UNNATURAL COASTAL FLOODS:

Sea level rise and the human fingerprint on U.S. floods since 1950

February 2016

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Princeton: One Palmer Square, Suite 330 Princeton, NJ 08542
Phone: +1 609 924-3800
Toll Free: +1 877 4-CLI-SCI / +1 877 425-4724
www.climatecentral.org

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REPORT AUTHORS

BENJAMIN H. STRAUSS, PhD

Vice President for Sea Level Rise and Climate Impacts, Climate Central

Dr. Strauss serves as Vice President for Sea Level and Climate Impacts at Climate Central. He is author of numerous scientific papers and reports on sea level rise, as well as architect of the Surging Seas suite of maps, tools and visualizations, viewed and used by millions of coastal stakeholders and others. Strauss has testified before the U.S. Senate, presented to state and local elected officials, and the White House has highlighted his work. His research and Surging Seas have been widely covered by U.S. and international media. He holds a Ph.D. in Ecology and Evolutionary Biology from Princeton and a B.A. in Biology from Yale.

ROBERT E. KOPP, PhD

Associate Director of the Rutgers Energy Institute

Dr. Kopp is Associate Director of the Rutgers Energy Institute and an Associate Professor in the Department of Earth & Planetary Sciences at Rutgers University. His research focuses on understanding uncertainty in past and future climate change, with major emphases on sea-level change and on the interactions between physical climate change and the economy. Prof. Kopp served as the lead scientist for the Economic Risks of Climate Change: An American Prospectus and was a contributing author to the Intergovernmental Panel on Climate Change's 2014 Fifth Assessment Report. He received his Ph.D. in geobiology from Caltech and his undergraduate degree in geophysical sciences from the University of Chicago.

WILLIAM V. SWEET, PhD

Senior Oceanographer, NOAA's Center for Operational Oceanographic Products & Service (CO-OPS)

Dr. Sweet is a Senior Oceanographer with NOAA's Center for Operational Oceanographic Products and Service (CO-OPS) within the National Ocean Service (NOS). He is focused on detecting and explaining trends and patterns affecting recurrent sea level behaviors important for shipping, emergency preparedness and resiliency efforts. His work is helping NOAA and other government agencies develop coastal planning guidance for an uncertain future. He received his Ph.D. in oceanography from North Carolina State University and his undergraduate in physics from the University of North Carolina at Chapel Hill.

REPORT AUTHORS

KLAUS BITTERMANN, PhD

Guest scientist at Potsdam Institute for Climate Impact Research (PIK)

Klaus Bittermann is a guest scientist at the Potsdam Institute for Climate Impact Research (PIK), where he was previously a NOAA-funded Ph.D. student. His research focuses on global sea level and its connection to temperature with the aim of improving projections as well as anthropogenic attribution. He received his undergraduate in Physics at the Institute for Astronomy and Astrophysics in Tuebingen with work on neutrino detection from space.

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CONTENTS

EXECUTIVE SUMMARY

Human-caused climate change is contributing to global sea level rise and consequently aggravating coastal floods. This analysis removes the assessed human-caused component in global sea level from hourly water level records since 1950 at 27 U.S. tide gauges, creating alternative histories simulating the absence of anthropogenic climate change. Out of 8,726 days when unaltered water level observations exceeded National Weather Service local "nuisance" flood thresholds for minor impacts, 5,809 days (3,517-7,332 days, >90% confidence interval) did not exceed thresholds in the alternative histories. In other words, human-caused global sea level rise effectively tipped the balance, pushing high water events over the threshold, for about two-thirds of the observed flood days. The fraction has increased from less than half in the 1950s, to more than three-quarters within the last decade (2005-2014), as global sea level has continued to rise.

Also within the last decade, at sites along Florida's Atlantic coast and the Keys, as well as in San Diego (La Jolla), Seattle, and Honolulu, more than 90% of observed flood days would not have occurred if the central estimate for anthropogenic sea level signal were removed. The same applies to more than half the flood days at each of the 25 out of 27 study gauges averaging more than one total nuisance flood day per year since 2005. Overall, gauges averaged 12.2 flood days per year over this period.

