Carbon choices determine US cities committed to futures below sea level

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Anthropogenic carbon emissions lock in long-term sea-level rise that greatly exceeds projections for this century, posing profound challenges for coastal development and cultural legacies. Analysis based on previously published relationships linking emissions to warming and warming to rise indicates that unabated carbon emissions up to the year 2100 would commit an eventual global sea-level rise of 4.3–9.9 m. Based on detailed topographic and population data, local high tide lines, and regional long-term sea-level commitment for different carbon emissions and ice sheet stability scenarios, we compute the current population living on endangered land at municipal, state, and national levels within the United States. For unabated climate change, we find that land that is home to more than 20 million people is implicated and is widely distributed among different states and coasts. The total area includes 1,185–1,825 municipalities where land that is home to more than half of the current population would be affected, among them at least 21 cities exceeding 100,000 residents. Under aggressive carbon cuts, more than half of these municipalities would avoid this commitment if the West Antarctic Ice Sheet remains stable. Similarly, more than half of the US population-weighted area under threat could be spared. We provide lists of implicated cities and state populations for different emissions scenarios and with and without a certain collapse of the West Antarctic Ice Sheet. Although past anthropogenic emissions already have caused sea-level commitment that will force coastal cities to adapt, future emissions will determine which areas we can continue to occupy or may have to abandon.

climate change | climate impacts | sea-level rise

Most studies on the projected impacts of anthropogenic climate change have focused on the 21st century (1). However, substantial research indicates that contemporary carbon emissions, even if stopped abruptly, will sustain or nearly sustain near-term temperature increases for millennia because of the long residence time of carbon dioxide in the atmosphere and inertia in the climate system, e.g., the slow exchange of heat between ocean and atmosphere (2–5). Earth system and carbon-cycle feedbacks such as the release of carbon from thawing permafrost or vegetation changes affecting terrestrial carbon storage or albedo may further extend and possibly amplify warming (6).

Paleontological records indicate that global mean sea level is highly sensitive to temperature (7) and that ice sheets, the most important contributors to large-magnitude sea-level change, can respond to warming on century time scales (8), while models suggest ice sheets require millennia to approach equilibrium (9). Accordingly, sustained temperature increases from current emissions are expected to translate to long-term sea-level rise (SLR). Through modeling and with support from paleontological data, Levermann et al. (10) found a roughly linear global mean sea-level increase of 2.3 m per 1 °C warming within a time-envelope of the next 2,000 y.

This relationship forecasts a profound challenge in light of warming likely to exceed 2 °C given the current path of emissions (11). Although relatively modest in comparison, projected SLR of up to 1.2 m this century has been estimated to threaten up to 4.6% of the global population and 9.3% of annual global gross domestic product with annual flooding by 2100 in the absence of adaptive measures (12). Higher long-term sea levels endanger a fifth of all United Nations Educational, Scientific and Cultural Organization world heritage sites (13). These global analyses depend on elevation data with multimeter rms vertical errors that consistently overestimate elevation and thus underestimate submergence risk (14). Here we explore the challenges posed under different scenarios by long-term SLR in the United States, where highly accurate elevation and population data permit robust exposure assessments (15, 16).

Our analysis combines published relationships between cumulative carbon emissions and warming, together with two possible versions of the relationship between warming and sea level, to estimate global and regional sea-level commitments from different emissions totals. The first version, the “baseline” case, employs a minor modification of the warming–SLR relationship from Levermann et al. (10) The second version, the “triggered” case, makes a major adjustment to explore an important possibility suggested by recent research, by assuming that an inevitable collapse of the West Antarctic Ice Sheet (WAIS) already has been set in motion (17–19).

For each case, we then use topographic, tidal, and census data to assess the contemporary populations living on implicated land nationwide, by state and by municipality. Although current populations will not experience full, long-term SLR, we use their exposure as a proxy for the challenge facing the more enduring built environment and the cultural and economic activity it embodies, given the strong spatial correlation between population and development. We focus most on cities, identifying and

Significance

As greenhouse gas emissions continue to rise, the window to limit global warming below 2 °C appears to be closing. Associated projections for sea-level rise generally range near or below 1 m by 2100. However, paleontological and modeling evidence indicates long-term sea-level sensitivity to warming that is roughly an order of magnitude higher. Here we develop relationships between cumulative carbon emissions and long-term sea-level commitment and explore implications for the future of coastal developments in the United States. The results offer a new way to compare different emissions scenarios or policies and suggest that the long-term viability of hundreds of coastal municipalities and land currently inhabited by tens of millions of persons hang in the balance.

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tabulating municipalities where committed sea levels would set land that is home to more than half (or other fractions) of the current population below the high tide line.

By "committed" or "locked in" warming or sea level in a given year, we refer to the long-term effects of cumulative anthropogenic carbon emissions through that year: the sustained temperature increase or SLR that will ensue on a time scale of centuries to millennia in the absence of massive and prolonged future active carbon removal from the atmosphere. We call a city "committed" when sea-level commitments would affect land supporting more than half of its current population (or another percentage of the population, if specified). We assume zero future emissions when assessing commitments for a given year, with the exception of one analysis incorporating future emissions implied by current energy infrastructure. When we associate years with warming, sea level, and city commitments, we are referencing the 21st century years when the commitments are established through cumulative emissions, not the years farther in the future when the commitments are realized through sustained temperature increases and SLR.

Warming Commitment

Numerous studies indicate a roughly linear relationship between total cumulative carbon emissions and century-scale global temperature increase, a ratio called the "transient climate response to carbon emissions" (3–6, 20). The Intergovernmental Panel on Climate Change (IPCC) judged a range of 0.8–2.5 °C per 1,000 gigatons of carbon (GtC) as 66% likely. For this study we prefer and use 0.7–2.0 °C, the 90% likely range from Gillett et al. (20), because it is observationally constrained. Furthermore, Gillett et al.'s central estimate of the transient response, 1.3 °C, very closely matches the 1.2 °C and 1.5 °C alternative IPCC estimates of warming per 1,000 GtC after 1,000 y from the end of emissions, assuming a midrange equilibrium climate sensitivity of 3 °C to the doubling of preindustrial carbon levels (6).

We estimate committed warming based on a distribution of possible transient response coefficient values from Gillett et al. and from future cumulative emissions under representative concentration pathways (RCPs) 2.6, 4.5, 6.0, and 8.5 (RCP Database version 2.0.5). For consistency, we approximate cumulative emissions through 2015 as 560 GtC based on historical values and forecasts under RCP 8.5 (21, 22); for a special case we add 199 GtC to this total to represent the future expectation of emissions already implicit in the current global energy infrastructure (23). Results range from 0.8 °C (0.5–1.0 °C) warming above preindustrial global temperature, committed by historic emissions, through 3.3 °C (2.3–4.2 °C), for RCP 8.5 through 2100 (see Table S1 for further information). We report 66% confidence intervals (CIs) for all quantities throughout this paper.

Sea-Level Commitment

We quantify sea-level commitment in the baseline case by building on Levermann et al. (10), who used physical simulations to model the SLR within a 2,000-y envelope as the sum of the contributions of (*i*) ocean thermal expansion, based on six coupled climate models; (*ii*) mountain glacier and ice cap melting, based on surface mass balance and simplified ice dynamic models; (*iii*) Greenland ice sheet decay, based on a coupled regional climate model and ice sheet dynamic model; and (*iv*) Antarctic ice sheet decay, based on a continental-scale model parameterizing grounding line ice flux in relation to temperature. Individual model parameterizations were constrained by paleontological data, and the overall modeled relationship between global temperature and sea level matched well against records from four previous warm periods: preindustrial, the last interglacial, marine isotope stage 11, and the mid-Pliocene.

The first three relationships from Levermann et al. (10) are monotonic, and we adopt them without modification. However, the wide range and finite number of simulation outputs render modeled relationships between temperature and Antarctic sea-level contribution locally nonmonotonic. The expected increase in Antarctic snowfall with warming could explain ice volume growth, but it is fair to assume that ice loss processes prevail in warmer climates (11). Here we define the future Antarctic ice volume loss committed for a global mean temperature increase T as the minimum loss across all temperature increases of T or greater. We apply this function to the median, 17th, and 83rd percentile curves from figure 2D in ref. 10 and thereby derive monotonic curves for minimum Antarctic sea-level contributions as a function of T.

To estimate uncertainty in total committed rise given some temperature increase, we use the derived Antarctic intervals, plus the ranges for the first three SLR components as shown in figure 2 A–C of ref. 10, as 17th/83rd percentile CIs from independent Gaussian distributions, a conservative simplifying assumption in that it narrows overall uncertainty compared with assuming any correlation. This method is commonly used, e.g., by the IPCC (11). To enable the assessment of a wide range of possible futures, we analyze 41 evenly spaced emissions totals from 500 to 2,500 GtC. For each total, we randomly sample 5,000 values of the transient response parameter assuming Gaussian distribution, compute warming levels, sample 5,000 random values from the distribution of each SLR component, given warming, and compute each component's global median and variance from the 25 million values thus generated.

In this baseline case we find that cumulative emissions through 2015 already have locked in 1.6 m (0–3.7 m) of global SLR relative to the present level. Sea-level commitment rises to 2.2 m (0.4–4.0 m) after factoring in future emissions implied by the current energy infrastructure and reaches medians of 2.4 or 7.1 m by the end of the century under RCP 2.6 or 8.5, respectively. Table S1 presents results based on all four RCP scenarios through 2050 and 2100 and on a range of fixed temperature increases.

