# Rising hazard of storm-surge flooding

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The 2017 Atlantic hurricane season is one for the history books. It has blown a number of records out of the water. Harvey dumped more rain on the United States than any previous hurricane. Irma maintained the highest category 5 longer than any storm anywhere in the world. September 2017 has accumulated the most cyclone energy of any month on record in the Atlantic. Last, but not least, if early estimates of damages hold up, three of the five costliest storms in US history will have occurred this year: Harvey, Irma, and Maria (1–3). The other two are Katrina and Sandy, which flooded New Orleans in 2005 and New York in 2012 (Fig. 1), respectively. A new study in PNAS by Garner et al. (4) tackles a critical and highly topical question: How will coastal flood risk change in the future on a warming Earth? They approach this question in a case study for New York, but most coastal cities in the world will be facing similar issues in the coming decades and, indeed, centuries.

Global warming affects the coastal flood hazard (by sea water, not rainfall) in two main ways. The first is through rising sea levels. The second is through changes in storm activity affecting the statistics of storm surges. How these factors combine depends strongly on local conditions. For New York City, Garner et al. (4) find that sea-level rise dominates a massive increase in flood risk, while changes in storm surge height are expected to be minimal. Let us first gather some basic facts about these two ingredients.

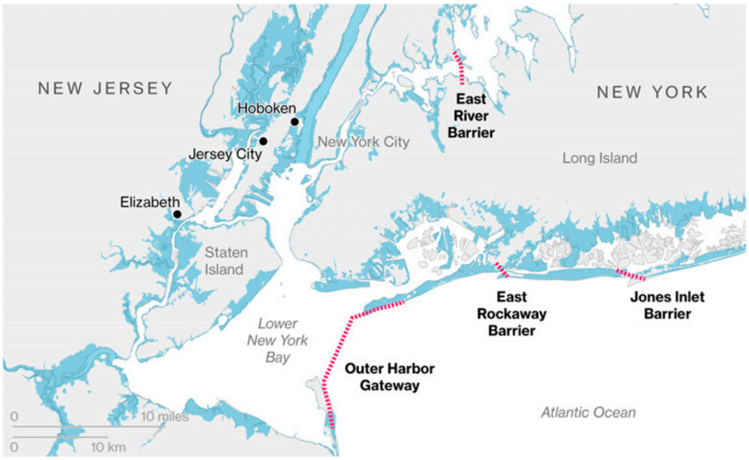


**Fig. 1. Map of New York City flooding resulting from hurricane Sandy, October 29, 2012. Dotted red lines show proposed future storm barriers. Image courtesy of Federal Emergency Management Agency, National Institute for Coastal & Harbor Infrastructure.**

Global sea levels are rising as a result of global warming. They have risen by ∼20 cm since the late 19th century, and the rise is accelerating in response to warming. Since satellite records began in 1993 the rate of rise is ∼3 cm per decade and is also accelerating (5). The main reasons are that the ocean waters expand as they heat up, and continental ice melts and adds water to the oceans. The latter increase in ocean mass was responsible for roughly half the global sea-level rise at the beginning of the satellite record but has risen since to about 70%, mainly due to an acceleration of mass loss from the Greenland Ice Sheet (5). The two remaining large ice sheets on Earth are also the main cause of concern for future long-term sea-level rise: Greenland holds enough ice to raise global sea levels by 7 m and Antarctica by 58 m. Both ice sheets are subject to possible instability when critical thresholds are crossed (6). For Greenland this is due to the positive ice-elevation feedback and for Antarctica it is due to the marine ice sheet instability mechanism. The slow mass loss from these ice sheets will continue for thousands of years in a warmer world and reach at least 2 m per degree of global warming (7, 8). We should remember that at the end of the last Ice Age, between 15,000 and 5,000 y before the present, two-thirds of the glacial ice sheets were lost in response to ∼5 °C of global warming, resulting in 120 m of global sea-level rise.

When it comes to the local sea-level rise, which is responsible for changes in local flood risk, additional climate factors are at play: changing ocean currents, the gravity fingerprint of shrinking ice sheets, and changes in prevailing winds. Factors unrelated to modern climate change can also be important on some coasts, like vertical land motions due to plate

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tectonics, the still-ongoing response to the end of the last glaciation (i.e., postglacial isostatic adjustment), or direct human intervention (e.g., due to water or oil withdrawal from below the ground, as in Venice, Italy and New Orleans).

The second ingredient in changing flood risk is changes in the properties of storms causing storm surges. The study here focuses on tropical storms, for which intensification (i.e., more storms of the strongest categories) can be expected in a warming climate. This expectation is based both on consideration of the energy source of tropical cyclones, namely high ocean temperatures at and below the sea surface (potential intensity theory), and on climate model simulations. A recent review concluded (9) that "we thus expect tropical cyclone intensities to increase with warming, both on average and at the high end of the scale, so that the strongest future storms will exceed the strength of any in the past." There is still some controversy over whether this signal is (and should be) already detectable with confidence in observational data, given high natural variability, inhomogeneous datasets, and a partial cancellation of the warming effect on cyclones by human-caused changes in atmospheric aerosol load.