In the central estimate, the human-caused increase in global sea level also accounts for more 80% of the increase in nuisance flood days between the period 1955-1984 and the period 1985-2014 – periods across which flood frequency tripled for study gauges collectively. Anthropogenic climate change is not just a problem for the future: through sea level rise, it is driving most coastal flooding in the United States today. There are human fingerprints on thousands of recent floods.

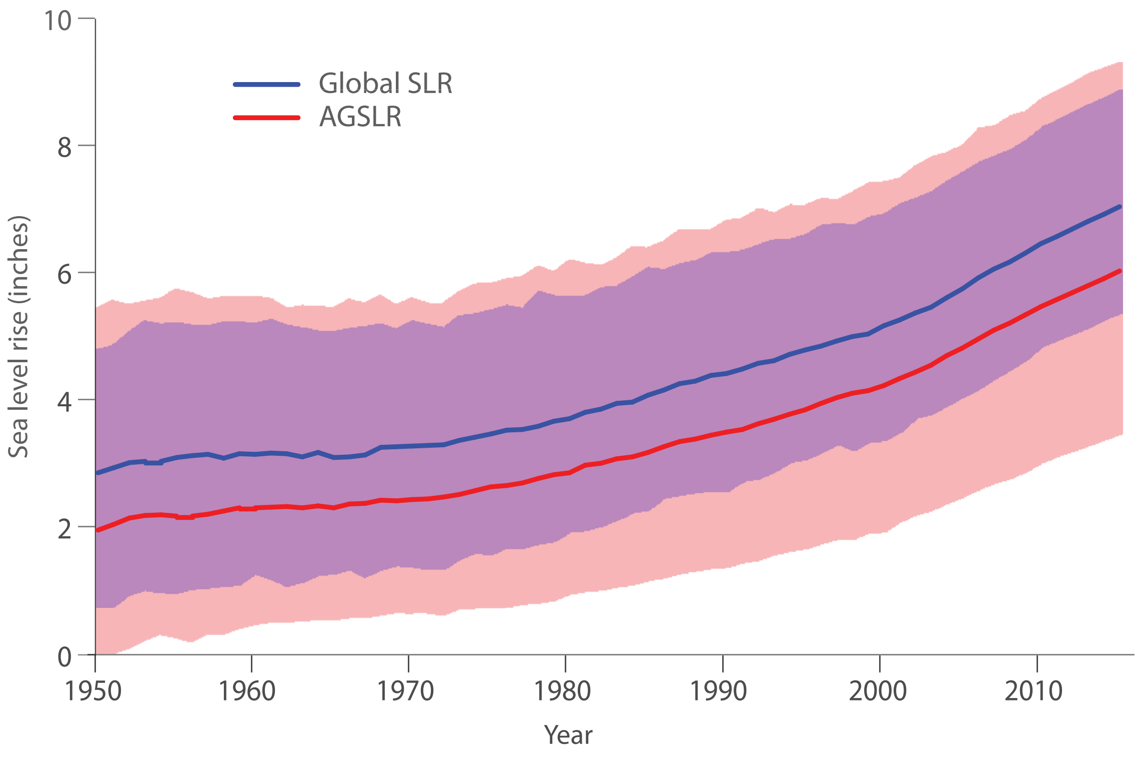
This analysis makes the simplifying assumption that the climate-driven human contribution to sea level across the U.S. is uniform and equal to the global mean contribution, putting aside smaller static-equilibrium and dynamic effects that vary in space and time.

