Inter-American Development Bank

Sea-Level Rise Threats in the Caribbean

Data, tools, and analysis for a more resilient future

Benjamin Strauss
Scott Kulp

Climate Central, Princeton, NJ

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Scope and Executive Summary

This report describes methodology used to develop extensive assessments of sea-level rise and coastal flood likelihoods and hazards in the Caribbean Basin, and summarizes high-level findings. The *Surging Seas* suite of online tools provides detailed complete results for local through national administrative units. The specific geography covered includes The Bahamas, Barbados, Jamaica, Trinidad and Tobago, Suriname, Guyana, Dominican Republic and Haiti, Dominica, Grenada, Saint Lucia, St Kitts and Nevis, Antigua and Barbuda, St Vincent and the Grenadines, Corn Island (Nicaragua), and San Blas (Panama).

Analysis incorporates local sea-level rise projections from the recent scientific literature at 13 tide gauges in the region. It develops future flood-likelihood forecasts at a series of standard heights by integrating sea-level projections with published local flood-probability statistics based on historical data and modeling. Finally, population and indexed economic activity are assessed in each location on land below each standard flood height. Economic activity or wealth/poverty is indexed by the density of Internet access points (e.g. wireless routers) on a fine spatial grid. These screening-level assessments are based on land elevations and projected water surface heights, and do not include dynamical modeling of storm surge, waves, structural damage, or potential natural habitat responses to rising sea levels such as wetland accretion or migration.

This is the first study to employ Climate Central's proprietary new CoastalDEM™ digital terrain model for land elevation data. CoastalDEM provides much greater vertical accuracy than other datasets available at Caribbean Basin scale, including NASA's Shuttle Radar Topography Mission (SRTM) data, and the AW3D30 dataset from the Japanese aerospace agency, both of which overestimate coastal elevations by more than 2 m on average – and thus underestimate sea-level rise and coastal flood threats.

Based on analysis using CoastalDEM and the best available population data for each location, roughly one million people live on land less than one vertical meter above local high tide lines within the geographic scope of this study. More than 600,000 occupy land less than 0.5 m above the tides. Guyana accounts for more than one-third of these totals; Haiti, Suriname, The Bahamas and the Dominican Republic are the other major contributors, in descending order. Among these, however, The Bahamas confront by far the greatest proportional threat: 32% of land, 25% of population, and 13% of Internet access points are below 0.5 m.

Integrated sea-level rise projections and flood risk analysis indicate that floods reaching at least 0.5 m above high tide line at shore will become common events throughout most of the Caribbean within half a century, and more likely sooner. Floods above 1 m may become common by the end of the century, and permanent sea-level rise exceeding this threshold is possible. Recent research suggests that Antarctic ice sheets may be less stable than previously anticipated. In this case, scenarios of unabated climate pollution lead to sea-level projections exceeding 1.5 m by 2100 across the Caribbean. Swift and sharp cuts in climate pollution, however, could reduce these projections by roughly 1 m.

In the much longer run, contemporary carbon emissions leading to 4 °C warming could lock in more than 8 m of sea-level rise unfolding across centuries. Limiting warming to 2 °C could limit sea-level increases to roughly 4 m, and projections translate 1.5 °C warming to about 3 m.

Humanity's carbon choices will thus have profound consequences for the Caribbean both in this century and far beyond. For many islands, some pathways will be manageable, and others will not.

Companion tools

This report is companion to a suite of online tools providing granular local maps and projections, plus analyses for national and subnational units within the study area. Different elements are designed to support planning for coastal resilience and to illustrate the stakes for the Caribbean of different carbon pollution and climate change pathways. Caribbean tools and analyses all employ Climate Central's proprietary elevation dataset, CoastalDEM™. The tools comprise:

