

Humboldt State University

## Digital Commons @ Humboldt State University

---

State & Federal Reports and Publications

Humboldt State University Sea Level Rise  
Initiative

---

11-3-2015

### Carbon choices determine US cities committed to futures below sea level

B H. Strauss

S Kulp

A Levermann

Follow this and additional works at: [https://digitalcommons.humboldt.edu/hsuslri\\_state](https://digitalcommons.humboldt.edu/hsuslri_state)

---

# Carbon choices determine US cities committed to futures below sea level

Benjamin H. Strauss<sup>a,1</sup>, Scott Kulp<sup>a</sup>, and Anders Levermann<sup>b,c</sup>

<sup>a</sup>Climate Central, Princeton, NJ 08542; <sup>b</sup>Potsdam Institute for Climate Impact Research, 14473 Potsdam, Germany; and <sup>c</sup>Physics Institute of Potsdam University, 14476 Potsdam, Germany

Edited by James Hansen, Columbia University, New York, NY, and approved September 18, 2015 (received for review June 8, 2015)

**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

**M**ost 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.**

Author contributions: B.H.S., S.K., and A.L. designed research; S.K. performed research; B.H.S. and S.K. analyzed data; and B.H.S., S.K., and A.L. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

Freely available online through the PNAS open access option.

<sup>1</sup>To whom correspondence should be addressed. Email: bstrauss@climatecentral.org.

This article contains supporting information online at [www.pnas.org/lookup/suppl/doi:10.1073/pnas.1511186112/-DCSupplemental](http://www.pnas.org/lookup/suppl/doi:10.1073/pnas.1511186112/-DCSupplemental).



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  $\sim 3.3$  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](http://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](http://vdatum.noaa.gov)). To include Alaska, we use the National Elevation Dataset ([nationalmap.gov/elevation.html](http://nationalmap.gov/elevation.html)) and a global grid for MHHW (provided by Mark Merrifield, University of Hawaii, Manoa, Hawaii) developed using the model TPX08 (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/geography/maps-data/data/tiger-line.html](http://www.census.gov/geography/maps-data/data/tiger-line.html)).

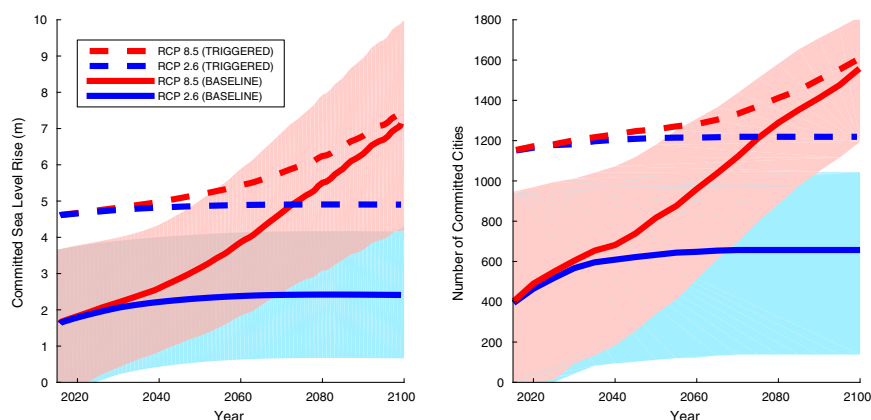
For each municipality and county we compute the population living 0.5–15 m below MHHW in increments of 0.5 m, assuming census blocks of uniform density, except for zero density over wetland areas (16). We interpolate each elevation–population relationship to estimate county populations on affected land 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

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.