See interactive online map with details and trends at each tide gauge: http://www.climatecentral.org/news/the-human-fingerprints-on-coastal-floods-20050

01. INTRODUCTION AND APPROACH

It is very well established that global sea level is rising and that this rise is linked to climate change (IPCC 2013). Only a small number of studies, however, have attempted to identify how much of the rise can be attributed to human influence, and all of these studies have depended upon analyses of the relatively short tide-gauge record (Jevrejeva *et al.* 2009; Becker *et al.* 2014; Dangendorf *et al.* 2015). Kopp *et al.* (2016) leverage a new, geologically based, 3,000-year reconstruction of sea-level change to estimate the relationship between temperature and rates of sea-level change. They then compare observed 20th century sea-level change against simulated change from counterfactual histories without 20th century global warming. The difference is the estimated rise attributable to humans (**Figure 1**).

Figure 1. *Estimates of total (black) and anthropogenic global sea level rise (AGSLR, in red) since 1900; shaded areas show confidence intervals. Total global sea level rise estimates from Hay et al. (2015) and anthropogenic fraction estimates from Kopp et al. (2016); time series extended through 2015 as described in text.*



Based on multiple methodologies, all four sea level attribution studies agree that human influence very likely (probability >90%) accounts for more than half of the observed 20th century rise. Among these studies, Kopp *et al.* (2016) employ the most extensive data to constrain analysis, and their analysis produces the most conservative results, in the sense of giving greater probability to lesser human contributions. We use Kopp *et al.* (2016)'s estimates for this analysis, extended through 2014.

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01. INTRODUCTION AND APPROACH

Just as sea levels have been rising, so too has the frequency of coastal floods, in particular recurrent minor or "nuisance" floods, often tidal in nature. Nuisance floods do not cause major damage, but do cause material harm, inconvenience and economic drag. The link between sea level rise and increased nuisance floods, with local water level exceedance thresholds defined by the National Weather Service based on historically observed minor impacts, is straightforward and well established (Sweet and Park 2014; Ezer and Atkinson 2014; Moftakhari *et al.* 2015). However, we are aware of no research to date that has isolated the effect of human-caused sea level rise on flooding. That is the objective of this analysis.

We reassess the tide gauge observations analyzed by Sweet and Park (2014) after removing the anthropogenic component of global sea level rise, year by year, from those records, and develop counterfactual totals for the number of hours and days when water levels exceeded local nuisance flood thresholds. We take the differences from observed exceedances as indicative of the human fingerprint on flooding through climate-driven global sea level rise.

All confidence intervals in this report represent greater than 90% probability within the study design, spanning from less than the 5th percentile to more than the 95th percentile of probability (see Technical Methodology for a fuller explanation).

02. RESULTS

Across the 27 study gauges, only 33% (16-60%) of observed flood days since 1950 would still have exceeded local nuisance flood thresholds after deducting the human contribution to global sea level rise from water level records. Stated differently, two-thirds (40-84%) of the 8,726 total flood days may be said in this framework to have been human-caused via climate change.

The number and fraction of flood days linkable to anthropogenic global sea level rise (AGSLR) have climbed steadily by decade, from about 45% (11-69%) near the beginning of the study period (1955-1964), to about 76% (56-89%) at its end (2005-2014) (Table 1). For this most recent decade, in other words, it is extremely likely – there is a greater than 95% probability – that more than half of observed flood days would not have occurred without the human contribution to global sea level.

Table 1. *Observed flood days that would not have exceeded nuisance flood thresholds if human-caused or anthropogenic sea level rise (AGSLR) were deducted from hourly water level records, as tabulated across all 27 study tide gauges.*

	Flood days linkable to AGSLR			
	Count		Percentage	
Period	Central estimate	[1]Very likely range	Central estimate	[1]Very likely range
1955-1964	249	59-385	45%	11-69%
1965-1974	379	129-564	54%	18-80%
1975-1984	497	215-716	56%	24-80%
1985-1994	733	414-939	64%	36-82%
1995-2004	1,384	860-1,695	71%	44-87%
2005-2014	2,507	1,837-2,914	76%	56-89%
1950-2014[2]	5,809	3,517-7,332	67%	40-84%

Removal of the anthropogenic global sea level rise component from hourly water level records would bring peak water levels below flood thresholds, eliminating the flood days printed in this table. Note: bottom row total includes flood days from 1950-1954, not separately shown.