- ***Surging Seas Risk Zone Map*** (ss2.climatecentral.org; **Figure 1**) shows areas vulnerable to submergence or flooding at different water levels. In the Caribbean, the map is based on CoastalDEM, and includes high-resolution population and Internet access point density layers.
- ***Surging Seas Risk Finder*** (riskfinder.org/caribbean; **Figure 2**) quantifies land, population and Internet access points exposed at different water levels for all Caribbean nations in the study area, as well as hundreds of subnational units. It additionally provides detailed local sea-level and flood-likelihood projections under multiple scenarios. *Risk Finder* is home to the comprehensive analytic results produced by this project, and offers extensive data table, map and figure downloads.
- ***Mapping Choices*** (choices.climatecentral.org; **Figure 3**) maps the long-term sea level consequences of different climate pathways, including carbon emissions leading to 1.5ºC, 2ºC, 3ºC or 4ºC warming.
- ***Picturing Choices*** (climatecentral.org/news/sea-level-stakes-for-the-caribbean-in-pictures-21770; **Figure 4**). Three pairs of photorealistic images compare potential future Caribbean scenes based on 4ºC vs. 2ºC warming, and the long-term sea level commitments shown by *Mapping Choices*.

Sea-level rise and coastal flood hazards

Climbing global temperatures bring rising sea levels worldwide. Melting glaciers and collapsing ice sheets swell the oceans, and increasing ocean temperatures cause seawater to expand. While rising tides are a threat to all coastal places, the Caribbean Basin is unusually vulnerable, due to the flat, low-lying topography, porous limestone bedrock, and tropical cyclones common to the area.

In 2017, the punishing hurricanes Irma and Maria provided sharp reminders of this vulnerability. Rare extreme events like these are already catastrophic to lives and infrastructure in the low elevation coastal zone, and will become even more so as sea-level rise continues to add to storm surge heights. At the same time, the Caribbean also faces threats from chronic low-grade flooding aggravated by sea-level rise, and eventually permanent inundation due to ever higher sea levels.

Global society must ultimately choose a carbon emissions pathway to follow over the coming years and decades, and this choice will have profound consequences for the Caribbean in the second half of the century. The difference between pathways could be amplified even further if recent research is correct in suggesting greater-than-expected instability in Antarctica. In such a case, low emissions scenarios could prevent the Caribbean from experiencing an additional 1 meter of sea level rise by 2100.

In almost any case, floods reaching 0.5 m above contemporary high tide levels appear likely to become common throughout the Caribbean within the next several decades to half-century. Floods reaching 1 m above today's high tide lines may become the new routine later in the century, especially in the case of rapid Antarctic ice loss.

Sea-Level Projections

The Intergovernmental Panel on Climate Change (IPCC) provides an authoritative voice in climate science. The most recent IPCC assessment report published "likely" ranges of sea-level-rise trajectories for this century, meant to approximate the 17th to 83rd percentile ranges of potential rise for each greenhouse gas emissions pathway evaluated (Church et al. 2013). The assessment did not include more extreme outcomes, which would be driven by ice loss from Greenland or Antarctica, because understanding of ice sheet behavior was considered too limited at the time by its authors.

This report considers two different sea-level models that build on top of the IPCC's work, and which provide local projections for the 13 tide gauges in this study. Kopp et al. (2014) used a very similar framework as IPCC, but added its missing extremes by using results from a structured expert elicitation from the world's leading ice sheet and glacier experts, eliciting estimated probabilities for different potential Greenland and Antarctic contributions (Bamber and Aspinall 2013). The overall outcome was an effectively probabilistic set of projections through the 99.9th percentile. Furthermore, Kopp et al. ("K14" hereafter) developed physically-based local projections based on the combined processes modeled, as well as on non-climatic local background effects such as sinking or rising land.

Local effects and variation are generally modest in the Caribbean. For example, under a high carbon emissions scenario, Representative Concentration Pathway 8.5 (Riahi et al. 2007), the median 21st-century sea-level-rise projection ranges from 0.74-0.83 m across 12 tide gauges in this study (**Table 1**; **Figure 6.** Median sea-level projections around the Caribbean basin for the year 2100 assuming unabated climate pollution (RCP 8.5), according to Kopp et al. 2014. Omits the study tide gauge at Belem, Brazil.**Error! Reference source not found.**). The remaining gauge is a modest outlier at 0.91 m, and is far from most of the areas in this study (the gauge is at Puerto Castilla, on the coast of Honduras).