Our findings here illustrate the strong sensitivity of committed SLR to emissions (Fig. 1, baseline curve). Central estimates of the current marginal (gradient) effect of emitting 1 GtC are to add 1.9 mm of committed sea level. Equivalently, for each unit volume of petroleum combusted, roughly 400 units of ocean

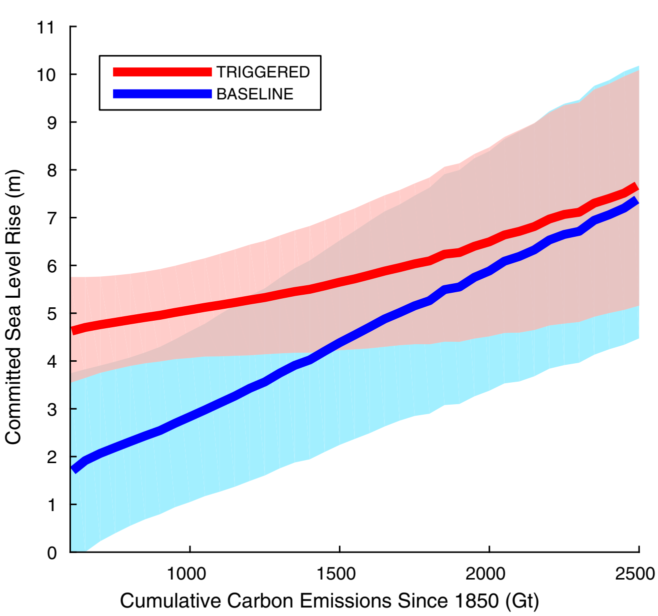

Fig. 1. Projections of long-term committed SLR as a function of cumulative carbon emissions, with 66% CIs, assuming (triggered case) or not assuming (baseline case) that eventual collapse of the WAIS is already inevitable.

volume are added, based on the average carbon fuel density of contemporary US petroleum consumption (24).

WAIS Collapse

Remote sensing studies indicate accelerating decay, plus bedrock topography favorable to collapse, for the Thwaites and Pine Island glaciers, two linchpins of the WAIS (18). Recent modeling work also points toward future collapse, even at reduced rates of warming and decay from the present (19). Topographic analysis (25) together with theory (26, 27) and expert judgment (28, 29) indicate that the highly interconnected marine component of West Antarctica is prone to marine ice sheet instability that would spread throughout the entire basin following the disintegration of the Thwaites and Pine Island glaciers. In light of the magnitude of such an event, we include a special triggered case in our analysis to represent the possibility that collapse already is inevitable. The baseline case includes the possibility of WAIS instability, depending upon emissions and warming; the triggered case differs only in enforcing collapse under any scenario at some time within Levermann et al.'s (10) 2,000-y envelope.

It is important to note that simulations suggesting destabilization of the Thwaites and Pine Island glaciers (17, 19) have been validated, at most, against a two-decade record, because historic data for West Antarctica are limited. Circumpolar deep-water circulation patterns appear to be driving recent WAIS decline (30, 31), but again the record of these patterns is sparse and brief and shows considerable variability, with no clear linkage to greenhouse gas forcing (19, 32–34). Nor is it completely certain that the loss of the Thwaites and Pine Island glaciers would lead to full WAIS destabilization. Accordingly, assumptions of complete West Antarctic collapse may be premature; however, we explore the triggered case because of its major potential impact.

The development and analysis of the triggered case is identical to the baseline case in every way except for the relationship between committed warming and the sea-level contribution from Antarctica. The Antarctic simulations used in Levermann et al. (10) do not isolate sea-level contribution subtotals from the WAIS, which has a total sea-level content of ~3.3 m (25). The triggered case thus screens out all Antarctic simulations contributing less than 3.3 m, because these could not include total WAIS collapse. [We assume the loss of the West Antarctic ice mass initially dominates over other losses of Antarctic ice mass, as is currently the case (35).] Remaining simulation outputs are divided into 0.2 °C bins to recompute the median, 17th, and 83rd percentile values of total Antarctic contributions. From here we revert again to the methodology used for the baseline case, rendering Antarctic contributions monotonic with respect to temperature and then taking random samples from the distributions of the transient response coefficient and of SLR components to develop overall relationships of SLR to emissions and their uncertainty (Fig. S1).

Above 2,000 GtC, the triggered and baseline cases are very similar, because there is enough warming to make WAIS collapse highly likely even under the baseline case. Below 1,500 GtC, results from the two cases diverge significantly, with much larger committed global sea levels when collapse is already assumed (Fig. 1). The triggered case accordingly implies a weaker relationship between future emissions and long-term SLR. The present marginal effect of emitting 1 GtC under the triggered case is roughly 0.6 mm of locked-in sea level, or about 125 units of added ocean volume per unit volume of petroleum combusted. Table S2 presents sea-level commitments for the triggered case under a range of scenarios.

Effects on Cities and Populated Land

Future sea levels committed under each of the emissions and Antarctic scenarios considered present serious implications for US coastal regions. To assess these implications, we translate global into local SLR projections using a model of spatial variation in sea-level contributions caused by isostatic deformation and changes in gravity as the Greenland and Antarctic ice sheets lose mass (36–38), represented as two global 0.5° matrices of scalar adjustment factors to the ice sheets' respective median global contributions to SLR and (squared) to their variances. We then derive gridded medians and CIs for local committed SLR including all components, based on cumulative emissions and ice sheet case.

To develop metrics for municipal commitments, we estimate, relative to the high tide line, the elevation below which is land that is home to 25, 50, or 100% of the 2010 population for each coastal municipality of any size in the United States. We use these heights as indicators of committed SLR likely to pose existential threats to the built cultural legacy of each locality as it exists today. We tabulate the cities where, by scenario and over time, the committed local sea level crosses these thresholds at lower, central, and upper SLR projections, further localized from the global 0.5° grid to city centroids using bilinear interpolation. We call the emissions levels corresponding to threshold sea levels the "critical cumulative emissions" for each municipality, and estimate whether and when these levels are reached under different emissions scenarios and ice sheet cases.

We also assess by county the total current population living on land exposed to different committed local sea levels, based on bilinear interpolation of projections to county centroids, and combine county results into state and national totals.

To assess topography as required for this analysis, we use LIDAR-based digital elevation models compiled and distributed by the National Oceanic and Atmospheric Administration (NOAA) (coast.noaa.gov/digitalcoast). We then recompute elevations relative to mean higher high water (MHHW) levels at nearest neighbors in NOAA's VDatum grid (vdatum.noaa.gov). To include Alaska, we use the National Elevation Dataset (nationalmap.gov/elevation.html) and a global grid for MHHW (provided by Mark Merrifield, University of Hawaii, Manoa, Hawaii) developed using the model TPXO8 (39). We use US census block boundaries and populations to determine localized population densities and municipality (census "place") and county boundaries for assessing threats at municipal through national levels (www.census.gov/geo/maps-data/data/tiger-line.html).

For each municipality and county we compute the population living 0.5–15 m below MHHW in increments of 0.5 m, assuming census blocks of uniform density, except for zero density over wetland areas (16). We interpolate each elevation–population relationship to estimate county populations on affected land at sea levels of interest and to estimate the thresholds below which selected fractions of each city population (i) live. We label the threshold for half of population as $h_i^{50\%}$. Each city's centroid coordinates, lat_i and lon_i, and the West Antarctic case x, then determine the smallest temperature T_{xi} such that $SLR_x(T_{xi}, lat_i, lon_i) - 0.16 \geq h_i^{50\%}$. The 0.16-m adjustment to projections of SLR above the preindustrial level reflects estimates of global mean SLR from the late 19th century through 1992 (40). 1992 is the midpoint of the reference period used to define MHHW at most US tide gauges, creating a match with our population analysis. We use 1992 global mean sea level as the "present" reference for all SLR projections reported here.

Calling $C^S(t)$ the cumulative carbon released under emissions scenario S by year t, each city's "commitment date," t_{xi}^S, then is determined as the earliest year for which the locked-in SLR exceeds the critical elevation threshold, i.e., when the product of the transient climate response with $C^S(t)$ exceeds T_{xi}. $C^S(t_{xi}^S)$ is the critical cumulative emissions level.

Results

In the baseline case, without any special assumptions concerning West Antarctica, cumulative emissions through 2015 commit SLR that translates to 414 (0–942) US municipalities where more than 50% of the population-weighted area will fall below the future high tide line. City commitments climb to 604 (92–1,011) after accounting

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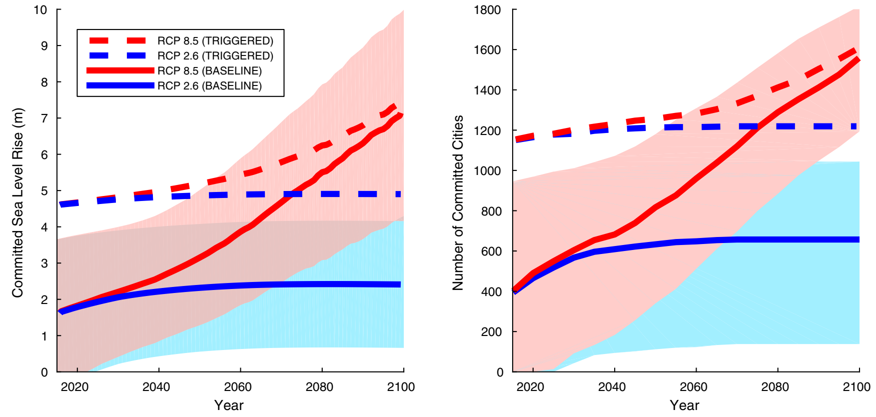

Fig. 2. Projections of committed global SLR (*Left*) and municipalities where more than half the population-weighted area would be affected (*Right*), under different emissions scenarios and assumptions about West Antarctica. The years shown relate to emissions and associated commitments, not to the timing of ensuing SLR. The 66% CIs are shown for the baseline Antarctic case only.

for future emissions implied by current energy infrastructure. The same sea levels would cover land where a total of 6.2 (0.0–15.1) million people live today across all coastal US states, or where 9.5 (0.0–17.4) million people live after accounting for emissions expected from infrastructure.