[1] "Very likely range" corresponds to a greater than 90% probability (see Technical Methodology).

[2] Bottom row total includes flood days from 1950-1954, not separately shown.

Analysis of flood hours instead of days yields highly similar findings – for example, only 37% (19-61%) of observed flood hours since 1950 would have still exceeded local nuisance flood thresholds after deducting AGSLR.

Table 2. *Local sea level rise (SLR), from Sweet and Park (2014); human-caused or anthropogenic global sea level rise (AGSLR) and the residual local SLR; and observed flood days that would not have exceeded nuisance flood thresholds if AGSLR were deducted from hourly water level records.*

Tide gauge location	Period:1950-2013			Flood days linkable to AGSLR — Period: 1950-2014				Period: 2005-2014			
	Local SLR (inches)	AGSLR (inches)	Local residual SLR (inches)	Count		Percentage		Count		Percentage	
	Central estimate	Central estimate	Central estimate	Central estimate	Very likely range	Central estimate	Very likely range	Central estimate	Very likely range	Central estimate	Very likely range
Boston, MA	6.0	3.5	2.4	93	42-117	62%	28-79%	41	25-48	72%	44-84%
Providence, RI	6.0	3.5	2.4	35	19-53	45%	24-68%	13	12-15	62%	57-71%
New London	6.2	3.5	2.7	36	14-46	49%	19-62%	10	6-11	56%	33-61%
Montauk, NY	8.2	3.5	4.6	31	20-41	46%	29-60%	16	11-17	73%	50-77%
Kings Point, NY	5.8	3.5	2.2	204	114-304	47%	26-70%	96	69-124	61%	44-79%
Battery, NY	7.4	3.5	3.9	53	26-67	54%	26-68%	31	19-33	79%	49-85%
Sandy Hook, NJ	9.7	3.5	6.1	320	200-409	60%	37-76%	164	119-199	70%	51-85%
Atlantic City, NJ	11.1	3.5	7.5	302	178-388	60%	35-77%	162	113-192	71%	49-84%
Philadelphia, PA	8.2	3.5	4.6	162	91-227	53%	30-75%	83	56-100	69%	47-83%
Lewes, DE	8.6	3.5	5.0	303	187-422	55%	34-77%	143	100-178	67%	47-83%
Baltimore, MD	7.4	3.5	3.8	187	111-258	60%	36-83%	92	67-110	72%	52-86%
Annapolis, MD	8.3	3.5	4.8	627	366-792	69%	40-87%	295	217-352	75%	55-89%
Washington D.C.	7.5	3.5	4.0	522	283-680	61%	33-79%	208	141-249	70%	48-84%
Sewells Point, VA	11.7	3.5	8.1	93	53-138	46%	26-68%	39	26-50	56%	37-71%
Wilmington, NC	5.6	3.5	2.0	613	408-739	77%	51-93%	308	230-359	82%	61-95%
Charleston, SC	7.2	3.5	3.6	461	269-586	72%	42-92%	176	118-205	80%	54-94%
Fort Pulaski, GA	8.1	3.5	4.6	340	225-418	77%	51-95%	134	110-147	88%	72-97%
Fernandina Beach, FL	5.8	3.5	2.3	42	26-50	78%	48-93%	16	13-16	100%	81-100%
Mayport, FL	6.5	3.5	2.9	73	53-82	84%	61-94%	44	36-45	98%	80-100%
Key West, FL	6.4	3.5	2.8	42	38-44	91%	83-96%	30	28-31	94%	88-97%
St Petersburg, FL	6.7	3.5	3.2	2	1-3	33%	17-50%	0	0-0	n/a	n/a
Galveston Bay, TX	16.4	3.5	12.8	3	2-3	20%	13-20%	1	1-1	25%	25-25%
Port Isabel, TX	10.7	3.5	7.2	214	148-249	77%	53-90%	104	82-114	86%	68-94%
La Jolla, CA	4.9	3.5	1.4	141	101-166	85%	61-100%	56	43-60	93%	72-100%
San Francisco, CA	4.0	3.5	0.4	329	200-420	69%	42-89%	81	63-92	82%	64-93%
Seattle, WA	4.2	3.5	0.7	71	35-82	75%	37-86%	26	17-28	90%	59-97%
Honolulu, HI	3.1	3.5	-0.4	510	307-548	92%	56-99%	138	115-138	100%	83-100%

"Very likely range" corresponds to a greater than 90% probability (see Technical Methodology).