K14 has been widely cited and used for local sea-level projections in the United States from city through federal levels. Recently, the State of California adopted K14 for its updated sea-level-rise guidance (Griggs et al. 2017), and the U.S. National Oceanic and Atmospheric Administration used K14 to assign probabilities to its latest sea-level scenarios, and to build local projections (Sweet et al. 2017).

K14 and the expert elicitation informing it were published before key new research emerged suggesting that Antarctica could lose ice faster than previously anticipated (DeConto and Pollard 2016). Kopp et al. (2017) (hereafter "K17") represents an early attempt to incorporate this new Antarctic science into local sea-level projections at global scale. K17 is the second sea-level model considered here. K17 does not provide probabilistic projections, as K14 does, because a probabilistic distribution of Antarctic outcomes based on DeConto and Pollard (2016) has not yet been developed. However, K17 does offer a frequency distribution of results from simulations based on this research, sampling a large, non-probabilistic range of input parameter values to the Antarctic model, and thus providing a range of plausible outcomes. Median (50th percentile / central) results should be considered more robust than the tails.

Both K14 and K17 make sea-level projections relative to the year 2000. For each model, this analysis considers standard high, moderate and low greenhouse gas emissions scenarios, respectively named Representative Concentration Pathways (RCPs) 8.5, 4.5, and 2.6, and widely used in climate modeling (Riahi et al. 2007; Clarke et al. 2007; van Vuuren et al. 2007). RCP 8.5 corresponds to an unabated increase in emissions; RCP 4.5 corresponds to reduced emissions roughly in line with fulfilling the Paris Agreement, and RCP 2.6 corresponds to large and immediate cuts, leading to net zero and then negative annual emissions in the second half of the century.

Table 2 compares median projections under K14 vs. K17 with unabated emissions or aggressive cuts. (*Risk Finder* provides more complete details.) The results indicate almost no difference in median projections across emissions scenarios through 2050 (just 0.01-0.04 m), and relatively little difference between models for the same period (0.01-0.09 m). However, divergences become important in the second half of the century. For example, under RCP 8.5, median projections according to K17 are 0.67-0.80 m greater than according to K14. Using K17, median projections are up to ~1 m greater under RCP 8.5 than RCP 2.6. The differences are substantially larger for higher percentile projections (e.g. 95th percentile). 95th percentile results for K17, included in *Risk Finder*, should, however, be interpreted with caution.

The tide gauges used in this study were selected because of the availability of local sea-level rise projections, and because each gauge is the nearest neighbor of at least one study area in this project, even if the gauge itself is not within the study area.

Tides and Floods

This report considers two hazards. First, as defined here, permanent inundation of land occurs when rising seas push the local high tide line above the land's elevation. Second, coastal flooding becomes higher and more frequent as sea level increases.

Permanent Inundation

Sea-level rise projections are water elevation *differences*. In order to identify land at risk, these differences must be added to some baseline water elevation. This study uses precise measurements of local mean sea level averaged across a 19-year (1993-2012) satellite altimetry record on a 2-arcminute resolution grid (Aviso 2015). An offset is then added to this average to approximate the local high tide line. The precise offset is the local difference between the standard tidal levels Mean Higher High Water (MHHW) and Mean Sea Level (MSL), based on the tidal model TPXO8 (Egbert et al. 2002). Model results were provided by Mark Merrifield, University of Hawai'i, at 2-arcminute resolution. Bilinear interpolation was used to upsample 2-arcminute results to 1-arcminute resolution, and nearest neighbor interpolation was then used to upsample to 1-arcsecond resolution (roughly 30 m, at the equator).

In other words, measured historical mean sea level, plus the modeled difference between mean sea level and mean high tide, plus projected sea-level rise, together form the basis for projecting future high tide lines and, from these, land in danger of permanent inundation under different scenarios. *Surging Seas Risk Zone Map* shows elevations relative to the baseline local high tide line (or more precisely, MHHW). Thus, for example, when the slider is set to 1 meter, the map colors land blue that is less than 1 m above MHHW. After 1 m of sea-level rise, these areas would be below the local high tide line.

