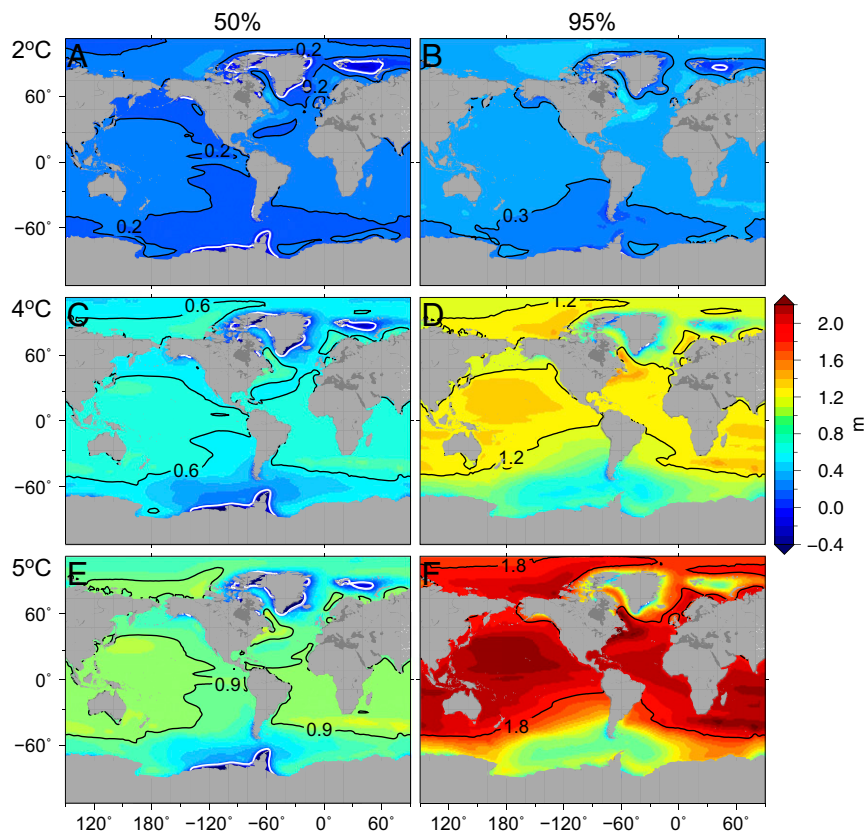


Fig. 2. Regional sea level projections for warming of (A and B) 2 °C (under RCP8.5), (C and D) 4 °C (under RCP8.5), and (E and F) 5 °C (under RCP8.5) relative to 1986–2005. A, C, and E show median projections, and B, D, and F show upper limits (95%). Black contours mark global sea level value, and white contours correspond to zero sea level rise.

Bamber and Aspinall (22). Two recent ice sheet model studies came to different conclusions regarding the plausibility of the high-end tail. Ritz et al. (24) concluded that Antarctic contributions of a meter or more are implausible, whereas DeConto and Pollard (25) find that, not only is this plausible, but it should even be considered likely. The wide uncertainties used in the present study are therefore supported by process models (24, 25). This difference in dealing with the ice dynamics uncertainties especially affects the key finding of this study that, with warming above 2 °C, coastal sea level rises are much larger than global mean sea level rise (Figs. 2, 4, and 5). Fractional variance of the individual sea level rise components varies considerably over time, with Antarctica accounting for 65% at 2 °C and 80% at 4 °C warming (Fig. S3). Despite incorporating observational constraints (24), model uncertainties are likely to remain high until key processes, such as large-scale calving (6, 26, 27), are better understood and parameterized (6, 17). Uncertainties in sea level projections for coastal areas are larger than those for global sea level rise due to the additional mechanisms having regional fingerprints, especially ocean dynamics (Figs. S1–S3). City subsidence potentially introduces large uncertainties in local sea level projections, with up to 3 m by 2100 expected in the case of Jakarta (28).