Table 2 breaks down results by individual tide gauge, and compares the most recent decade to the full study period. The fraction of high water events that would not have registered as flood days, after removing AGSLR, has increased at all sites but two. At these, St. Petersburg and Galveston, relatively high flood thresholds (>2.4 ft) provide very small sample sizes.

The sites with the greatest numbers of flood days, both overall and linkable to AGSLR, are strongly concentrated in the mid-Atlantic states, where a wide, shallow continental shelf and energetic wind and current regimes frequently push tides above relatively low nuisance flood levels. Small sea level increments here are moving high densities of previously subcritical events just above local flood thresholds, extending the reach and impacts of more common storms and tides.

At study gauges along Florida's Atlantic coast and the Keys, as well as in Seattle, Honolulu, and near San Diego (La Jolla), the anthropogenic global sea level signal must be included to realize more than 90% of flood days over the last decade (CIs for individual gauges in table). The same applies to more than half the flood days at each of the 25 study gauges averaging more than one total nuisance flood per year since 2005 (mean annual value, 12.2).

Table 3 illustrates changes from one 30-year period, 1955-1984, to the next, 1985-2014. In the central estimate, human-caused global sea level rise accounts for more than 80% of the increase in nuisance flood days across all tide gauges. Across the study tide gauges, AGSLR as a fraction of local sea level rise (calculated from **Table 2** columns 2 and 3) is positively correlated with the fraction of the increase in flood days that AGSLR can explain (Pearson's $r = 0.50$).

At most gauges, residual flood days not linkable to AGSLR also increased (**Table 3**, column 7), due to factors such as land subsidence or dynamic sea level rise. However, residual flood days declined at all Pacific gauges, in line with eastern Pacific sea level trends that have lagged the global mean over the last several decades, likely connected with dynamic effects from the Pacific Decadal Oscillation (Zhang and Church 2012).

See interactive online map with details and trends at each tide gauge: http://www.climatecentral.org/news/the-human-fingerprints-on-coastal-floods-20050

Table 3. *Changes in flood days across two 30-year periods: total observed increase, increase linkable to AGSLR, and change linkable to residual factors (other than AGSLR)*

	Total observed flood days		Total observed increase in flood days	Increase in flood days linkable to AGSLR		Residual increase	Percentage increase in flood days linkable to AGSLR	
Tide gauge location	(1) 1955-1984	(2) 1985-2014	From period (1) to (2)	Central estimate	Very likely range	Central estimate	Central estimate	Very likely range
Boston, MA	51	90	39	37	32-39	2	95%	82-100%
Providence, RI	36	42	6	9	1-13	-3	150%	17-217%
New London	28	42	14	11	11-12	3	79%	79-86%
Montauk, NY	23	42	19	17	12-17	2	89%	63-89%
Kings Point, NY	135	279	144	111	98-127	33	77%	68-88%
Battery, NY	32	63	31	34	24-33	-3	110%	77-106%
Sandy Hook, NJ	108	420	312	255	186-286	57	82%	60-92%
Atlantic City, NJ	83	414	331	223	156-272	108	67%	47-82%
Philadelphia, PA	96	199	103	85	71-101	18	83%	69-98%
Lewes, DE	155	388	233	174	129-193	59	75%	55-83%
Baltimore, MD	70	227	157	127	103-139	30	81%	66-89%
Annapolis, MD	193	701	508	394	296-459	114	78%	58-90%
Washington D.C.	265	568	303	240	205-268	63	79%	68-88%
Sewells Point, VA	51	151	100	61	37-72	39	61%	37-72%
Wilmington, NC	115	678	563	445	342-522	118	79%	61-93%
Charleston, SC	132	496	364	302	207-347	62	83%	57-95%
Fort Pulaski, GA	103	329	226	195	152-224	31	86%	67-99%
Fernandina Beach, FL	16	34	18	23	18-20	-5	128%	100-111%
Mayport, FL	13	71	58	57	47-57	1	98%	81-98%
Key West, FL	5	41	36	34	30-36	2	94%	83-100%
St Petersburg, FL	2	3	1	1	0-1	0	100%	0-100%
Galveston Bay, TX	7	8	1	1	1-2	0	100%	100-200%
Port Isabel, TX	38	238	200	169	128-188	31	85%	64-94%
La Jolla, CA	32	133	101	102	75-101	-1	101%	74-100%
San Francisco, CA	169	286	117	138	102-125	-21	118%	87-107%
Seattle, WA	37	53	16	19	19-21	-3	119%	119-131%
Honolulu, HI	164	387	223	235	209-225	-12	105%	94-101%
TOTAL	2159	6383	4224	3499	2708-3883	725	83%	64-92%