**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.



1. Field C, et al. (2014) *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge Univ Press, Cambridge, UK).
2. Solomon S, Plattner G-K, Knutti R, Friedlingstein P (2009) Irreversible climate change due to carbon dioxide emissions. *Proc Natl Acad Sci USA* 106(6): 1704–1709.
3. Eby M, et al. (2009) Lifetime of anthropogenic climate change: Millennial time scales of potential CO<sub>2</sub> and surface temperature perturbations. *J Clim* 22(10):2501–2511.
4. Friedlingstein P, et al. (2011) Long-term climate implications of twenty-first century options for carbon dioxide emission mitigation. *Nat Clim Chang* 1(9):457–461.
5. Zickfeld K, et al. (2013) Long-term climate change commitment and reversibility: An EMIC intercomparison. *J Clim* 26(16):5782–5809.
6. Collins M, et al. (2013) *Long-term Climate Change: Projections, Commitments and Irreversibility. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, eds Stocker TF, et al. (Cambridge Univ Press, Cambridge, UK), pp 1029–1136.
7. Dutton A, et al. (2015) Sea-level rise due to polar ice-sheet mass loss during past warm periods. *Science* 349(6244):aaa4019.
8. Grant KM, et al. (2012) Rapid coupling between ice volume and polar temperature over the past 150,000 years. *Nature* 491(7426):744–747.
9. Abe-Ouchi A, et al. (2013) Insolation-driven 100,000-year glacial cycles and hysteresis of ice-sheet volume. *Nature* 500(7461):190–193.
10. Levermann A, et al. (2013) The multimillennial sea-level commitment of global warming. *Proc Natl Acad Sci USA* 110(34):13745–13750.
11. Stocker TF, et al. (2013) *Climate Change 2013: The Physical Science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge Univ Press, Cambridge, UK).
12. Hinkel J, et al. (2014) Coastal flood damage and adaptation costs under 21st century sea-level rise. *Proc Natl Acad Sci USA* 111(9):3292–3297.
13. Marzeion B, Levermann A (2014) Loss of cultural world heritage and currently inhabited places to sea-level rise. *Environ Res Lett* 9(3):034001.
14. Shortridge A, Messina J (2011) Spatial structure and landscape associations of SRTM error. *Remote Sens Environ* 115(6):1576–1587.
15. Gesch DB (2009) Analysis of lidar elevation data for improved identification and delineation of lands vulnerable to sea-level rise. *J Coast Res Special Issue* 53:49–58.
16. Strauss BH, Ziemiński R, Weiss JL, Overpeck JT (2012) Tidally adjusted estimates of topographic vulnerability to sea level rise and flooding for the contiguous United States. *Environ Res Lett* 7(1):014033.
17. Favier L, et al. (2014) Retreat of Pine Island Glacier controlled by marine ice-sheet instability. *Nat Clim Chang* 5(2):1–5.
18. Rignot E, Mouginot J, Morlighem M, Seroussi H, Scheuchl B (2014) Widespread, rapid grounding line retreat of Pine Island, Thwaites, Smith, and Kohler glaciers, West Antarctica, from 1992 to 2011. *Geophys Res Lett* 41(10):3502–3509.
19. Joughin I, Smith BE, Medley B (2014) Marine ice sheet collapse potentially under way for the Thwaites Glacier Basin, West Antarctica. *Science* 344(6185):735–738.
20. Gillett NP, Arora VK, Matthews D, Allen MR (2013) Constraining the ratio of global warming to cumulative CO<sub>2</sub> emissions using CMIP5 simulations. *J Clim* 26(18): 6844–6858.
21. Riahi K, Grübler A, Nakicenovic N (2007) Scenarios of long-term socio-economic and environmental development under climate stabilization. *Technol Forecast Soc Change* 74(7):887–935.
22. Peters G, Andrew R, Boden T, Canadell J (2013) The challenge to keep global warming below 2 °C. *Nat Clim Chang* 3(1):4–6.