Coastal Flooding

Long before permanent inundation, the same areas would be subject to increased flooding caused by rising seas interacting with tides, storm surge, and waves to cause temporary extreme sea levels. This study and *Surging Seas Risk Finder* use modeled local relationships between flood height and flood probability (called return level curves), together with sea-level projections, to estimate the chances of different events in different time frames. For example, if a flood *0.5 m* above MHHW has a 10% annual probability, then after 0.5 m of sea-level rise, a flood *1 m* above MHHW will have a 10% annual probability. (This report uses flood height or flood as a synonym for extreme sea level, thus indicating flood height at the shore; inland flood heights during individual events vary spatially, as described in the next section, *Other Key Assumptions*.)

Return level curves are taken from the Global Tides and Surge Reanalysis (GTSR) (Muis et al. 2016). A critical caveat is that GTSR appears to underestimate most flood heights in most areas globally, including the Caribbean, where, for example, the heights of 10% annual probability floods are underestimated by 0.10-0.50 m (Muis et al. 2016). This underestimation increases for rarer extremes (e.g. 1% annual chance floods) in areas such as the Caribbean that are affected by tropical cyclones (Muis et al. 2016; Buchanan et al. 2017). *Therefore, results presented here and in Risk Finder (for single- and multi-year flood likelihoods) should be treated more as lower bounds for risk, not risk estimates.* This report accordingly focuses on milder high-frequency floods, and *Risk Finder* presents projections for sea-level rise plus mild or moderate (but not extreme) floods. Such lower-grade floods do not pose the same immediate safety and structural threats as major floods driven by hurricane storm surges. However, chronic floods can threaten infrastructure, homes, home values, and habitability, and in general, they affect people much more often.

Table 3 and **Figure 7** report GTSR flood heights for standard flood probabilities at study tide gauges across the region. Height differences between "annual" flood levels (heights exceeded on average once per year – sometimes more, sometimes less) and decadal flood levels (heights exceeded on average once per decade, and with roughly 10% probability annually) are universally small, ranging from 0.02-0.11 m. For all but one gauge, 0.08 m or less of sea-level rise is enough to turn a "10-year" flood into an annual event on average. The height differences between 10% and 1% annual probability floods are even smaller.

These small differences explain how, as seen in *Risk Finder*, the annual probability of a flood exceeding a given elevation threshold can jump from near 0% to near 100% within one decade: because the jump should typically require on the order of just 0.10 m of sea-level rise. Since flood heights are underestimated by GTSR, however, each flood level is actually more likely than what the tool presents, and could approach 100% annual probability sooner than shown. Developing and employing improved return level curves for the Caribbean should be a high priority for future work.

Based on the curves available from GTSR, **Table 4** presents annual likelihoods of floods exceeding the fixed levels of 0.5 m or 1 m MHHW in certain years, integrating sea-level projections from different models, and assuming RCP 4.5 (roughly consistent with meeting the emissions goals of the Paris climate agreement). Because GTSR underestimates risk, values should be considered lower bound estimates.

Table 4 thus indicates that floods exceeding 0.5 m MHHW are likely to become common at most Caribbean locations in fewer than 50 years, and may undergo rapid transitions from being rare to frequent events. Floods exceeding 1 m MHHW are likely to become common by the end of the century in the case of more rapid Antarctic collapse scenarios (model K17), and also without collapse at any locations where GTSR may underestimate flood heights by ~0.5 m. Floods exceeding 1.5 m will probably remain rare this century in the absence of rapid Antarctic collapse or other drivers of faster-than-expected sea-level rise. The exposure analysis in this report thus focuses on 0.5 and 1 m.

For description of methods used in *Risk Finder* to integrate sea-level projections with return level curves, in order to generate annual (single-year) and also accrued (multi-year) flood probabilities, see Tebaldi et al. (2012) and Buchanan et al. (2016), upon which the approach is based.