Many cities, under pressure to expand urban area and housing either because of urban migration or due to rising property prices, are building on land left previously unoccupied because of flood risk. For example, in Guangzhou (China), 6% of the population (4) currently live within 0.5 m of sea level. Guangzhou may be globally the most economically vulnerable city to rising sea levels by the middle of the 21st century, with estimated losses of \$254 million per year under a sea level rise of 0.2 m (4); however, other cities in India, Bangladesh, and Southeast Asia (Table 2 and Table S2) will likely have larger

populations at risk by that date (29, 30). In several coastal cities, current land subsidence exceeds observed sea level rise (15, 28, 31, 32). Economic development in urban areas of megacities drives the growing demand for groundwater, therefore increasing subsidence rates, with 2025 projected (15, 28) sinking of Jakarta (1.8 m), Manila (0.4 m), Ho Chi Minh City (0.2 m), Bangkok (0.19 m), New Orleans (>0.2 m), and the western Netherlands (0.07 m). The costs of local rising sea levels for coastal cities will be much larger than those due to socioeconomic changes, and could amount to US \$ 1 trillion per year in the absence of appropriate adaptation measures (4). Subsidence projected for Jakarta by 2100 varies between 2.3 m and 3.0 m, depending on groundwater management scenario (28). Hence, individual city actions allow for mitigation of, or must provide adaptation to, subsidence; this contrasts with climate-driven sea level rise, which is a global problem that requires global solutions. Without restrictions on groundwater extraction, development of alternative water supplies, and natural and artificial recharge of aquifers, parts of Jakarta, Ho Chi Minh City, Bangkok, and numerous other coastal cities will sink below sea level.

Currently, and despite implementation of climate mitigation measures in several regions (33), global greenhouse gas emissions are following the highest, RCP 8.5, emission trajectory (34, 35). Geoengineering, either by solar radiation management (36) or targeted at preventing sea level rise (37), is being explored as a supplement greenhouse gas mitigation or stop-gap approach to limit some impacts of dangerous warming. However, although the potential exists to reduce global temperatures by, e.g., stratospheric sulfate aerosol injection, there are doubts as to its effectiveness at the quantities needed to reduce radiative forcing from RCP8.5 to, e.g.,

