Rapid accumulation of committed sea-level rise from global warming

Benjamin H. Strauss[1]
Climate Central, Princeton, NJ 08542

As carbon emissions and scientific research have accumulated over recent years, climate scientists have come to see global climate change as an increasingly urgent threat (1, 2). In PNAS, Levermann et al. (3) provide a powerful new indicator of danger. When their findings on the long-term sensitivity of global sea level to global warming (~2.3 m/°C) are put in the context of recent research on the sensitivity of global temperature to cumulative carbon dioxide emissions (4), simple analyses suggest (described below) that we have already committed to a long-term future sea level >1.3 or 1.9 m higher than today and are adding about 0.32 m/decade to the total: 10 times the rate of observed contemporary sea-level rise (5). By midcentury, the central estimate of commitment would rise to >3.1 m assuming today's trends continue or to 2.1 m under an aggressive emissions cutting and atmospheric carbon dioxide removal scenario. Both scenarios threaten the future viability of many hundreds of coastal municipalities in the United States alone, but the low emissions path would likely spare hundreds more, including many major cities.

Many studies have projected sea levels throughout the 21st century (6). The great majority show strongly accelerated rates of rise by 2100, but only a few project past then (7, 8). Among these, the work of Levermann et al. stands out for matching physical models with evidence of ancient sea-level responses to temperature and for focusing on the amount of sea-level rise rather than its more elusive rate. (In a loose analogy, it is trivial to predict a pile of ice in a warm room will all melt, but demanding to predict the exact rates over time.) This tactic was key to their multifaceted effort, which addressed thermal expansion of warming oceans, melting glaciers, and mass loss from Greenland and Antarctic ice sheets.

The 2,000-y envelope Levermann et al. use may soften the implications of their research. However, numerous studies suggest that cumulative carbon emissions will contribute to warming and thus drive sea-level rise for many millennia (9, 10). Two thousand years is a short enough period to have profound cultural significance, and the commitments projected may unfold more swiftly.

The international community has largely agreed on a target of 2 °C warming from preindustrial times as a safe level. However, according to Levermann et al., 2 °C implies a long-term commitment for 4.8 m of mean global sea-level rise. That increase is nearly twice the height of hurricane Sandy's peak storm surge at The Battery in New York City and exceeds the average elevations of major coastal cities across the globe.

Further implications emerge when the work of Levermann et al. is combined with findings on the sensitivity of global mean temperature to cumulative carbon emissions. The most recent observationally constrained analysis indicates a transient climate response to cumulative carbon emissions (TCRE) of 1.3 °C warming (0.7–2.0 °C, 90% CI) per trillion tons C (4). This relationship suggests we have already committed to an additional 1.3 m of rise above the current sea level (range of 0.6–2.2 m, based on the CI for TCRE), given emissions since 1850 (~528 billion tons) and accounting for the small global rise (~0.21 m) already observed since the late 19th century (11). For convenience, I estimated historic emissions from historic (1850–2005) and projected (2006–2012) emissions provided under Representative Concentration Pathway 8.5 (RCP8.5) (12), because actual emissions have tracked just above RCP8.5 since 2006 (1). Based on the 2012 annual emissions rate under RCP8.5, including land-use change emissions, we are growing our future sea-level rise commitment by 0.32 m (0.17–0.49 m) per decade.

Similar analyses can be further applied to contrast the standard RCP scenarios being used by the Intergovernmental Panel on Climate Change. Fig. 1*A* illustrates the implied sea-level rise commitment differential between the two most extreme of these: RCP8.5, the no-policy, highest emissions scenario (attaining net radiative forcing of 8.5 W/m^2 by 2100); and RCP2.6, the lowest

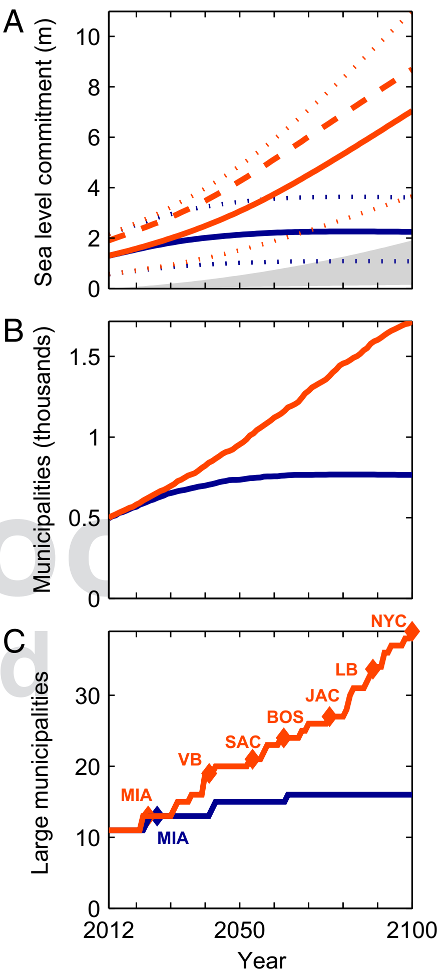

Fig. 1. Projected rapid accumulation of long-term global sea-level rise commitment (*A*) and threats to coastal municipalities in the contiguous United States (*B* and *C*). RCP8.5 projections shown in orange and RCP2.6 in blue. The gray shaded area in *A* represents the range of 21st-century sea-level rise projections (6) to contrast with projected zero emission commitments (ZECs) (solid lines), shown with ranges (dotted lines) as described in the text. The heavy dashed line shows estimated commitments based on 5% annual reductions (instead of ZECs) after abandonment of RCP8.5. Curves (*B*) show the number of municipalities of any size with at least 25% of the current population living below ZECs plus high tide plotted as a function of commitment year, whereas *C* includes only municipalities >100,000 in population. Cities >350,000 are labeled individually: MIA, Miami, FL; VB, Virginia Beach, VA; SAC, Sacramento, CA; JAC, Jacksonville, FL; BOS, Boston, MA; LB, Long Beach, CA; NYC, New York, NY.