The severity of a storm surge depends not only on the intensity of storms but also on their size (with larger storms leading to greater storm surges) and on their tracks. Hurricane Sandy, which flooded parts of the New York subway, is a case in point: It achieved the largest diameter of any Atlantic hurricane on record, and it made a peculiar sharp left turn to hit the coast near New York because the usual, northeastward path across the Atlantic Ocean was blocked by a high-pressure system south of Greenland.

Extratropical storms can also cause major flooding and some changes to these storms are expected (e.g., a southward shift of the storm track in the Southern Hemisphere). Impacts of global warming on extratropical storm risk will depend strongly on the region considered (10).

In some locations, especially shallow marginal seas like the North Sea, sea level and storm surge height cannot just be added together, because the two interact: A higher sea level (and thus deeper water) makes it easier for wind and waves to push water toward the shore. For the German Bight, for example, a 1-m higher sea level will make a given storm surge and its waves run up not just 1 m higher but closer to 1.5 m, and in some places even 2 m higher (11). For New York this is not a significant issue.

Assessing future flood risk thus requires three ingredients: (*i*) a model of future storm activity, (*ii*) model simulations of the local storm surges caused by these storms, and (*iii*) projections of future local sea-level rise. Each of these components has its own uncertainties which need to be explored (e.g., by multimodel ensemble simulations), and a proper probabilistic method to combine these three ingredients into a consistent risk assessment is required. This is exactly what Garner et al. (4) provide in an exemplary way for New York City.

What they find is a massive increase in flooding risk for the "Big Apple," driven almost entirely by sea-level rise. Perhaps surprisingly, they do not expect the intensification of tropical cyclones to raise the flood hazard, because intensification and increase in storm size are compensated by the storm tracks shifting further offshore in the future, making it less likely for storms to affect New York. As already found in a predecessor study, what used to be a once-in-500-y flood in preindustrial times has already become a once-in-25-y flood in the modern era, thanks to past local sea-level rise (12). The majority of this rise is due to postglacial adjustment and thus has a natural cause. However, human-caused global warming has now accelerated sea-level rise severalfold and taken over as its dominant cause.

The new study predicts that already over the next 30 y this preindustrial 500-y flood event will become a 5-y flood event. This is practically inevitable regardless of our future emissions, as sea level change has great inertia and thus does not respond on a 30-y time scale to climate mitigation efforts. Adaptation is therefore crucial for New York, and the city's decades-long discussion on flood protection schemes has gained new impetus after Hurricane Sandy (13). Such a massive increase in flood frequency is not an unexpected outcome of sea-level rise. Earlier studies have found a similar increase for New York (14), and the Intergovernmental Panel on Climate Change has documented that a modest sea-level rise (0.5 m) multiplies the flood frequency for many coastal sites by factor of 100 or even 1,000 (see figure 13.25 in ref. 10).

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Climate mitigation does make a big difference to sea-level rise on longer time scales, and so does the stability of the Antarctic Ice Sheet. Here, the authors have included novel simulations for sea-level rise from Antarctic ice loss as an alternative scenario, which leads to ∼13 m of global sea-level rise by the year 2300 for unmitigated global warming and ∼4 m with moderate mitigation (∼3 °C warming above preindustrial). It is difficult to imagine how New York City could survive either of these scenarios.

So, what can we take away from the new study by Garner et al. (4)? First of all, what they provide is an exploration of risk rather than a forecast. One key result is that the major increase in future flood risk will probably be driven by sea-level rise and not by an increase in violent storms. I suspect that the same will turn out to be true for many coastal sites around the world. If this is true, this is an advantage for coastal planning, since the relatively smooth future sea-level change can be predicted rather well at least several decades ahead, unlike the dynamics of the atmosphere and the resulting changes in storm characteristics. In the longer run, however, sea-level rise becomes less predictable due to the potential for the likewise complex ice flow dynamics in Greenland and Antarctic outlet glaciers starting to have a major impact.

There are some important caveats, and they are discussed well by Garner et al. (4). The assessment of changes in storm characteristics, especially their tracks, hinges on still-coarse climate models' capturing all of the relevant dynamics correctly. For example, climate models tend to underestimate Arctic sea-ice loss, which—according to several studies—acts to make a high-pressure system over the northern Atlantic south of Greenland more likely (15–18). This is just the kind of unusual pressure system which pushed Sandy into New York. A further wild card is the potential decline of the Atlantic meridional overturning circulation (19), also known as the Gulf Stream System, which could affect pressure patterns and storm tracks in the atmosphere (20, 21) as well as sea level on the US eastern coast (22).

One thing is certain, however. As a result of global warming, global sea-levels will continue to rise for centuries, pushing up flood risks around the world. Those who ignore this fact do so at their peril.

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