Other Key Assumptions

Each national and subnational area analyzed in *Risk Finder* is paired with a nearby tide gauge, in order to provide local sea-level rise and flood likelihood projections pertaining to the area. Neighboring areas can have different probabilities for the same flood height due to a variety of factors, such as differing local topography, bathymetry and shore orientation. Local sea-level rise should be more consistent across distance, but may also vary due to factors such as local rates of land subsidence. **Table 1**, **Table 3**, **Figure 6** and **Figure 7** give a sense of these variations. Overall, integrated sea-level and flood-likelihood projections show a notable degree of regional consistency within the Caribbean, suggesting that nearest-neighbor tide gauges should provide robust projections for most areas.

(The most likely exception to this rule is for Guyana and Suriname, which are paired with the distant but nonetheless nearest-available tide gauge in Belem, Brazil. This tide gauge appears to experience much greater water level departures than all the Caribbean gauges in this study (**Table 3**), possibly due to a different tidal regime. No data were available for this study to indicate whether the regimes in Guyana and Suriname are more aligned with Belem or the Caribbean, or are intermediate or otherwise distinct.)

Flood-likelihood projections are developed from sea-level projections combined with extreme water-level statistics based on analysis of historic water levels and their reconstruction. This method assumes no future changes in storm patterns. Some climate studies project increasing major storms and surges in some areas – in particular, increasing frequency of major hurricanes – suggesting greater future threats (e.g. Lin et al. 2012, Grinsted et al. 2012, Grinsted et al. 2013).

Because GTSR is already known to underestimate the *current* probability of extreme storm surges and flooding, projections in *Risk Finder* may generally be treated as lower limits or underestimates of true flood probabilities.

For integrated assessments considering both flood probability and exposure, this bias is mitigated because hazard exposure in this study (see next section) is computed based on all land below a specified elevation, such as 1 m MHHW. This approach provides robust exposure estimates for permanent sea-level rise, but generally overestimates exposure for transient flood events. During a flood, water takes time to propagate from the shore to inland areas, and friction forces resist it as it does. As a result, water surfaces slope slightly downward in the inland direction, unless the peak flood height at the shore is sustained for sufficiently long. In other words, extreme sea levels at the shore are generally higher than the flood heights seen inland. Overestimated flood exposures may thus counterbalance underestimated flood probabilities in the ensemble of this analysis. Regardless, the use of consistent methodologies across the entire Caribbean basin should provide useful relative indices of threat in different areas.

This study does not include data or consideration of any protective levees or seawalls which may be present.

Hazard exposure

Threats from sea-level rise and coastal flooding depend not only on the timing, severity and likelihood of these hazards, but also upon the land, population and economic infrastructure exposed to them. Assessing the latter depends importantly on accurate elevation data. This is the first study to employ CoastalDEM, a high vertical accuracy elevation dataset developed by Climate Central, to assess coastal inundation exposure in the Caribbean.

Based on CoastalDEM and demographic data, The Bahamas, Guyana and Suriname have the largest fractions of their populations occupying land below 0.5 m or 1 m MHHW, by wide margins among all study areas. Guyana, Haiti and the Dominican Republic have the largest total populations on low-lying land, with The Bahamas and Suriname not far behind.

The Bahamas, Saint Lucia, Suriname and Guyana appear to have the largest fractions of economic infrastructure exposures in the group.

More extensive and detailed results for national and also subnational units are available in *Risk Finder*, and include analyses of extra variables in Kingston and St. Andrew's parishes, Jamaica, and in Nassau (New Providence), The Bahamas.

Elevation data

CoastalDEM30™ is a 1 arc-second (~30 meter) horizontal resolution digital elevation model based on SRTM 3.0, a near-global dataset derived from satellite radar during a NASA mission in 2000. SRTM is known to contain significant error caused by factors such as topology, vegetation, buildings, and random noise (Shortridge & Messina 2011; LaLonde et al. 2010). On average, SRTM elevations are too high, and cause major underestimation of coastal sea-level and flood threats (Kulp and Strauss 2016). Climate Central's analysis indicates that the performance of the Japanese elevation dataset AW3D30 in coastal areas is slightly inferior to SRTM, with higher biases and error scatter.

Climate Central has estimated SRTM elevation error in coastal areas between (and including) 1-20m in nominal SRTM elevation. Each pixel in a CoastalDEM raster represents the adjusted elevation at that point - the result of subtracting estimated error from SRTM 3.0. CoastalDEM was built to improve analysis related to coastal flood exposure due to sea-level rise and storm surge (Kulp and Strauss 2017).