Median commitments from purely historic emissions are much larger under the triggered case, at 1,153 municipalities and 19.8 million people, with current energy infrastructure adding less than 5% marginal increases beyond these higher base levels.

Although starting from different points, the total commitments for both the baseline and triggered cases climb with accumulating future emissions (Fig. 2). Commitments within each case begin to diverge after 2030 depending upon the emissions scenario and diverge strongly after midcentury. However, business-as-usual emissions through 2100 (RCP 8.5) lead to similar final results under either Antarctic case, with 1,544 or 1,596 municipalities, respectively, committed at 50% (union of confidence intervals, 1,185–1,825), affecting land that is home to current populations of 26.3 or 27.4 million people (union of intervals 20.6–32.1 million). These patterns arise because at high emissions levels the total Antarctic contribution to SLR equals or exceeds the sea-level content of the WAIS in most simulations, so very few simulations must be filtered out from the triggered case, making it nearly identical to the baseline case. The slopes of change from low- to high-emissions scenarios (or for any addition to historic emissions) are greater for the baseline case, because it starts from a lower point.

Table 1. US municipalities and populated land avoiding commitment under different carbon emissions scenarios compared with RCP 8.5

Emissions end year	WAIS assumption	Avoidable commitments by emissions scenario: RCP 2.6	RCP 4.5	RCP 6.0
Municipalities (count >50% committed)				
2050	Baseline	170	107	124
2050	Triggered	41	17	23
2100	Baseline	889	633	368
2100	Triggered	380	325	238
Populated land (2010 population, in millions of persons)				
2050	Baseline	3.5	2.0	2.3
2050	Triggered	0.8	0.4	0.5
2100	Baseline	15.8	11.1	6.4
2100	Triggered	6.6	5.6	4.0

Values are based on differences between median estimates; see text for a description of WAIS assumptions.

Contrasted with the high-emissions scenario RCP 8.5, aggressive curtailment of emissions under RCP 2.6 can lead to the avoidance of commitment for nearly 900 US municipalities, and, more broadly, for land that is home to 15.8 million people in the baseline case, using central estimates, and for nearly 400 municipalities and land that is home for 6.6 million people assuming WAIS collapse. Intermediate scenarios yield intermediate results; Table 1 gives details. Fourteen cities with more than 100,000 contemporary residents can avoid locking in this century; the largest include Jacksonville and St. Petersburg in Florida; Chesapeake, Norfolk, and Virginia Beach in Virginia; and Sacramento and Stockton in California (Fig. 3). Under RCP 8.5, a median of 25 cities this large would be committed under the baseline case, and 27 cities of this size would be committed under the triggered case.

Using a pure temperature-based reference frame, the United Nations Framework Convention on Climate Change's Cancun Agreement target of 2 °C warming would translate to 1,119 (748–1,392) or 1,327 (1,123–1,516) cities committed under the baseline or triggered assumptions, respectively, and would affect land that is home to 19.0 (11.6–25.0) or 23.0 (16.8–28.1) million people today, respectively. Warming of 4 °C would increase central estimates to more than 1,745 cities and 30 million people under either assumption.

Under all scenarios, Florida has the plurality or majority of committed cities with total population greater than 100,000. Under all but the two most extreme scenarios (fixed 4 °C warming or RCP 8.5 through 2100), Florida holds 40% or more of the population living on potentially affected land. After Florida, the next three most affected states are California, Louisiana, and New York, in different orders for different scenarios, reflecting the wide geographic distribution of the SLR commitment challenge.

For more extensive details, Tables S1 (baseline) and S2 (triggered) present broken-out results including projections of committed sea levels based on historical emissions, four RCP scenarios through 2050 and 2100, and fixed warming amounts from 1.5 to 4 °C; tabulations of all municipalities locking in at these sea levels, using 25, 50, and 100% commitment thresholds; and tabulations limited to large cities. Tables S3–S6 list the individual large cities committed at different thresholds under each emissions scenario and ice sheet case, by year. Tables S7–S9 (baseline case) and S10–S12 (triggered case) show the population living on implicated land, by state and for the US total of coastal states, under all emissions and temperature scenarios and time frames.

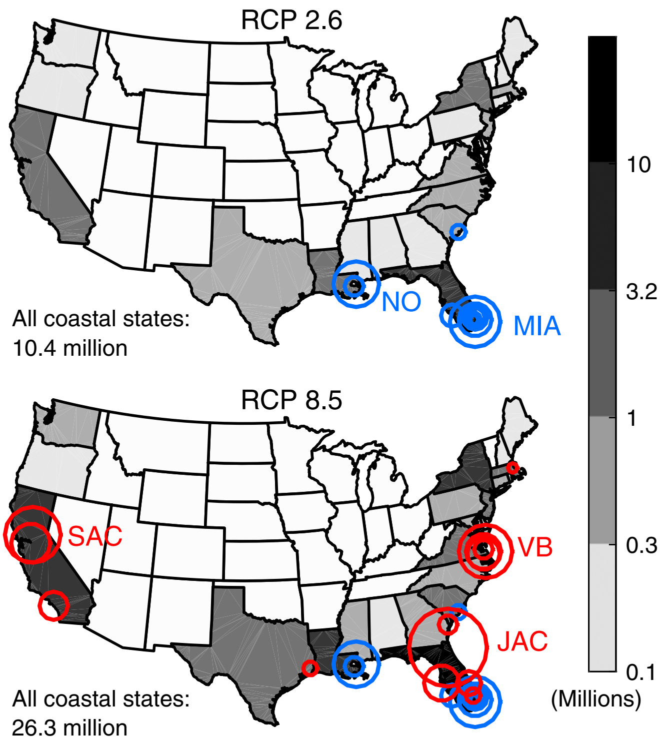

Fig. 3. State and total populations on land and major cities in which the majority of the population occupies land committed to fall below future high tide lines given emissions through 2100 under RCP 2.6 (blue city markers on both maps) or 8.5 (red city markers) and assuming the baseline Antarctic case (see text). Only implicated cities with total populations exceeding 100,000 are shown; the marker radius is proportional to the total city population, ranging from 105,162 (Cambridge, MA) to 819,050 (Jacksonville, FL) persons. Table S4 lists all plotted cities by name and provides the critical cumulative emissions totals needed for commitment and the corresponding commitment years under all four RCP scenarios. The five most populated cities are labeled here in descending order: JAC, Jacksonville, FL; SAC, Sacramento, CA; VB, Virginia Beach, VA; MIA, Miami; and NO, New Orleans. Table S8 lists individual state values for all scenarios, including Alaska and Hawaii, which are not shown here but are included in the coastal states' totals.

Discussion

Our analysis makes a series of simplifying assumptions similar to those made in a previous commentary (41). One is a focus on warming driven only by carbon, ignoring short-lived climate pollutants, because of our emphasis on long-term commitment. Another is that, other than the carbon removal already incorporated in RCP 2.6, large-scale active withdrawal of carbon from the atmosphere via human efforts will not be feasible or effective. We leave out potential reductions in Atlantic Meridional Overturning Circulation, which could temporarily add ~1 m of local sea level to East Coast locations at peak rates of Greenland melt (42–44).

A fourth simplification is the use of arbitrary thresholds to define commitment for cities. Because the mean SLR combines with episodic storm-driven floods, some municipalities—e.g., in southern Florida, with its high risk of hurricanes and its porous bedrock—are unlikely to survive challenges lesser than the focal 50% cutoff, but others may be able to use measures such as levees to manage greater challenges. Tables S1 and S2 include tabulations at a 25% cutoff, which in most cases leads to roughly a quarter more city commitments than seen with the 50% cutoff, and at a 100% cutoff, which broadly reduces city commitments by well more than half.

In this century, many large cities that do not commit at 50% do lock in at 25% under various RCP scenarios. For the baseline case, the cities in this set with more than 300,000 residents are New York City; Boston; Long Beach, CA; Honolulu; Tampa, FL; and Corpus Christi, TX. In the same size category, 100% of New Orleans commits under RCP 6.0 or 8.5. Tables S3 and S4 list all cities with populations exceeding 100,000 that lock in under any baseline scenario at 25, 50, and 100% thresholds and detail critical cumulative emissions totals, sea-level increments, and lock-in years for each city. Tables S5 and S6 provide the same results for scenarios under the triggered assumption.

Most of the municipalities included in this analysis are a great deal smaller than 100,000. As an illustration, the 1,596 cities committed at 50% under RCP 8.5 through 2100 under the triggered case have a mean population of 11,862 persons and a median population of 2,915 persons.

In a fifth simplification of this analysis, we restrict our scope to the United States. Clearly, the legacies of many more cities and nations, with less wealth to defend themselves, will be threatened globally. A recent study found that all of North America is home to ~5% of the world's coastal population living less than 10 m above sea level (45); accordingly, we address here only a small fraction of the overall challenge.

Sea-level threats to long-term cultural legacy are the main focus of this analysis. However, committed sea-level projections also may usefully inform nearer-term coastal and urban planning. For example, assuming RCP 2.6 to be a best-case scenario would give planners local estimates for minimum eventual SLR—a benchmark well above most 21st century projections, making explicit the transience of current needs. The implication is that measures aimed at lower amounts of SLR will suffice only for a limited time, suggesting the value of flexible approaches that can be extended in the future without prohibitive costs and continual rebuilding.

