Carbon choices determine US cities committed to futures below sea level

Benjamin H. Strauss[a,1], Scott Kulp[a], and Anders Levermann[b,c]

[a]Climate Central, Princeton, NJ 08542; [b]Potsdam Institute for Climate Impact Research, 14473 Potsdam, Germany; and [c]Physics Institute of Potsdam University, 14476 Potsdam, Germany

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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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[1]To whom correspondence should be addressed. Email: bstrauss@climatecentral.org.

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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

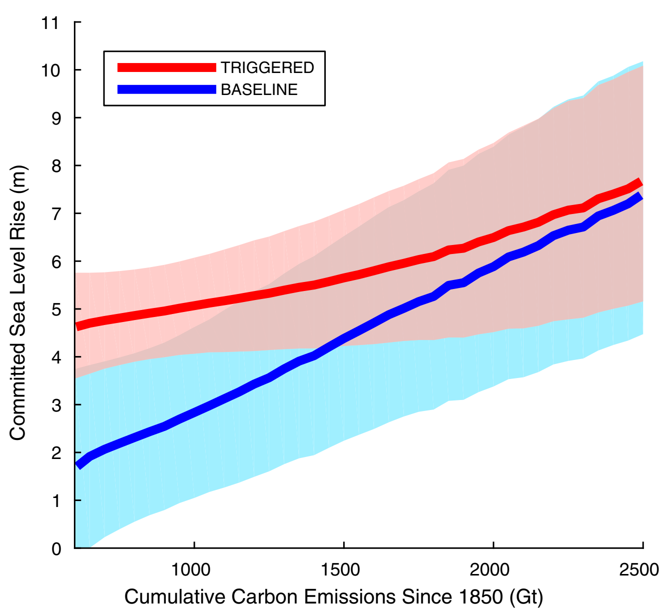

Fig. 1. Projections of long-term committed SLR as a function of cumulative carbon emissions, with 66% CIs, assuming (triggered case) or not assuming (baseline case) that eventual collapse of the WAIS is already inevitable.

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

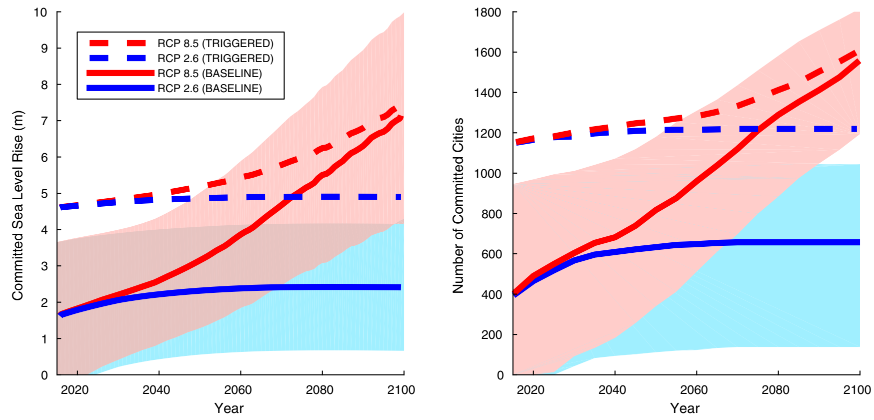

Fig. 2. Projections of committed global SLR (*Left*) and municipalities where more than half the population-weighted area would be affected (*Right*), under different emissions scenarios and assumptions about West Antarctica. The years shown relate to emissions and associated commitments, not to the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

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.

for any addition to historic emissions) are greater for the baseline case, because it starts from a lower point.

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.

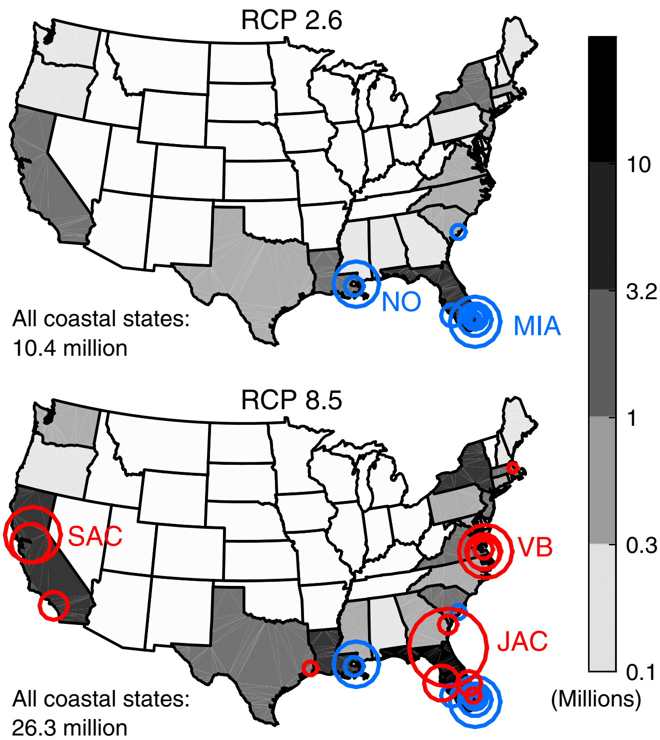

Fig. 3. State and total populations on land and major cities in which the majority of the population occupies land committed to fall below future high tide lines given emissions through 2100 under RCP 2.6 (blue city markers on both maps) or 8.5 (red city markers) and assuming the baseline Antarctic case (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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