Table 5 gives CoastalDEM30 vertical error rates in the contiguous United States, Australia, Puerto Rico, and Nassau in The Bahamas, and shows dramatic improvements over SRTM, and **Figure 5** maps estimated error. Error is evaluated through extensive comparison against high-accuracy airborne lidar-based elevations (high-resolution satellite stereophoto-derived elevations in Nassau) using very large numbers of data points for each listed geography (n > 1,000,000; except n = 233,553 in Nassau). Similar improvements outside of these areas are generally expected, but not guaranteed. Results for Puerto Rico and Nassau may be particularly indicative for other parts of the Caribbean with similar vegetation, development patterns and topography as either place. However, the metrics given are large-scale averages, and performance may vary across small spatial scales, as **Figure 5** shows.

When checked against elevations from NASA's ICESat space lidar product, median global bias in corrected areas drops from 1.93m (SRTM) to -0.24m (CoastalDEM). CoastalDEM performance as measured by ICESat throughout the Caribbean shows a slightly greater improvement (**Table 5**; $n \cong$ 370,000). However, these numbers are sensitive to noise, outliers, and gaps in coverage in ICESat, and so comparisons to elevations derived from airborne lidar are much more reliable.

Population and economic data

For consistent Caribbean-wide population exposure assessment, this report employs 2010 data from LandScan, a 1 km horizontal resolution ambient population density grid (Bright et al. 2011).

Risk Finder substitutes preferred sources where available, including WorldPop data for 2015 at 100m resolution; and the most recent census data available for Kingston and Saint Andrew parishes in Jamaica and Nassau (New Providence) in The Bahamas (Jamaica 2011; The Commonwealth of The Bahamas 2012). In Kingston and Saint Andrew, exposure of population above and below the poverty line is additionally assessed, also based on the census. In Nassau, exposure of housing (total, occupied, and vacant) is additionally assessed.

Economic exposure is analyzed across the entire study area using a 100m resolution grid of the density of Internet access points (APs) provided by Skyhook Wireless, covering the years 2015-2017. APs include wireless routers and cellular towers. High AP densities commonly align with core urban business districts, whereas zero or low densities in populated areas more likely correspond to relatively impoverished areas. **Figure** 8 illustrates this relationship by plotting AP density per capita against percentage of population below the poverty line, by Census district in Kingston, Jamaica.

Exposure analysis

This report (**Table 6**-**Table 9**) and *Risk Finder* assess exposure of land, population, APs and other variables at a series of fixed heights above local high tide lines. Water may reach each height (e.g. 1 m MHHW) through sea-level rise, coastal flooding, or a combination of these factors, on different timelines with different probabilities, depending upon the scenario.

These elevation-based assessments are best interpreted as screening for concentration of risk. While statistical flood risk modeling informs estimates of the likelihood of surpassing each study height under different scenarios and time frames, at the shore, assessments do not include dynamical modeling of storm surge, waves or structural damage from simulated storms, nor potential natural habitat responses to rising sea levels such as wetland accretion or migration. More detailed and accurate elevation data, such as may be derived from airborne lidar, used as input for detailed local dynamical models, can together provide critical additional information for planning and development on the ground in high-risk areas.

The headline result from the current assessment is that among areas studied, The Bahamas confront by far the greatest threat to land, population and property, as a fraction of national totals. An estimated 32% of Bahamas land, 25% of population, and 13% of Internet access points are at elevations below 0.5 m MHHW, and thus at risk of chronic flooding within the coming several decades. Guyana and Suriname follow next in population exposure, at 14% and 10%; all other study areas are below 2% at this water level. For absolute count of population exposed, however, Guyana leads, followed by the Dominican Republic and Haiti (each of these three has close to 100,000 people living on land below 0.5 m MHHW), followed by The Bahamas (77,000) and Suriname (52,000). After The Bahamas, Saint Lucia has a notably large fraction of APs (6%) below 0.5 m.