Nonetheless, a recent probabilistic assessment based on IPCC projections and expert elicitations on ice sheet behavior assigns a 0.5% chance that global SLR will exceed 6.3 m by 2200 under RCP 8.5 (46), suggesting that all but the highest committed levels discussed here could be attained in the relatively near term.

Summary and Conclusions

Cumulative carbon emissions lead to roughly proportional temperature increases expected to endure for millennia (6). These sustained increases translate to increments of SLR far exceeding the projections for this century, as ice sheets approach equilibrium with temperature over time (10). We find that within a 2,000-y envelope there is a strong relationship between cumulative emissions and committed sea level under either of our tested assumptions about WAIS stability, but the relationship is particularly steep when we do not assume collapse to be inevitable. In the latter case especially, rapid and deep cuts in carbon emissions could help many hundreds of coastal US municipalities avoid extreme future difficulties. However, historic carbon emissions appear already to have put in motion long-term SLR that will endanger the continuity and legacy of hundreds more municipalities, and so long as emissions continue, the tally will continually increase.

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Supporting Information

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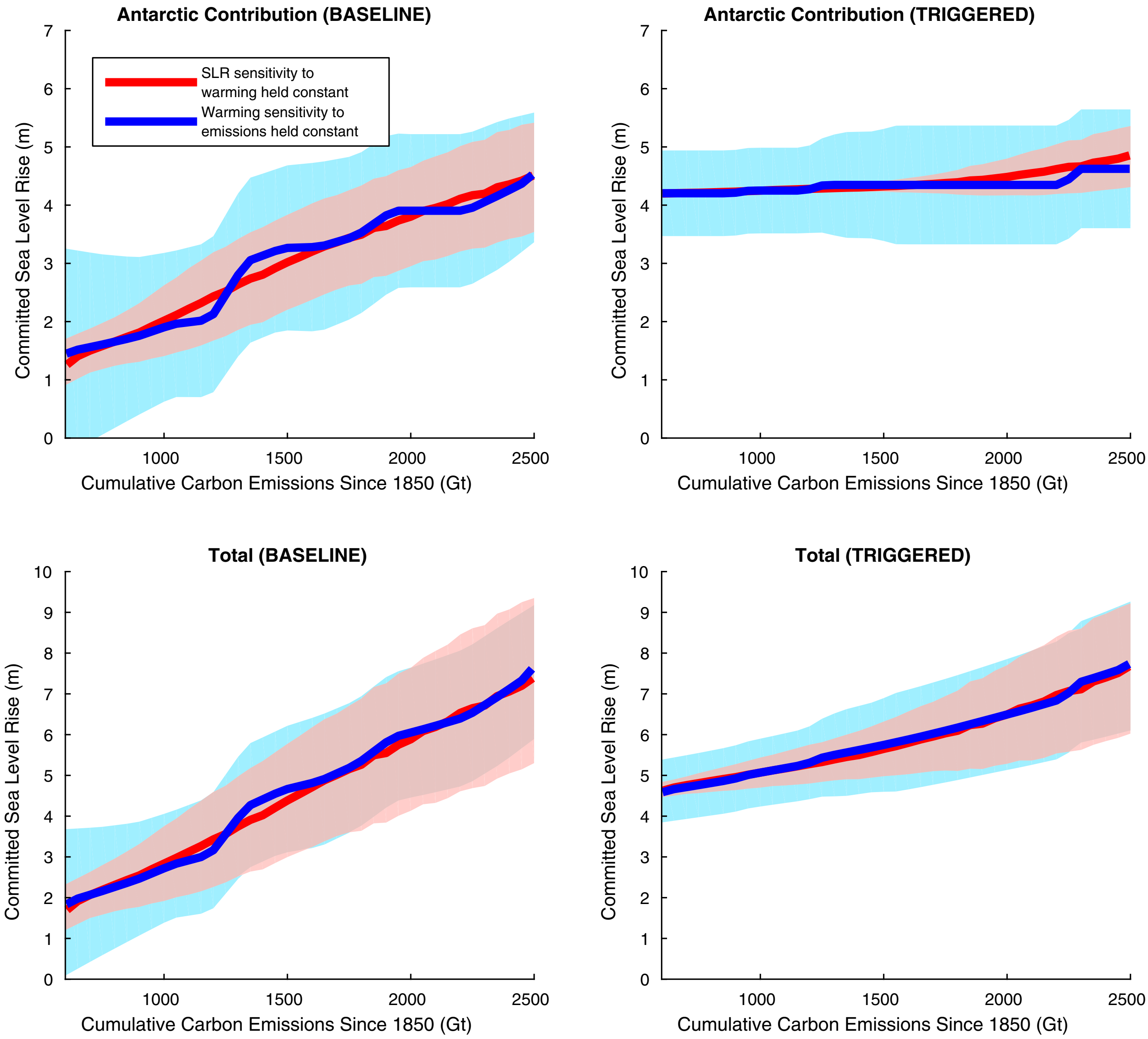

Fig. S1. Antarctic (*Upper Row*) and total (*Lower Row*) projections of committed SLR, given cumulative emissions and the baseline or triggered assumption regarding WAIS collapse. Blue lines and shading represent central and 66% CI estimates based on SLR sensitivity to warming, holding constant the transient climate response to emissions at its median value. Red lines and shading represent the central and 66% CI estimates based on warming sensitivity to the transient response, holding constant the sensitivity of SLR to warming at its median value.

Table S1. Total US municipalities becoming locked in so that 25, 50, or 100% of their 2010 population-weighted area will fall below the future committed high tide line, making no assumption about WAIS collapse (baseline case)

					Committed US municipalities–baseline case for WAIS					
					With 25% threshold		With 50% threshold		With 100% threshold	
Emissions end date	Emissions scenario	Cumulative emissions, GtC	Committed warming, °C (CI)	Committed SLR, m (CI)	All municipalities (CI)	>100,000 residents (CI)	All municipalities (CI)	>100,000 residents (CI)	All municipalities (CI)	>100,000 residents (CI)
2015	Historical	560	0.8 (0.5–1.0)	1.6 (0.0–3.7)	675 (0–1,261)	14 (0–25)	414 (0–942)	6 (0–17)	14 (0–199)	0 (0–2)
2015+	Historical + EIEI	800	1.0 (0.7–1.3)	2.2 (0.4–4.0)	846 (165–1,335)	17 (2–26)	604 (92–1,011)	8 (2–19)	38 (8–283)	0 (0–3)
2050	RCP 2.6	802	1.1 (0.8–1.4)	2.3 (0.6–4.1)	889 (227–1,347)	15 (2–26)	636 (119–1,028)	9 (2–19)	50 (8–283)	0 (0–3)
	RCP 4.5	940	1.3 (0.9–1.6)	2.7 (0.9–4.4)	989 (361–1,396)	19 (2–26)	699 (208–1,082)	11 (2–19)	84 (11–330)	0 (0–3)
	RCP 6.0	913	1.2 (0.9–1.6)	2.6 (0.8–4.3)	973 (341–1,387)	18 (2–26)	682 (190–1,071)	11 (2–19)	83 (9–315)	0 (0–3)
	RCP 8.5	1110	1.5 (1.1–1.9)	3.1 (1.3–5.0)	1,121 (528–1,499)	22 (7–27)	809 (335–1,175)	16 (2–21)	128 (11–384)	0 (0–4)
2100	RCP 2.6	840	1.1 (0.8–1.5)	2.4 (0.7–4.2)	919 (273–1,362)	15 (2–26)	655 (140–1,043)	11 (2–19)	83 (8–283)	0 (0–3)
	RCP 4.5	1,266	1.7 (1.2–2.2)	3.6 (1.7–5.6)	1,232 (713–1,575)	24 (15–28)	911 (460–1,272)	17 (7–22)	199 (14–470)	2 (0–5)
	RCP 6.0	1,678	2.3 (1.6–2.9)	5.0 (2.7–7.2)	1,490 (1,057–1,826)	27 (21–42)	1,176 (756–1,479)	21 (15–24)	386 (126–683)	4 (0–7)
	RCP 8.5	2,430	3.3 (2.3–4.2)	7.1 (4.3–9.9)	1,894 (1,504–2,176)	44 (27–53)	1,544 (1,185–1,812)	25 (21–35)	741 (411–1,021)	8 (4–13)
Not applicable	Fixed warming	Not applicable	1.5	2.9 (1.6–4.2)	1,042 (612–1,369)	21 (12–26)	744 (372–1,052)	15 (4–19)	103 (14–284)	0 (0–3)
			2.0	4.7 (3.0–6.3)	1,441 (1,054–1,736)	27 (21–36)	1,119 (748–1,392)	20 (15–23)	353 (121–610)	4 (0–6)
			3.0	6.4 (4.7–8.2)	1,770 (1,460–2,024)	39 (27–46)	1,415 (1,127–1,677)	23 (20–30)	653 (355–869)	6 (4–11)
			4.0	8.9 (6.9–10.8)	2,101 (1,841–2,339)	49 (42–54)	1,748 (1,499–1,938)	34 (25–37)	943 (714–1,134)	12 (7–14)

Projections assume zero additional emissions after emissions end dates listed, except for the historical + EIEI scenario. EIEI is the expected future emissions implied by existing energy infrastructure, as estimated in ref. 23. The years shown relate to emissions and associated commitments, not to the timing of ensuing warming or SLR. CIs are shown spanning 17th–83rd percentiles, the 66% ("likely") range. Committed warming is in reference to the preindustrial global mean temperature, and committed SLR is in reference to global mean sea level in 1992. Note: the relationship between committed warming and committed SLR is different for fixed warming vs. all other scenarios, because all other scenarios involve distributions of warming amounts, and warming translates nonlinearly into SLR.