Very likely ranges are based on taking differences or ratios using the very likely range endpoints for AGSLR-linked flood days.

03. DISCUSSION

The dramatic effects of human-attributable global sea level rise on the frequency of flooding come despite some methodological choices which may bias results to underestimate overall human influence. The first of these is employing Kopp *et al.* (2016), the sea level attribution study currently presenting the most conservative estimates for the anthropogenic component of global rise.

We further omit consideration of potentially human-caused and climate-linked dynamic changes in local sea level. Setting aside the influence of land subsidence, sea level rise along the U.S. Atlantic coast has accelerated faster than the global mean since about 1975 (Kopp 2013). This acceleration may have resulted from a shift in the location of the Gulf Stream or a slowing of its flow, either of which would allow warmer, low-density waters to penetrate farther north along the Atlantic seaboard (e.g. Sallenger *et al.* 2012, Ezer *et al.* 2013, Yin and Goddard 2013). More than 70% of the tide gauges and more than 80% of the flood days in this analysis are on the Atlantic coast. If this regional sea-level acceleration has resulted from anthropogenic climate change, our analysis may underestimate anthropogenic influence on flooding for these gauges and overall. However, ocean dynamics exhibit considerable natural variability, so it may be premature to ascribe these changes to human influence (Kopp 2013).

We also omit spatial fingerprints associated with changes in Earth's gravitational field, rotation, and crustal flexure caused by the ice-sheet and glacial contributions to 20th century sea level rise. Based on Marzeion *et al.* (2012)'s estimates of glacier mass changes from 1901-2009 and the fingerprints used by Kopp *et al.* (2014), these effects may dampen the glacier contribution to sea-level rise in the Pacific Northwest by ~50% (due to the proximity of shrinking Alaskan glaciers) and in the U.S. Northeast by ~20%, with the dampening effect diminishing to the south; they may also enhance the glacier contribution to sea-level rise in Hawaii by ~10%. Glaciers account for roughly one-third of observed 20th century sea-level rise (IPCC 2013), so these effects should lead to deviations from the global mean of less than 10% throughout the entire contiguous United States except for the Pacific Northwest (represented only by Seattle in this study), where deviations may reach roughly up to 20%.

Given the current state of the science on the human contribution to ocean dynamics and the relatively small effects of fingerprints, we suggest that a globally uniform human contribution to climate-driven sea level rise can serve as a reasonable simplifying assumption for U.S. coastal flood attribution studies.

We do not assess any non-climatic anthropogenic effects on local sea level, such as land subsidence caused by the extraction of subterranean natural gas, oil, or water, common in the western Gulf of Mexico and parts of the Atlantic coastal plain. These human activities increase flooding, but not via climate change.