The same rankings generally follow for exposures below 1 m, but with larger fractions and totals involved. Population exposure in the Dominican Republic, however, does not grow as steeply as in some other places, and so it loses its place in the ranking to The Bahamas.

Table 8 compares population exposure estimates based on LandScan vs. WorldPop data in study locations where both are available. Assuming both datasets represent total population with reasonable accuracy, the higher-resolution WorldPop should provide more accurate estimates of coastal exposure by distinguishing at a finer scale between populations occupying higher vs. lower parcels of land. (The most accurate analysis would use even finer data, the footprints of individual homes.) Results are clearly correlated, but suggest that at 0.5 m, Guyana may face double the exposure indicated by LandScan, propelling it into the most threatened position on both an absolute and relative basis. Suriname's exposure also increases, while Haiti is flat and the Dominican Republic appears to have lower exposure. 100 m resolution WorldPop data are not currently available for The Bahamas and a number of other study areas.

Overall within the geographic scope of this analysis, some 453,000 people live on land less than 0.5 m above local high tide lines, and 768,000 occupy on land below 1 m, based on LandScan data. Substituting

WorldPop data, where available, these numbers jump to best estimates of 607,000 and 966,000, respectively.

As the first step in developing these estimates, this analysis classifies all areas as either land or ocean, as defined by the SRTM water body dataset (SWBD). To estimate exposure to any given water level, the analysis then counts all land below that elevation. This approach means that wetland areas that SWBD does not classify as ocean are counted as land area that could be affected, even though already wet. The approach also includes low-lying areas that appear isolated from the ocean by intervening higher-elevation areas. Two main considerations justify this choice. First, the bedrock under many Caribbean islands is porous limestone, so water may penetrate through the ground itself. And second, while CoastalDEM shows much less noise than NASA's SRTM, upon which it is based, residual speckling is still evident in some areas when an elevation threshold is applied. It is reasonable to expect that part of a speckled area should be below the elevation threshold applied; hence, isolated speckles below the threshold are counted as exposed.

Because the elevation grid has a finer resolution than population and AP grids, the latter are upsampled to the finer grid. If part of a population or AP grid cell extends over present-day ocean or another water body (as defined by the SWBD), zero population or AP density is assigned to this part, and the density of the balance of the cell is compensated upward to achieve the same cell-wide total value before down-sampling to the elevation grid.

Exposure assessments are tabulated within the boundaries of administrative units from levels 0 to 2 (national to county equivalent) in the database GADM 2.0 (University of Berkeley et al. 2012).

In interpreting results, it is important to note that if during a high tide or a storm, water reaches a particular level at a point along the shore, such as a study tide gauge, that height must be maintained over time before reaching farther inland. Exposure values in this study and *Risk Finder* might thus be seen as corresponding to the maximum area that could be affected by a flood of a certain height, depending on how long it lasts. It is also the case that actual storms create uneven flood surfaces depending on factors such as wind direction; this analysis cannot capture the dynamics of an individual event. However, these considerations do not apply when evaluating exposure from sea level rise acting alone, since sea level rise is effectively permanent.

Analysis does not account for erosion, marsh accretion or migration, future flood controls, new construction, population growth or decline, or other dynamic factors that may affect exposure.

Long-term consequences for climate choices

Due to the long half-life of carbon dioxide in the atmosphere, and a range of climate feedbacks, carbon emissions will cause sea levels to rise not only this century, but also for many more to come. The contrast between the consequences from high vs. low emissions scenarios is far greater in the long term than by 2100, with sea level increases that may exceed 8 m in 4 °C warming scenarios (Strauss et al. 2015). Long-term sea level increases may exceed 4 m in 2 °C scenarios, and 3 m after 1.5 °C warming. The *Mapping Choices* online tool (choices.climatecentral.org) illustrates these contrasts and thus the stakes across the Caribbean, updated from the original version by using CoastalDEM for the region. Corresponding photorealistic images for a downtown scene from each of Kingston, Jamaica; Nassau, The Bahamas; and Georgetown, Guyana, are also available on the web (climatecentral.org/news/sea-level-stakes-for-the-caribbean-in-pictures-21770). Online documentation and the *Mapping Choices* report provide more detail on the science and core methodology behind these maps and images.