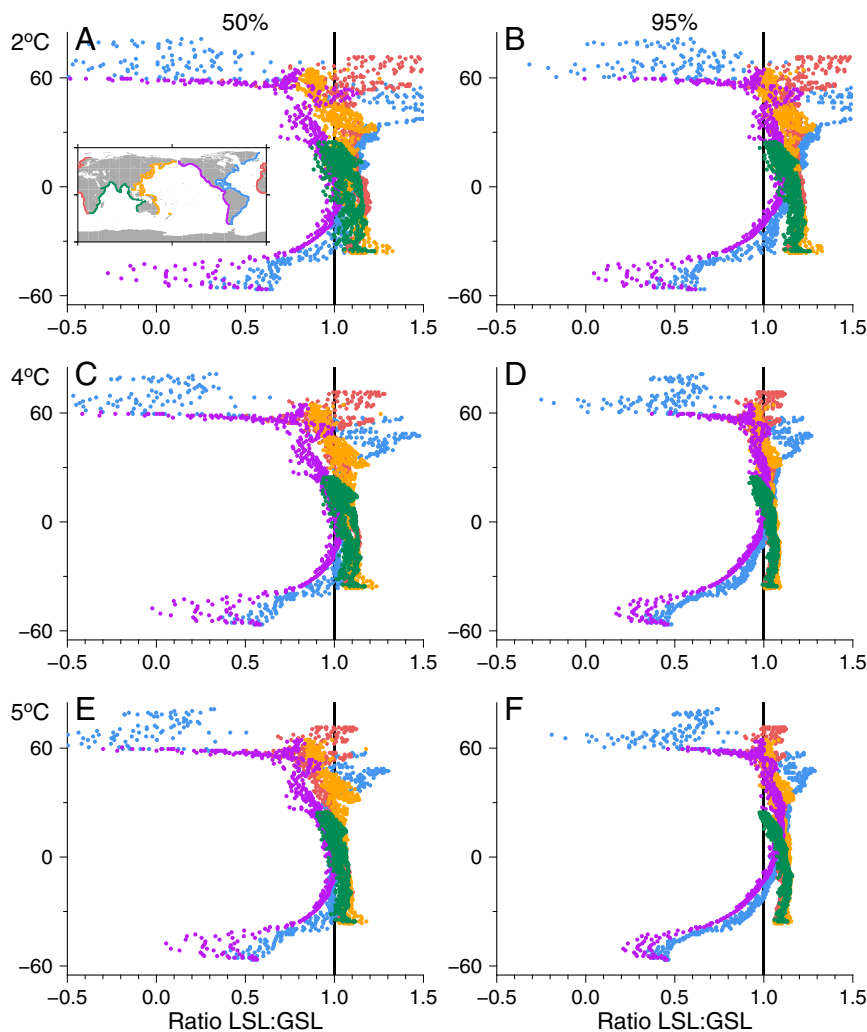


Fig. 3. (A, C, and E) Ratio of projected local (1° grid cells close to coastline) median (50%) sea level rise to global median sea level rise and (B, D, and F) ratio of projected 95% local to 95% global sea level rise with RCP8.5 along global coastlines for warmings of (A and B) 2°C , (C and D) 4°C , and (E and F) 5°C . Colored points show the regional sea level projections for coastlines (color-coded grid points on *Inset* map in A). Vertical black line represents ratio of 1.

RCP4.5 levels (36, 38). Furthermore, the success of geoengineering schemes for combatting sea level rise also depends on preventing warm ocean waters from reaching the undersides of floating ice masses fringing Antarctica; this mechanism depends on complex interactions of surface winds, sea ice, and ocean circulation, and some simulations suggest that aerosol injection may not alter these as desired (39).

After 2040, if warming continues well above 2°C as under the RCP8.5 scenario, global sea level rise will exceed $10\text{ mm}\cdot\text{y}^{-1}$ by 2083. At 4°C warming, more than 80% of coastlines will exceed a median global sea level of 0.6 m. Historically unprecedented changes in sea level rise (Fig. 4) with warming above 2°C will limit time for adaptation in the vast areas of agricultural land, wetlands, beaches, and coastal cities affected. Some low-lying developing countries (e.g., Bangladesh and Vietnam) and small islands will be expected to deal with very high impacts, and associated annual damage and adaptation costs will be several percentage points of gross domestic product (5, 40). Sea level rise of 2 m will lead to the displacement of urban populations: 2.5 million living in low-lying areas of Miami; 2.1 million in Guangzhou; 1.8 million in Mumbai; and more than 1 million each in Osaka, Tokyo, New Orleans, New York, and Ho Chi Minh City (4). The impacts of sea level rise in coastal regions

will not be uniform (Figs. 2 and 4), and the challenge of adapting to extremely rapid sea level rise will affect individuals, communities, countries, and the global population. The next generation or two will face unprecedented challenges to protect coastal United Nations Educational, Scientific and Cultural Organization Cultural World Heritage sites (41) such as Venice, Alexandria, and Qal'at al-Bahrain as well as vulnerable tropical coastal ecosystems.

Materials and Methods

We use a probabilistic approach (10, 16) in which the main sea level components are represented by pdfs to accommodate the considerable uncertainties existing in these components. For regional sea level projections, we follow the approach of Grinsted et al. (10) and combine fingerprints of the main sea level components,

$$\text{RSL} = F(T) + F(G) + F(\text{Gr}) + F(A) + F(\text{LW}) + F(\text{GIA}), \quad [1]$$

where RSL is regional sea level, $F(T)$, $F(G)$, $F(\text{Gr})$, $F(A)$, $F(\text{LW})$ are the fingerprints [$F()$], respectively, of steric sea level changes plus dynamical changes in sea surface height (T); ice loss from glaciers (surface mass balance) (G); ice loss from Greenland (surface mass balance and ice dynamics) (Gr); ice loss from Antarctica ice sheet (surface mass balance and ice dynamics) (A); and land water, including water storage in artificial reservoirs and groundwater mining (LW). To generate regional sea level