23. Raupach MR, et al. (2014) Sharing a quota on cumulative carbon emissions. *Nat Clim Chang* 4(10):873–879.
24. US Energy Information Administration (2012) *Annual Energy Review 2011* (USEIA, Washington, DC).
25. Bamber JL, Riva REM, Vermeersen BL, LeBrocq AM (2009) Reassessment of the potential sea-level rise from a collapse of the West Antarctic Ice Sheet. *Science* 324(5929):901–903.
26. Weertman J (1974) Stability of the junction of an ice sheet and an ice shelf. *J Glaciol* 13(67):3–11.
27. Schoof C (2007) Ice sheet grounding line dynamics: Steady states, stability, and hysteresis. *J Geophys Res* 112(F3):F03528.
28. Levermann A, et al. (2011) Potential climatic transitions with profound impact on Europe. *Clim Change* 110(3–4):845–878.
29. Bamber JL, Aspinall WP (2013) An expert judgement assessment of future sea level rise from the ice sheets. *Nat Clim Chang* 3(4):424–427.
30. Jacobs SS, Jenkins A, Giulivi CF, Dutrieux P (2011) Stronger ocean circulation and increased melting under Pine Island Glacier ice shelf. *Nat Geosci* 4(8):519–523.
31. Thoma M, Jenkins A, Holland D, Jacobs S (2008) Modelling Circumpolar Deep Water intrusions on the Amundsen Sea continental shelf, Antarctica. *Geophys Res Lett* 35(18):2–7.
32. Jacobs S, et al. (2013) Getz Ice Shelf melting response to changes in ocean forcing. *J Geophys Res Ocean* 118(9):4152–4168.
33. Dutrieux P, et al. (2014) Strong sensitivity of Pine Island ice shelf melting to climatic variability. *Science* 343(6167):174–178.
34. Assmann KM, et al. (2013) Variability of circumpolar deep water transport onto the Amundsen Sea Continental shelf through a shelf break trough. *J Geophys Res Ocean* 118(12):6603–6620.
35. Velicogna I, Sutterley TC, van den Broeke MR (2014) Regional acceleration in ice mass loss from Greenland and Antarctica using GRACE time-variable gravity data. *Geophys Res Lett* 41(22):8130–8137.
36. Mitrovica JX, Milne GA (2003) On post-glacial sea level: I. General theory. *Geophys J Int* 154(2):253–267.
37. Kendall RA, Mitrovica JX, Milne GA (2005) On post-glacial sea level - II. Numerical formulation and comparative results on spherically symmetric models. *Geophys J Int* 161(3):679–706.
38. Mitrovica JX, Wahr J, Matsuyama I, Paulson A (2005) The rotational stability of an ice-age earth. *Geophys J Int* 161(2):491–506.
39. Egbert GD, Erofeeva SY (2002) Efficient inverse modeling of barotropic ocean tides. *J Atmos Ocean Technol* 19(2):183–204.
40. Church JA, White NJ (2006) A 20th century acceleration in global sea-level rise. *Geophys Res Lett* 33(1):L01602.
41. Strauss BH (2013) Rapid accumulation of committed sea-level rise from global warming. *Proc Natl Acad Sci USA* 110(34):13699–13700.
42. Levermann A, Griesel A, Hofmann M, Montoya M, Rahmstorf S (2005) Dynamic sea level changes following changes in the thermohaline circulation. *Clim Dyn* 24(4): 347–354.
43. Yin J, Schlesinger ME, Stouffer RJ (2009) Model projections of rapid sea-level rise on the northeast coast of the United States. *Nat Geosci* 2(4):262–266.
44. Hu A, Meehl GA, Han W, Yin J (2011) Effect of the potential melting of the Greenland Ice Sheet on the Meridional Overturning Circulation and global climate in the future. *Deep Sea Research Part II Topical Studies in Oceanography* 58(17–18):1914–1926.
45. Lichter M, Vafeidis AT, Nicholls RJ, Kaiser G (2011) Exploring data-related uncertainties in analyses of land area and population in the “Low-Elevation Coastal Zone” (LECZ). *J Coast Res* 27(4):757–768.
46. Kopp RE, et al. (2014) Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites. *Earths Futur* 2(8):383–406.