Table S2. Total US municipalities becoming locked in so that 25, 50, or 100% of their 2010 population-weighted area will fall below the future committed high tide line, assuming inevitable collapse of the WAIS under any scenario (triggered case)

					Committed US municipalities–triggered case for WAIS					
					With 25% threshold		With 50% threshold		With 100% threshold	
Emissions end date	Emissions scenario	Cumulative emissions, GtC	Committed warming, °C (CI)	Committed SLR, m (CI)	All municipalities	>100,000 residents	All municipalities	>100,000 residents	All municipalities	>100,000 residents
2015	Historical	560	0.8 (0.5–1.0)	4.6 (3.5–5.8)	1,475 (1,261–1,690)	27 (25–33)	1,153 (931–1,343)	20 (17–23)	370 (199–553)	4 (2–6)
2015+	Historical + EIEI	800	1.0 (0.7–1.3)	4.8 (3.8–5.8)	1,516 (1,335–1,697)	27 (26–34)	1,202 (1,011–1,356)	22 (19–23)	426 (283–582)	4 (3–6)
2050	RCP 2.6	802	1.1 (0.8–1.4)	4.9 (3.9–5.8)	1,528 (1,348–1,704)	28 (26–34)	1,210 (1,025–1,357)	22 (19–23)	427 (283–583)	4 (3–6)
	RCP 4.5	940	1.3 (0.9–1.6)	5.0 (4.0–6.0)	1,549 (1,365–1,713)	28 (26–34)	1,234 (1,046–1,372)	22 (19–23)	427 (283–590)	4 (3–6)
	RCP 6.0	913	1.2 (0.9–1.6)	5.0 (4.0–6.0)	1,546 (1,363–1,712)	28 (26–34)	1,228 (1,046–1,371)	22 (19–23)	427 (283–590)	4 (3–6)
	RCP 8.5	1,110	1.5 (1.1–1.9)	5.2 (4.1–6.2)	1,569 (1,376–1,747)	28 (26–37)	1,251 (1,056–1,399)	22 (19–23)	445 (300–611)	5 (3–6)
2100	RCP 2.6	840	1.1 (0.8–1.5)	4.9 (4.0–5.9)	1,536 (1,354–1,707)	28 (26–34)	1,216 (1,035–1,361)	22 (19–23)	427 (283–585)	4 (3–6)
	RCP 4.5	1,266	1.7 (1.2–2.2)	5.3 (4.1–6.6)	1,581 (1,379–1,774)	28 (26–40)	1,271 (1,059–1,437)	22 (19–23)	472 (302–656)	5 (3–6)
	RCP 6.0	1,678	2.3 (1.6–2.9)	5.9 (4.3–7.5)	1,704 (1,437–1,915)	34 (27–44)	1,358 (1,115–1,563)	23 (20–26)	585 (353–774)	6 (4–8)
	RCP 8.5	2,430	3.3 (2.3–4.2)	7.4 (5.0–9.9)	1,957 (1,645–2,195)	46 (32–53)	1,596 (1,307–1,825)	27 (23–35)	796 (504–1024)	8 (5–13)
Not applicable	Fixed warming	Not applicable	1.5	5.2 (4.4–6.0)	1,560 (1,410–1,710)	28 (27–34)	1,249 (1,097–1,369)	22 (20–23)	443 (345–590)	5 (4–6)
			2.0	5.7 (4.5–7.0)	1,666 (1,445–1,864)	32 (27–42)	1,327 (1,123–1,516)	23 (20–25)	537 (353–735)	6 (4–7)
			3.0	6.9 (5.3–8.5)	1,839 (1,575–2,042)	42 (28–48)	1,499 (1,277–1,700)	25 (22–32)	709 (461–894)	7 (5–11)
			4.0	9.4 (7.5–11.3)	2,150 (1,927–2,374)	52 (44–54)	1,798 (1,575–1,978)	34 (26–37)	995 (794–1,160)	12 (8–14)

EIEI is the expected future emissions implied by existing energy infrastructure, as estimated in ref. 23. The years shown relate to emissions and associated commitments, not to the timing of the ensuing warming or SLR. See the legend of Table S1 for further documentation.

Table S3. Cities exceeding 100,000 residents where 25% of the 2010 population-weighted area will fall below the future committed high tide line, making no assumption about WAIS collapse (baseline case)

City	State	Total population	Population rank	Critical cumulative emissions, GtC	Committed SLR, m	Commitment year			
						RCP 8.5	RCP 6.0	RCP 4.5	RCP 2.6
Beaumont	TX	118,286	37	1,840	5.4	2080			
Boston	MA	617,594	3	930	2.8	2045	2055	2050	
Bridgeport	CT	144,229	26	2,070	6.2	2090			
Brownsville	TX	175,023	21	2,260	6.9	2095			
Cambridge	MA	105,162	42	AE	1.5	AE	AE	AE	AE
Cape Coral	FL	153,809	24	590	1.9	2020	2020	2020	2020
Charleston	SC	119,875	36	AE	1.6	AE	AE	AE	AE
Chesapeake	VA	221,576	17	980	2.9	2045	2060	2055	
Clearwater	FL	107,685	38	1,970	6.0	2085			
Coral Springs	FL	121,062	35	900	2.8	2040	2050	2050	
Corpus Christi	TX	305,184	11	1,870	5.6	2085			
Elizabeth	NJ	124,969	33	1,910	5.7	2085			
Elk Grove	CA	152,772	25	1,860	5.5	2080			
Fort Lauderdale	FL	165,521	22	AE	1.2	AE	AE	AE	AE
Hampton	VA	137,373	30	910	2.7	2040	2050	2050	
Hayward	CA	142,760	27	2,140	6.5	2090			
Hialeah	FL	224,634	16	AE	1.5	AE	AE	AE	AE
Hollywood	FL	139,946	28	AE	1.5	AE	AE	AE	AE
Honolulu (Urban)	HI	337,248	9	1,210	3.9	2055	2075	2090	
Huntington Beach	CA	189,992	19	AE	1.1	AE	AE	AE	AE
Jacksonville	FL	819,050	2	1,720	5.1	2075			
Jersey City	NJ	247,597	13	1,270	3.7	2060	2075		
Long Beach	CA	458,815	5	2,010	6.1	2090			
Metairie	LA	138,481	29	AE	0.1	AE	AE	AE	AE
Miami	FL	399,457	7	AE	1.7	AE	AE	AE	AE
Miami Gardens	FL	107,167	40	AE	1.6	AE	AE	AE	AE
Miramar	FL	107,278	39	AE	1.2	AE	AE	AE	AE
New Haven	CT	129,779	32	2,400	7.2	2100			
New Orleans	LA	343,467	8	AE	0.2	AE	AE	AE	AE
New York	NY	8,175,083	1	2,160	6.5	2095			
Newport News	VA	180,659	20	2,070	6.3	2090			
Norfolk	VA	242,751	15	900	2.7	2040	2050	2050	
Oxnard	CA	197,820	18	2,190	6.7	2095			
Palm Bay	FL	103,190	44	2,220	6.8	2095			
Pembroke Pines	FL	123,802	34	AE	1.3	AE	AE	AE	AE
Port St. Lucie	FL	164,438	23	1,550	4.6	2070	2095		
Richmond	CA	103,668	43	2,410	7.4	2100			
Sacramento	CA	466,486	4	1,100	3.2	2050	2065	2070	
Savannah	GA	136,286	31	1,220	3.5	2060	2075	2090	
St. Petersburg	FL	244,767	14	AE	1.7	AE	AE	AE	AE
Stockton	CA	277,588	12	AE	1.4	AE	AE	AE	AE
Tampa	FL	335,654	10	1,380	4.0	2065	2085		
Virginia Beach	VA	436,497	6	950	2.9	2045	2055	2055	
Wilmington	NC	106,476	41	2,120	6.4	2090			

The alphabetical list includes the SLR increment required for each city to commit at 25%, together with the corresponding central estimate of critical cumulative emissions. Committed SLR in turn corresponds to these emissions. AE indicates that historical emissions already have exceeded the critical level. Where applicable, RCP columns indicate future 21st century years (rounded to the nearest multiple of 5) when different RCPs will exceed each city's critical emissions level. The years shown relate to emissions and associated commitments, not to the timing of the ensuing warming or SLR. Rows for the 10 largest cities are shaded.