Table 2. Probabilistic projections (5%, 50%, and 95% quantiles) of sea level rise (meters) in selected cities with warming of 2 °C, 4 °C, and 5 °C

City	2 °C			4 °C			5 °C		
	5%	50%	95%	5%	50%	95%	5%	50%	95%
Bangkok	0.12	0.19	0.32	0.35	0.59	1.17	0.49	0.87	1.91
Dublin	0.10	0.18	0.31	0.28	0.52	1.12	0.36	0.73	1.79
Glasgow	0.03	0.11	0.25	0.11	0.38	0.97	0.15	0.54	1.58
Guangzhou	0.12	0.21	0.34	0.36	0.62	1.20	0.51	0.91	1.93
Hamburg	0.17	0.27	0.40	0.42	0.69	1.25	0.56	0.95	1.95
Ho Chi Minh	0.12	0.20	0.33	0.37	0.62	1.20	0.50	0.90	1.96
Hong Kong	0.13	0.20	0.32	0.37	0.61	1.18	0.52	0.90	1.90
Jakarta	0.11	0.18	0.30	0.34	0.58	1.12	0.49	0.85	1.80
Kuala Lumpur	0.11	0.18	0.31	0.33	0.58	1.19	0.47	0.86	1.92
Lagos	0.14	0.21	0.34	0.38	0.62	1.20	0.52	0.90	1.92
London	0.12	0.20	0.33	0.30	0.55	1.15	0.38	0.75	1.82
Manila	0.13	0.20	0.34	0.37	0.63	1.22	0.51	0.92	1.99
New Orleans	0.16	0.24	0.37	0.39	0.63	1.27	0.52	0.88	2.01
New York	0.20	0.31	0.46	0.48	0.78	1.43	0.64	1.09	2.24
San Francisco	0.10	0.16	0.30	0.27	0.49	1.15	0.37	0.73	1.87

No corrections for local subsidence rate have been applied.

projections for particular degree (2 °C, 4 °C, and 5 °C) warming, we randomly sample the pdf of each sea level component (Fig. 1 C and E–H). We simultaneously produce fingerprints for each component (excluding GIA, which is a nonclimate related component) by scaling the normalized fingerprint of each component by their associated random samples. We then sum the fingerprints of the sea level components making, in total, 5,000 realizations of sea level. This allows us to create a pdf for each grid point in our map of regional sea level projections associated with 2 °C, 4 °C, and 5 °C warming. To account for the redistribution of ocean mass due to GIA,

we add the time-integrated global field of sea level from the ICE 6G model (13) to the sum of sea level components.

Fig. 1 C and E–H shows the pdfs for each individual component with 2 °C, 4 °C, and 5 °C warming used for calculation of regional sea level patterns. For the $F(T)$ component, we calculate pdfs from the available outputs of 33 climate models (Table S1) in the World Climate Research Program CMIP5 (42). Dynamical changes in sea level (zos; here we give the CMIP5 variable names) and global average steric sea level change (zossga) for time slices 2030–2050 (2 °C) and 2070–2090 (4 °C) warming were used to accommodate the uncertainties in global temperature warmings (Fig. 1A) under RCP8.5. Inverse barometric corrections were made using atmospheric pressure and atmospheric water content to zos. Model drift for historical simulations (1850–2005) and projections (2006–2100) in zossga and zos was corrected using linear regression of the full-length pre-industrial control run from each model experiment and at each grid node independently. The multimodel ensemble means from global average steric sea level change (zossga) and dynamic sea level (zos) for each individual model are shown in Fig. S1 for 2 °C, 4 °C, and 5 °C warmings.