03. DISCUSSION

This study does not consider potential trends in storms and storm surge over the 65-year study period, despite some evidence of an increase in major wide-area surge events along U.S. Gulf and Atlantic coasts correlated with warmer global temperatures (Grinsted *et al.* 2012). However, since less extreme (more typical) storm surge events, which do not reveal long-term trends in the 20th century (Zhang *et al.* 2000), far outnumber major surge events (e.g. those associated with Hurricanes Sandy or Katrina), our results are less sensitive to any possible major event trends.

It is finally worth remembering that many other factors, not linked to human activity, contribute to local sea level rise, and thus to total and residual flooding (**Table 3**). Such contributors include global sea-level change unrelated to 20th century anthropogenic global warming, as well as natural variability in atmospheric/ocean dynamics, the ongoing response to the end of the last ice age, and local land motion. While less important than AGSLR at most study gauges (**Table 3**, final two columns), these factors compound the accelerating flood challenges that coastal communities already face.

We expect that individuals almost always associate coastal floods with their shortest-term causes, such as a very high tide or a storm surge. It is remarkable and uncomfortable to discover that the majority of U.S. coastal floods since 1950 appear to have another necessary driver: us.

04. TECHNICAL METHODOLOGY

Estimating the human contribution to sea level rise

We extend Kopp *et al.* (2016)'s assessment of 20th century anthropogenic global sea level rise through 2014. Kopp *et al.* (2016) considered two counterfactual 20th century temperature histories: in one, global mean temperature returned in the 20th century to its 500-1800 CE mean level, while in the other, global mean temperature returned to its 500-1800 CE linear trend. We extrapolate the temperature trends in the two counterfactual scenarios to 2014 and use these extended counterfactual scenarios, together with HadCRUT4 temperature data, to drive the semi-empirical sea-level model described by Kopp *et al.* (2016). From the semi-empirical results, we calculate the fraction of global sea level rise since 1900 that would not have occurred under the counterfactuals. We multiply these estimated fractions by 1000 samples from the probability distribution of global mean sea level estimated by Hay *et al.* 2015's Kalman smoother analysis of tide-gauge data, which has higher temporal resolution than the Common Era reconstruction in Kopp *et al.* (2016). We extend the Hay *et al.* samples, which end in 2010, to 2014 by assuming that the 2000-2010 trend in each sample continued over 2011-2014. All values are calculated with respect to the mean sea level in 1900 CE, at which time the anthropogenic contribution is assumed to be zero.

This results in four probabilistic distributions of anthropogenic global sea level rise by year, based on all combinations of the two counterfactual temperature scenarios and the two Common Era temperature reconstructions used in Kopp *et al.* (2016). To integrate these four distributions, we take for each year from 1901-2014 the mean of the four medians as our central estimate; the minimum of the 5th percentile estimates as our lower confidence limit; and the maximum of the 95th percentile as our upper confidence limit. Contemplating all four distributions, our confidence range is necessarily but indeterminately wider than 90% probability.

Assessing flood exceedances

We employ verified hourly water level data from the NOAA Center for Operational Oceanographic Products and Services (CO-OPS; http://tidesandcurrents.noaa.gov) at the same tide gauges analyzed in Sweet and Park, extended through the end of 2014, and employ the same nuisance flood thresholds for each site. Emergency managers and Weather Forecasting Offices of the National Weather Service establish nuisance flood thresholds locally. These elevation thresholds represent heights above high tide associated with minor impacts from years of impact monitoring (moderate and major impact thresholds are also empirically assigned). Not all tide gauges have a nuisance flood threshold assigned, and this study includes only those that do and where hourly records are available since 1950.

We tabulate hourly and daily threshold exceedances by calendar year. We tabulate exceedances for the observed record, and for counterfactual records in which the lower, central and upper annual estimates of the anthropogenic component of global sea level rise are first deducted from the observed water levels.

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Princeton: One Palmer Square, Suite 330 Princeton, NJ 08542
Phone: +1 609 924-3800
Toll Free: +1 877 4-CLI-SCI / +1 877 425-4724
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