Table S4. Cities exceeding 100,000 residents where 50 or 100% of the 2010 population-weighted area will fall below the future committed high tide line, making no assumption about WAIS collapse (baseline case)

City	State	Total population	Population rank	Critical cumulative emissions, GtC	Committed SLR, m	Commitment year RCP 8.5	Commitment year RCP 6.0	Commitment year RCP 4.5	Commitment year RCP 2.6
Commitment threshold: 50%									
Beaumont	TX	118,286	22	2,210	6.6	2095			
Cambridge	MA	105,162	25	940	2.8	2045	2055	2055	
Cape Coral	FL	153,809	14	820	2.5	2035	2045	2040	2060
Charleston	SC	119,875	21	790	2.4	2035	2040	2040	2050
Chesapeake	VA	221,576	10	1,360	4.0	2065	2080		
Coral Springs	FL	121,062	20	1040	3.1	2050	2060	2060	
Fort Lauderdale	FL	165,521	12	AE	1.6	AE	AE	AE	AE
Hampton	VA	137,373	17	1,000	2.9	2045	2060	2060	
Hialeah	FL	224,634	9	AE	1.7	AE	AE	AE	AE
Hollywood	FL	139,946	15	630	2.1	2025	2025	2025	2025
Huntington Beach	CA	189,992	11	1,160	3.4	2055	2070	2080	
Jacksonville	FL	819,050	1	2,320	7.0	2100			
Metairie	LA	138,481	16	AE	0.3	AE	AE	AE	AE
Miami	FL	399,457	4	820	2.5	2035	2045	2040	2060
Miami Gardens	FL	107,167	24	570	1.8	2020	2020	2020	2020
Miramar	FL	107,278	23	AE	1.6	AE	AE	AE	AE
New Orleans	LA	343,467	5	AE	0.3	AE	AE	AE	AE
Norfolk	VA	242,751	8	980	2.9	2045	2060	2055	
Pembroke Pines	FL	123,802	19	AE	1.6	AE	AE	AE	AE
Port St. Lucie	FL	164,438	13	1,880	5.8	2085			
Sacramento	CA	466,486	2	1,700	5.0	2075			
Savannah	GA	136,286	18	1,650	4.9	2075	2100		
St. Petersburg	FL	244,767	7	1,550	4.6	2070	2095		
Stockton	CA	277,588	6	950	2.8	2045	2055	2055	
Virginia Beach	VA	436,497	3	1,320	3.9	2060	2080		
Commitment threshold: 100%									
Cape Coral	FL	153,809	3	1,950	6.0	2085			
Hialeah	FL	224,634	2	1,160	3.5	2055	2070	2080	
Hollywood	FL	139,946	4	2,240	7.0	2095			
Metairie	LA	138,481	5	1,210	3.5	2055	2075	2090	
Miami Gardens	FL	107,167	8	1,790	5.5	2080			
Miramar	FL	107,278	7	2,420	7.5	2100			
New Orleans	LA	343,467	1	1,540	4.5	2070	2095		
Pembroke Pines	FL	123,802	6	1,340	4.0	2065	2080		

The years shown relate to emissions and associated commitments, not to the timing of ensuing warming or SLR. Rows for the 10 largest cities are shaded underneath each commitment threshold level. See the legend of Table S3 for further documentation.

Table S5. Cities exceeding 100,000 residents where 25% of the 2010 population-weighted area will fall below the future committed high tide line, assuming inevitable collapse of the WAIS under any emissions scenario (triggered case)

City	State	Total population	Population rank	Critical cumulative emissions, GtC	Committed SLR, m	Commitment year			
						RCP 8.5	RCP 6.0	RCP 4.5	RCP 2.6
Beaumont	TX	118,286	39	1,310	5.4	2060	2080		
Boston	MA	617,594	3	AE	2.8	AE	AE	AE	AE
Bridgeport	CT	144,229	28	1,770	6.2	2080			
Brownsville	TX	175,023	22	2,050	6.9	2090			
Cambridge	MA	105,162	44	AE	1.5	AE	AE	AE	AE
Cape Coral	FL	153,809	25	AE	1.9	AE	AE	AE	AE
Charleston	SC	119,875	38	AE	1.6	AE	AE	AE	AE
Chesapeake	VA	221,576	17	AE	2.9	AE	AE	AE	AE
Clearwater	FL	107,685	40	1,600	6.0	2075	2095		
Coral Springs	FL	121,062	37	AE	2.8	AE	AE	AE	AE
Corpus Christi	TX	305,184	11	1,420	5.6	2065	2085		
Elizabeth	NJ	124,969	35	1,520	5.7	2070	2090		
Elk Grove	CA	152,772	26	1,380	5.5	2065	2085		
Fort Lauderdale	FL	165,521	23	AE	1.2	AE	AE	AE	AE
Hampton	VA	137,373	32	AE	2.7	AE	AE	AE	AE
Hayward	CA	142,760	29	1,860	6.5	2080			
Hialeah	FL	224,634	16	AE	1.5	AE	AE	AE	AE
Hollywood	FL	139,946	30	AE	1.5	AE	AE	AE	AE
Honolulu (urban)	HI	337,248	9	AE	3.9	AE	AE	AE	AE
Huntington Beach	CA	189,992	20	AE	1.1	AE	AE	AE	AE
Jacksonville	FL	819,050	2	770	5.1	2035	2040	2040	2045
Jersey City	NJ	247,597	13	AE	3.7	AE	AE	AE	AE
Long Beach	CA	458,815	5	1,660	6.1	2075	2100		
Metairie	LA	138,481	31	AE	0.1	AE	AE	AE	AE
Miami	FL	399,457	7	AE	1.7	AE	AE	AE	AE
Miami Gardens	FL	107,167	42	AE	1.6	AE	AE	AE	AE
Miramar	FL	107,278	41	AE	1.2	AE	AE	AE	AE
Mobile	AL	195,111	19	2,400	7.6	2100			
New Haven	CT	129,779	34	2,210	7.2	2095			
New Orleans	LA	343,467	8	AE	0.2	AE	AE	AE	AE
New York	NY	8,175,083	1	1,890	6.5	2085			
Newport News	VA	180,659	21	1,770	6.3	2080			
Norfolk	VA	242,751	15	AE	2.7	AE	AE	AE	AE
Oxnard	CA	197,820	18	1,950	6.7	2085			
Palm Bay	FL	103,190	46	1,990	6.8	2085			
Pasadena	TX	149,043	27	2,420	7.7	2100			
Pembroke Pines	FL	123,802	36	AE	1.3	AE	AE	AE	AE
Port St. Lucie	FL	164,438	24	AE	4.6	AE	AE	AE	AE
Richmond	CA	103,668	45	2,220	7.4	2095			
Sacramento	CA	466,486	4	AE	3.2	AE	AE	AE	AE
Savannah	GA	136,286	33	AE	3.5	AE	AE	AE	AE
St. Petersburg	FL	244,767	14	AE	1.7	AE	AE	AE	AE
Stockton	CA	277,588	12	AE	1.4	AE	AE	AE	AE
Tampa	FL	335,654	10	AE	4.0	AE	AE	AE	AE
Virginia Beach	VA	436,497	6	AE	2.9	AE	AE	AE	AE
Wilmington	NC	106,476	43	1,830	6.4	2080			

The years shown relate to emissions and associated commitments, not to the timing of ensuing warming or SLR. See the legend of Table S3 for further documentation.

Table S6. Cities exceeding 100,000 residents where 50 or 100% of the 2010 population-weighted area will fall below the future committed high tide line, assuming inevitable collapse of the WAIS under any emissions scenario (triggered case)

City	State	Total population	Population rank	Critical cumulative emissions, GtC	Committed SLR, m	Commitment year			
						RCP 8.5	RCP 6.0	RCP 4.5	RCP 2.6
Commitment threshold: 50%									
Beaumont	TX	118,286	23	1,990	6.6	2085			
Cambridge	MA	105,162	26	AE	2.8	AE	AE	AE	AE
Cape Coral	FL	153,809	14	AE	2.5	AE	AE	AE	AE
Charleston	SC	119,875	22	AE	2.4	AE	AE	AE	AE
Chesapeake	VA	221,576	10	AE	4.0	AE	AE	AE	AE
Coral Springs	FL	121,062	21	AE	3.1	AE	AE	AE	AE
Elk Grove	CA	152,772	15	2,410	7.6	2100			
Fort Lauderdale	FL	165,521	12	AE	1.6	AE	AE	AE	AE
Hampton	VA	137,373	18	AE	2.9	AE	AE	AE	AE
Hialeah	FL	224,634	9	AE	1.7	AE	AE	AE	AE
Hollywood	FL	139,946	16	AE	2.1	AE	AE	AE	AE
Huntington Beach	CA	189,992	11	AE	3.4	AE	AE	AE	AE
Jacksonville	FL	819,050	1	2,130	7.0	2090			
Metairie	LA	138,481	17	AE	0.3	AE	AE	AE	AE
Miami	FL	399,457	4	AE	2.5	AE	AE	AE	AE
Miami Gardens	FL	107,167	25	AE	1.8	AE	AE	AE	AE
Miramar	FL	107,278	24	AE	1.6	AE	AE	AE	AE
New Orleans	LA	343,467	5	AE	0.3	AE	AE	AE	AE
Norfolk	VA	242,751	8	AE	2.9	AE	AE	AE	AE
Palm Bay	FL	103,190	27	2,270	7.5	2095			
Pembroke Pines	FL	123,802	20	AE	1.6	AE	AE	AE	AE
Port St. Lucie	FL	164,438	13	1,410	5.8	2065	2085		
Sacramento	CA	466,486	2	730	5.0	2030	2035	2035	2035
Savannah	GA	136,286	19	590	4.9	2020	2020	2020	2020
St. Petersburg	FL	244,767	7	AE	4.6	AE	AE	AE	AE
Stockton	CA	277,588	6	AE	2.8	AE	AE	AE	AE
Virginia Beach	VA	436,497	3	AE	3.9	AE	AE	AE	AE
Commitment threshold: 100%									
Cape Coral	FL	153,809	3	1,570	6.0	2070	2095		
Hialeah	FL	224,634	2	AE	3.5	AE	AE	AE	AE
Hollywood	FL	139,946	4	2,020	7.0	2090			
Metairie	LA	138,481	5	AE	3.5	AE	AE	AE	AE
Miami Gardens	FL	107,167	8	1,030	5.5	2050	2060	2060	
Miramar	FL	107,278	7	2,230	7.5	2095			
New Orleans	LA	343,467	1	AE	4.5	AE	AE	AE	AE
Pembroke Pines	FL	123,802	6	AE	4.0	AE	AE	AE	AE

The years shown relate to emissions and associated commitments, not to the timing of ensuing warming or SLR. Rows for the 10 largest cities are shaded underneath each commitment threshold level. See the legend of Table S3 for further documentation.