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[1]E-mail: bstrauss@climatecentral.org.

emissions scenario (2.6 W/m^2) (13). RCP2.6 includes rapid cuts far deeper than contemplated in major emitter nation agendas and further assumes active net removal of carbon from the atmosphere late in the century. Commitments under both scenarios nonetheless exceed the full range of projected sea-level rise for this century (6). Fig. 1*A* and other estimates in this commentary present ranges based on the 90% CI of TCRE. The warming-commitment relationship cone shown in figure 2*E* of Levermann et al. implies a similar magnitude of ranges for the estimates made in this commentary, but the meaning of the cone is less precisely defined than the TCRE CI and thus not considered further here.

One set of consequences implied by high vs. low continuing emissions is starkly different futures for the world's coastal cities. A brief analysis of the contiguous United States illustrates this. Fig. 1 *B* and *C* shows projected increases in US municipalities with at least 25% of the current population living on land lower than the committed future high tide line, based on the RCPs considered here and a previous elevation-based national coastal vulnerability assessment (14). The results indicate that ∼500 American towns and cities are already committed, now home to 6.0 million (median population, 2,235; mean, 11,924). However, results also show that the choice of emissions pathway today can make a difference of hundreds more municipalities by midcentury. The contrast may be even stronger for incorporated cities with populations >350,000: seven become committed this century under RCP8.5 vs. only Miami under RCP2.6.

Using a more stringent 50% threshold, Miami, Virginia Beach, Sacramento, and Jacksonville still commit this century under RCP8.5, and more than 1,400 municipalities overall commit by 2100. Alternatively, thresholds lower than 25% may be untenable for many communities, given factors such as the layout and defensibility of critical infrastructure.

This consideration of US municipal vulnerability omits the regional deviations from global sea-level change caused by shifting gravitational pulls on the ocean and related effects as ice sheets lose mass. As modeled by Levermann et al., however, these deviations have relatively minor net consequences for the contiguous United States.

The emissions-based estimates thus far presented are zero emissions commitments (ZECs), assuming an immediate halt to emissions following each year evaluated. However, economic and political inertia pose important obstacles to rapid emissions reductions, and modeling suggests that it is nearly impossible to reach annual average reductions >5% (15). ZECs make useful thought experiments, allowing estimates of literal commitments to date, but are clearly biased low compared with achievable targets. To help illustrate a lower limit on this bias, the dashed curve in Fig. 1*A* incorporates an assumed sudden transition to an aggressive 5% annual reduction rate

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downstream of each year evaluated on the RCP8.5 trajectory. This leads to estimates of commitment averaging 36% or 1.2 m higher over the balance of the century and suggests a best estimate of the current commitment from historic emissions of >1.9 m.

RCP2.6 already includes aggressive reductions, so the same analysis is not appropriate. The main question around RCP2.6 is whether the global community can achieve it.

One more set of implications from Levermann et al. is worth visiting here. Simple calculations integrating TCRE indicate that emitting 1 metric ton of carbon may increase ocean volume by 1,092 m^3 (588–1680 m^3) in the long run. Similarly, combusting 1 ton of coal ultimately adds 621 m^3 (334–955 m^3) to the ocean, and a single liter of petroleum adds 647 times its volume (348–996 L), assuming mean fuel carbon densities from current US consumption (16). This is an extraordinary illustration of the sensitivity of the Earth system.

Levermann et al. assume that each increment of warming they analyze is essentially sustained across two millennia. A meaningful drop in global temperature from its peak during this period would weaken their findings. However, a significant body of research points to multimillennial endurance of warming due to carbon emissions, even as future atmospheric carbon levels slowly drop (9, 10). Furthermore, estimates in this commentary use several counterbalancing assumptions. With the noted exception of the heavy dashed line in Fig. 1*A*, estimates are based on ZECs. Calculations use TCRE, as opposed to the higher peak warming response to cumulative carbon emissions, and they ignore the contribution of non-CO_2 climate pollutants. Estimates also adhere to a 2,000-y time frame, although paleontological evidence (17) as well as Levermann et al.'s own analysis suggest that sea level is even more sensitive to temperature at longer time scales.

Levermann et al.'s findings underscore the extraordinary and enduring sensitivity of global sea level to warming caused by carbon emissions. Their implications for the future of humanity are profound. The coastal resilience measures that global cities are beginning to weigh and implement cannot be seen as solutions to a fixed problem, but rather as first steps in a long journey. The current trend in carbon emissions likely implies the eventual crippling or loss of most coastal cities in the world. However, within a rapidly closing window, deep and rapid cuts in carbon pollution may have the potential to avert this fate.

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