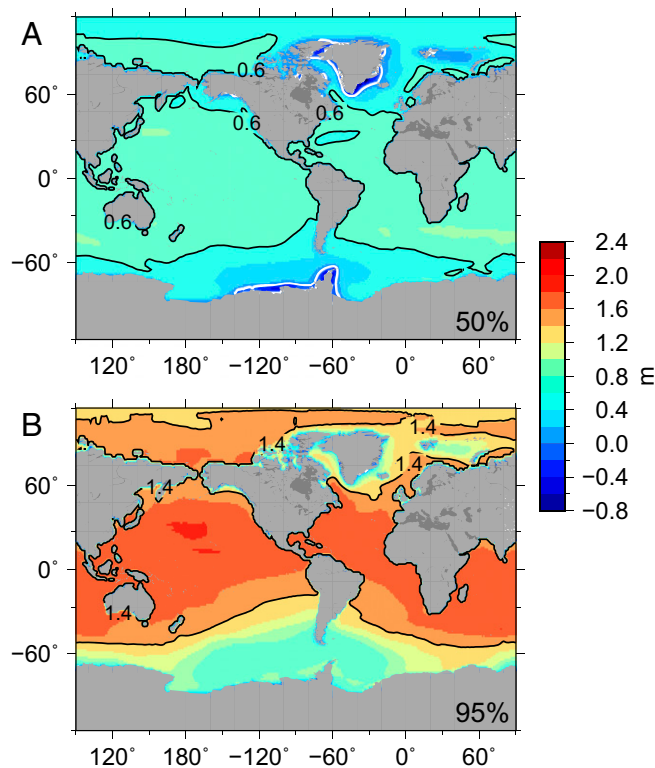


Fig. 4. Increases in regional sea level change under 5 °C warming compared with 2 °C: (A) median increases and (B) increases in the 95th percentile. Black line marks increases of (A) 0.6 m and (B) 1.4 m in global average sea level. White line corresponds to zero sea level rise.

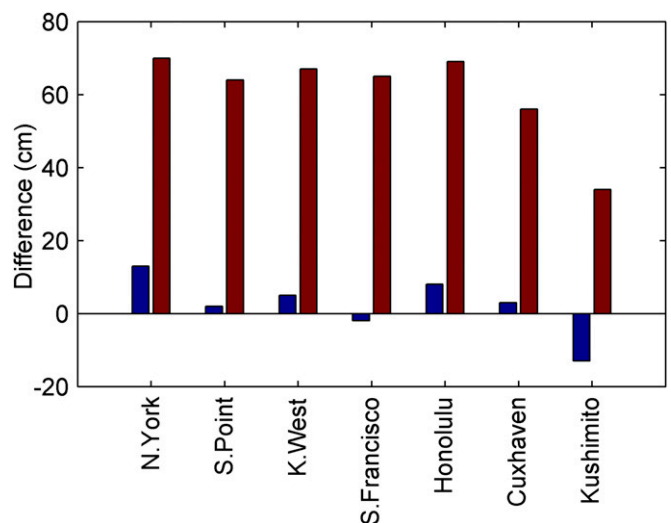


Fig. 5. Difference in sea level projections (centimeters) for median (blue) and 95th percentile (brown) with RCP8.5 scenario at individual locations by 2100 (this study; Table S3) (9). This difference is mainly due to distinction in defining the contribution from the ice sheets, particularly how the expert assessments from ice dynamicists (22) is accounted for.

For other components [$F(G)$, $F(Gr)$, $F(A)$, and $F(LW)$] from Eq. 1, we construct pdfs by using the component pdfs for the year 2100 (16) and assume constant change of rate over the 21st century to construct curves of sea level components, with tests for scaling following the approach of Perrette et al. (43). We fit a pdf to sea level components at 2100 using the forward model of the Burr distribution (44, 45),

$$f(x|\alpha, c, k) = \frac{\frac{kc}{\alpha} \left(\frac{x}{\alpha}\right)^{c-1}}{\left[1 + \left(\frac{x}{\alpha}\right)^c\right]^{k+1}}, \quad [2]$$

where α is the scale parameter and c and k are shape parameters ($x; \alpha; c; k > 0$). We search over α , c , and k using the Nelder–Mead simplex method (46) to create a pdf whose distribution minimizes the root-mean-square between modeled and “observed” 5%, 50%, and 95% probabilities for each component

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