Table S7. Coastal state and US total 2010 census populations living on land falling below future committed high tide lines under different emissions scenarios through 2050, making no assumptions about the inevitability of WAIS collapse (baseline case)

State	Population (in thousands of persons) living below committed sea levels by scenario: median (white) and 17th–83rd percentile estimates (shaded)											
	Historical emissions		Historical + EIEE		RCP 2.6 through 2050		RCP 4.5 through 2050		RCP 6.0 through 2050		RCP 8.5 through 2050	
Alaska	29	0–40	33	1–44	33	22–45	35	25–48	35	24–48	37	27–52
Alabama	12	0–42	20	0–51	21	1–52	27	4–57	26	3–56	35	8–63
California	587	0–1,377	836	0–1,608	876	242–1,644	1,013	321–1,765	981	303–1,736	1,208	446–1,943
Connecticut	47	0–125	72	0–151	76	0–156	89	16–171	86	14–167	108	30–192
District of Columbia	1	0–8	3	0–12	3	0–12	5	1–14	4	1–14	7	1–17
Delaware	23	0–58	34	0–71	36	1–73	42	8–81	41	7–79	50	16–91
Florida	2,465	0–6,556	4,268	0–7,360	4,535	220–7,492	5,177	497–7,965	5,029	433–7,854	5,978	1,296–8,594
Georgia	65	0–216	107	0–266	114	10–274	138	22–300	132	20–294	177	40–332
Hawaii	100	0–219	153	4–243	159	6–246	180	17–260	176	12–257	204	65–278
Louisiana	1,098	0–1,507	1,242	0–1,628	1,264	741–1,647	1,331	849–1,709	1,316	825–1,696	1,422	985–1,790
Massachusetts	223	0–496	330	0–558	344	3–568	389	67–600	379	60–593	446	136–645
Maryland	67	0–182	103	0–219	109	4–225	130	24–244	125	21–240	157	43–272
Maine	7	0–22	11	0–27	12	0–28	15	2–31	14	2–30	18	4–35
Mississippi	14	0–65	23	0–84	25	2–87	34	5–98	32	4–95	50	9–117
North Carolina	126	0–284	180	0–325	189	28–331	216	52–353	210	47–348	253	90–385
New Hampshire	6	0–12	8	0–14	8	0–14	9	2–15	9	2–15	11	4–17
New Jersey	338	0–742	482	0–846	504	8–863	573	108–918	558	92–905	662	223–997
New York	411	0–1,320	710	0–1,616	758	2–1,662	909	82–1,815	876	68–1,782	1,116	221–2,019
Oregon	13	0–29	18	0–35	19	5–36	22	7–38	21	6–38	26	10–42
Pennsylvania	10	0–54	17	0–78	19	0–83	27	3–97	25	3–93	40	6–116
Rhode Island	10	0–34	17	0–42	18	0–44	22	3–48	21	3–47	28	6–54
South Carolina	134	0–363	205	0–431	216	18–442	257	45–479	247	40–471	313	88–530
Texas	155	0–419	236	0–512	250	35–529	296	60–586	285	55–572	360	105–675
Virginia	168	0–847	333	0–1,021	366	20–1,042	494	46–1,109	464	41–1,095	685	96–1,193
Washington	74	0–130	92	0–146	95	32–149	105	48–157	103	46–155	118	62–167
US total	6,181	0–15,148	9,533	4–17,388	10,052	1,400–17,743	11,535	2,314–18,959	11,194	2,132–18,678	13,508	4,017–20,617

Projections assume zero additional emissions after emissions end dates listed, except for the historical + EIEI scenario. EIEI is the expected future emissions implied by existing energy infrastructure, as estimated in ref. 23. The years shown relate to emissions and associated commitments, not to the timing of ensuing warming or SLR. Levels of committed warming and SLR associated with each scenario are shown in Table S1. US totals include only the listed states and the District of Columbia.

Table S8. Coastal state and US total 2010 census populations living on land falling below future committed high tide lines under different emissions scenarios through 2100, making no assumptions about the inevitability of WAIS collapse (baseline case)

State	Population (in thousands of persons) living below committed sea levels by scenario: median (white) and 17th–83rd percentile estimates (shaded)							
	RCP 2.6 through 2100		RCP 4.5 through 2100		RCP 6.0 through 2100		RCP 8.5 through 2100	
Alaska	34	23–46	40	30–54	50	36–61	63	51–74
Alabama	23	2–53	42	12–70	60	32–89	93	64–141
California	911	263–1,675	1,384	596–2,106	1,871	1,128–2,610	2,750	2,009–3,482
Connecticut	80	10–160	125	47–211	178	96–264	265	180–350
District of Columbia	4	1–13	8	1–20	15	5–24	24	16–33
Delaware	38	5–75	58	23–102	85	45–137	140	87–208
Florida	4,704	294–7,611	6,595	2,590–9,082	8,346	5,665–10,097	10,308	8,729–11,342
Georgia	120	16–281	216	65–355	316	155–395	400	332–430
Hawaii	165	8–250	223	110–292	276	201–328	343	294–388
Louisiana	1,283	773–1,664	1,507	1,100–1,860	1,752	1,379–2,047	2,085	1,801–2,294
Massachusetts	357	44–576	495	219–683	614	408–792	793	616–974
Maryland	115	15–230	181	66–299	255	140–381	386	261–487
Maine	13	2–28	21	7–39	32	16–52	52	31–75
Mississippi	27	3–90	65	14–133	108	42–185	196	119–250
North Carolina	196	35–337	285	127–415	368	234–517	535	381–692
New Hampshire	9	1–15	12	6–18	16	10–23	23	16–30
New Jersey	524	56–877	739	334–1,068	946	605–1,259	1,270	958–1,582
New York	801	38–1,703	1,312	404–2,203	1,886	981–2,720	2,744	1,912–3,599
Oregon	20	6–36	30	13–45	40	24–54	56	43–77
Pennsylvania	21	2–86	54	10–133	103	31–196	201	106–321
Rhode Island	19	2–45	34	10–60	50	24–78	78	51–108
South Carolina	227	28–452	363	134–576	503	284–686	701	526–823
Texas	262	43–543	420	156–770	633	331–1,067	1,147	699–1,754
Virginia	395	29–1,061	849	169–1,258	1,148	577–1,386	1,394	1,176–1,512
Washington	98	41–151	130	74–176	162	112–204	210	168–268
US total	10,443	1,739–18,060	15,189	6,316–22,031	19,813	12,560–25,650	26,255	20,625–31,295

Projections assume zero additional emissions after emissions end dates listed. The years shown relate to emissions and associated commitments, not to the timing of ensuing warming or SLR. Levels of committed warming and SLR associated with each scenario are shown in Table S1. US totals include only the listed states and the District of Columbia.

Table S9. Coastal state and US total 2010 census populations living on land falling below future committed high tide lines under different fixed long-term warming scenarios, making no assumptions about the inevitability of WAIS collapse (baseline case)

State	Population (in thousands of persons) living below committed sea levels by scenario: median (white) and 17th–83rd percentile estimates (shaded)							
	1.5 °C warming		2 °C warming		3 °C warming		4 °C warming	
Alaska	36	26–50	48	35–60	58	46–70	72	60–82
Alabama	31	5–60	57	27–85	82	53–120	130	87–174
California	1,097	372–1,842	1,775	1,025–2,512	2,441	1,706–3,179	3,360	2,626–4,043
Connecticut	97	20–179	169	88–255	236	149–321	323	238–401
Dist. of Columbia	5	1–15	14	4–23	22	12–29	30	23–38
Delaware	45	11–85	80	42–130	118	71–183	188	122–257
Florida	5,540	761–8,250	8,010	5,244–9,926	9,755	7,679–10,996	11,168	10,019–11,827
Georgia	153	28–314	300	138–391	383	277–420	424	391–441
Hawaii	191	37–268	265	187–321	320	264–366	384	339–420
Louisiana	1,370	909–1,744	1,710	1,332–2,015	1,979	1,665–2,212	2,253	2,032–2,433
Massachusetts	412	84–618	596	384–774	732	550–912	912	732–1,091
Maryland	141	30–256	242	128–368	343	219–451	457	351–560
Maine	16	3–32	30	14–50	44	26–67	67	44–90
Mississippi	40	6–106	99	34–175	165	90–234	243	180–263
North Carolina	232	66–366	353	216–496	469	331–640	658	488–782
New Hampshire	10	3–16	15	9–22	20	14–28	28	20–35
New Jersey	609	147–950	912	566–1,229	1,164	842–1,466	1,480	1,177–1,798
New York	991	116–1,897	1,799	893–2,635	2,453	1,599–3,290	3,321	2,483–4,131
Oregon	24	8–40	38	22–52	51	36–70	74	53–88
Pennsylvania	32	4–104	95	25–184	161	77–280	285	165–390
Rhode Island	24	4–51	48	22–75	68	41–97	98	68–129
South Carolina	280	59–500	478	256–670	644	445–777	794	667–892
Texas	323	76–623	588	298–1,009	959	549–1,501	1,637	1,057–2,190
Virginia	571	61–1,145	1,108	491–1,373	1,342	1,035–1,463	1,473	1,359–1,620
Washington	111	54–161	157	105–198	192	150–243	254	200–312
US total	12,383	2,893–19,673	18,984	11,584–25,030	24,202	17,929–29,414	30,114	24,982–34,487

Pure warming scenarios assume long-term fixed warming levels, and make no predictions about the timing of ensuing SLR. Levels of committed SLR associated with each scenario are shown in Table S1. US totals include only the listed states and the District of Columbia.

Table S10. Coastal state and US total 2010 census populations living on land falling below future committed high tide lines under different emissions scenarios through 2050, assuming the inevitable collapse of the WAIS under any scenario (triggered case)

	Population (in thousands) living below committed sea levels by scenario: median (white) and 17th–83rd percentile estimates (shaded)											
State	Historical emissions		Historical + EIEE		RCP 2.6 through 2050		RCP 4.5 through 2050		RCP 6.0 through 2050		RCP 8.5 through 2050	
Alaska	50	37–61	52	38–62	52	38–62	52	39–63	52	39–63	53	39–64
Alabama	59	32–87	62	36–90	63	36–90	64	38–92	64	37–91	66	40–94
California	1,835	1,126–2,539	1,922	1,221–2,627	1,936	1,237–2,641	1,975	1,281–2,682	1,967	1,272–2,673	2,025	1,336–2,732
Connecticut	182	102–263	191	111–272	193	112–274	197	116–278	196	115–277	203	121–284
Dist. of Columbia	15	6–24	17	7–25	17	7–25	18	7–25	18	7–25	18	8–25
Delaware	86	48–136	91	52–142	92	52–144	94	54–147	94	54–146	97	56–151
Florida	8,297	5,751–10,003	8,572	6,105–10,160	8,617	6,162–10,185	8,748	6,313–10,262	8,719	6,283–10,245	8,903	6,482–10,358
Georgia	314	159–393	329	180–397	331	184–398	337	194–400	336	191–399	344	206–402
Hawaii	272	201–323	280	211–329	281	212–330	285	217–332	284	216–332	289	222–336
Louisiana	1,740	1,383–2,025	1,779	1,427–2,056	1,785	1,434–2,061	1,802	1,455–2,075	1,798	1,450–2,072	1,824	1,481–2,091
Massachusetts	625	433–793	644	457–812	648	461–815	657	472–824	655	470–822	668	486–836
Maryland	257	148–377	269	160–390	272	162–392	278	168–397	276	166–396	286	175–404
Maine	33	17–53	35	19–55	35	19–56	36	20–57	36	20–57	37	21–58
Mississippi	106	43–179	114	51–188	116	52–189	120	56–194	119	55–193	125	61–199
North Carolina	368	242–508	383	259–529	386	261–532	393	269–542	391	267–540	402	278–554
New Hampshire	16	10–23	17	11–24	17	11–24	17	11–24	17	11–24	18	12–25
New Jersey	956	634–1,255	993	674–1,286	999	680–1,292	1,016	699–1,307	1,012	695–1,304	1,036	722–1,325
New York	1,917	1,051–2,711	2,010	1,148–2,800	2,025	1,164–2,815	2,069	1,211–2,858	2,059	1,201–2,849	2,122	1,267–2,911
Oregon	40	24–53	42	26–55	42	27–55	43	27–56	43	27–55	44	29–57
Pennsylvania	105	35–194	114	41–207	115	42–209	120	46–216	119	45–214	125	50–224
Rhode Island	52	27–78	54	29–81	55	30–81	56	31–83	56	31–83	58	33–85
South Carolina	501	292–678	525	318–694	529	323–696	540	335–704	538	332–702	554	350–712
Texas	618	332–1,027	661	363–1,080	669	368–1,089	692	382–1,115	687	379–1,109	721	400–1,149
Virginia	1,154	630–1,382	1,190	718–1,395	1,196	732–1,397	1,211	774–1,403	1,208	765–1,402	1,231	822–1,410
Washington	161	113–200	166	119–206	167	120–206	169	123–209	168	123–208	172	127–212
US total	19,758	12,876–25,363	20,512	13,779–25,961	20,634	13,927–26,058	20,989	14,339–26,344	20,912	14,252–26,281	21,420	14,822–26,696

Projections assume zero additional emissions after emissions end dates listed, except for the historical + EIEI scenario. EIEI is the expected future emissions implied by existing energy infrastructure, as estimated in ref. 23. The years shown relate to emissions and associated commitments, not the timing of ensuing warming or SLR. Levels of committed warming and SLR associated with each scenario are shown in Table S2. US totals include only the listed states and the District of Columbia.

Table S11. Coastal state and US total 2010 census populations living on land falling below future committed high tide lines under different emissions scenarios through 2100, assuming the inevitable collapse of the WAIS under any scenario (triggered case)

State	Population (in thousands of persons) living below committed sea levels by scenario: median (white) and 17th–83rd percentile estimates (shaded)							
	RCP 2.6 through 2100		RCP 4.5 through 2100		RCP 6.0 through 2100		RCP 8.5 through 2100	
Alaska	52	38–62	54	40–64	57	44–67	65	55–76
Alabama	63	37–91	68	41–96	76	49–108	100	71–149
California	1,947	1,249–2,652	2,070	1,382–2,776	2,282	1,595–2,990	2,904	2,197–3,602
Connecticut	194	113–275	208	125–289	228	145–309	284	203–363
District of Columbia	17	7–25	19	8–26	21	11–28	26	19–34
Delaware	92	53–145	100	59–155	112	68–171	154	99–220
Florida	8,654	6,209–10,206	9,014	6,633–10,443	9,502	7,336–10,777	10,595	9,253–11,458
Georgia	333	186–398	350	216–403	372	258–412	406	358–432
Hawaii	282	214–330	292	227–339	309	250–353	353	308–395
Louisiana	1,790	1,440–2,065	1,843	1,504–2,104	1,925	1,612–2,164	2,131	1,880–2,325
Massachusetts	650	464–818	677	497–846	717	543–887	832	664–1,004
Maryland	273	164–393	293	181–410	325	210–434	409	292–505
Maine	35	19–56	38	22–60	43	25–65	57	36–79
Mississippi	117	53–191	129	65–203	150	82–221	211	138–254
North Carolina	388	263–535	410	286–565	446	319–610	574	416–714
New Hampshire	17	11–24	18	12–25	20	13–27	24	17–32
New Jersey	1,003	685–1,296	1,054	741–1,342	1,130	822–1,416	1,332	1,044–1,635
New York	2,037	1,178–2,827	2,169	1,318–2,957	2,366	1,547–3,159	2,922	2,134–3,738
Oregon	42	27–55	45	30–58	48	34–65	61	46–80
Pennsylvania	117	43–211	129	53–231	150	71–261	227	127–339
Rhode Island	55	30–82	59	34–86	66	40–93	85	58–113
South Carolina	532	326–698	566	363–719	617	421–752	728	580–841
Texas	675	372–1,096	747	418–1,182	873	500–1,345	1,262	811–1,856
Virginia	1,200	744–1,399	1,248	858–1,416	1,316	1,001–1,444	1,418	1,254–1,538
Washington	167	121–207	174	130–215	185	144–230	220	178–278
US total	20,734	14,048–26,138	21,775	15,242–27,010	23,338	17,142–28,387	27,379	22,240–32,061

Projections assume zero additional emissions after emissions end dates listed. The years shown relate to emissions and associated commitments, not to the timing of ensuing warming or SLR. Levels of committed warming and SLR associated with each scenario are shown in Table S1. US totals include only the listed states and the District of Columbia.

Table S12. Coastal state and US total 2010 census populations living on land falling below future committed high tide lines under different fixed long-term warming scenarios, assuming the inevitable collapse of the WAIS under any scenario (triggered case)

	Population (in thousands of persons) living below committed sea levels by scenario: median (white) and 17th–83rd percentile estimates (shaded)							
State	1.5 °C warming		2 °C warming		3 °C warming		4 °C warming	
Alaska	53	40–64	56	43–67	61	50–72	74	63–84
Alabama	67	40–94	75	48–105	89	62–132	143	96–179
California	2,035	1,346–2,741	2,235	1,552–2,943	2,639	1,933–3,339	3,546	2,848–4,134
Connecticut	204	122–285	225	142–306	258	177–339	344	264–416
District of Columbia	19	8–26	21	11–27	24	15–32	33	24–39
Delaware	98	57–152	110	67–168	134	85–199	206	141–271
Florida	8,924	6,512–10,375	9,422	7,193–10,714	10,119	8,513–11,191	11,380	10,449–11,921
Georgia	345	208–402	368	250–410	395	322–426	430	402–444
Hawaii	290	223–336	305	244–350	334	286–376	396	353–426
Louisiana	1,828	1,485–2,094	1,909	1,591–2,152	2,050	1,772–2,257	2,304	2,106–2,461
Massachusetts	669	488–837	712	537–882	779	610–951	959	787–1,128
Maryland	287	176–405	320	205–431	375	254–472	483	387–583
Maine	37	21–59	42	25–64	50	31–72	73	51–96
Mississippi	126	62–199	146	78–218	186	112–244	252	203–265
North Carolina	403	279–556	439	313–602	514	372–671	693	544–805
New Hampshire	18	12–25	20	13–27	22	16–29	30	23–37
New Jersey	1,039	725–1,328	1,119	810–1,404	1,243	943–1,537	1,564	1,268–1,863
New York	2,130	1,276–2,918	2,338	1,514–3,130	2,671	1,876–3,481	3,550	2,735–4,285
Oregon	44	29–57	48	33–63	54	41–74	78	58–90
Pennsylvania	125	50–225	147	69–256	190	102–305	315	200–408
Rhode Island	58	33–85	65	39–92	76	50–104	106	77–135
South Carolina	556	353–713	608	410–746	684	511–803	825	709–908
Texas	726	404–1,156	847	482–1,309	1,078	659–1,640	1,795	1,208–2,231
Virginia	1,234	828–1,411	1,305	984–1,439	1,382	1,155–1,490	1,509	1,398–1,645
Washington	172	127–213	183	141–227	204	164–257	270	214–322
US total	21,487	14,903–26,756	23,064	16,796–28,132	25,611	20,112–30,496	31,358	26,608–35,175

Pure warming scenarios assume long-term fixed warming levels, and make no predictions about the timing of ensuing SLR. Levels of committed SLR associated with each scenario are shown in Table S1. US totals include only the listed states and the District of Columbia.