These long-term projections offer the sobering and important reminder that any current measures to increase coastal resilience should not be considered as complete solutions, but rather as early steps in a longer journey.

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***Table 1**. Probabilistic sea-level projections according to K14 and assuming unabated emissions (RCP 8.5). Median values given with credible intervals (5th - 95th percentiles) in parentheses. Units of meters.*

Tide gauge location	2050	2100	2200
Virginia Key, Florida	0.32 (0.19-0.47)	0.83 (0.46-1.32)	1.99 (1.01-3.82)
Settlement Point, The Bahamas	0.32 (0.18-0.47)	0.82 (0.43-1.32)	1.98 (0.98-3.81)
Gibara, Cuba	0.27 (0.14-0.41)	0.74 (0.36-1.22)	1.85 (0.77-3.74)
Guantanamo Bay, Cuba	0.29 (0.16-0.43)	0.79 (0.41-1.28)	1.95 (0.88-3.85)
Port Royal, Jamaica	0.30 (0.10-0.51)	0.81 (0.31-1.40)	2.04 (0.75-4.03)
Port Au Prince, Haiti	0.28 (0.08-0.50)	0.79 (0.29-1.37)	1.97 (0.71-3.93)
Puerto Plata, Dominican Republic	0.28 (0.07-0.50)	0.77 (0.26-1.37)	1.94 (0.66-3.91)
Magueyes Island, Puerto Rico	0.27 (0.16-0.39)	0.76 (0.39-1.24)	1.89 (0.86-3.77)
Pointe-A-Pitre, Guadeloupe	0.28 (0.08-0.49)	0.78 (0.28-1.37)	1.97 (0.66-3.98)
Puerto Castilla, Honduras	0.35 (0.16-0.55)	0.91 (0.41-1.49)	2.18 (0.96-4.15)
Puerto Limon, Costa Rica	0.27 (0.13-0.43)	0.76 (0.34-1.30)	1.90 (0.79-3.85)
Cristobal, Panama	0.31 (0.19-0.43)	0.82 (0.47-1.31)	2.02 (0.98-3.95)
Belem, Brazil	0.27 (0.16-0.40)	0.77 (0.41-1.26)	1.92 (0.87-3.79)

***Table 2**. Median sea-level projections according to two models (K14, K17) under low (RCP 2.6) and high (RCP 8.5) emissions scenarios.*

	Year: 2050				Year: 2100				Year: 2200			
	RCP 2.6		RCP 8.5		RCP 2.6		RCP 8.5		RCP 2.6		RCP 8.5	
Tide gauge location	K14	K17	K14	K17	K14	K17	K14	K17	K14	K17	K14	K17
Virginia Key, Florida	0.28	0.27	0.33	0.36	0.54	0.62	0.84	1.63	1.03	1.20	2.00	8.13
Settlement Point, The Bahamas	0.28	0.27	0.32	0.36	0.54	0.61	0.83	1.63	1.04	1.17	1.98	8.13
Gibara, Cuba	0.24	0.28	0.27	0.30	0.47	0.64	0.74	1.54	0.90	1.23	1.86	7.96
Guantanamo Bay, Cuba	0.26	0.25	0.29	0.32	0.51	0.59	0.79	1.58	0.99	1.13	1.96	8.07
Port Royal, Jamaica	0.27	0.28	0.30	0.27	0.54	0.64	0.82	1.49	1.04	1.23	2.05	7.88
Port Au Prince, Haiti	0.26	0.25	0.29	0.32	0.52	0.59	0.79	1.58	1.02	1.13	1.97	8.07
Puerto Plata, Dominican Republic	0.25	0.28	0.28	0.31	0.51	0.64	0.78	1.55	0.99	1.23	1.95	8.01
Magueyes Island, Puerto Rico	0.24	0.28	0.27	0.31	0.49	0.64	0.76	1.55	0.95	1.23	1.90	8.01
Pointe-A-Pitre, Guadeloupe	0.26	0.24	0.29	0.31	0.52	0.57	0.79	1.56	1.02	1.11	1.97	8.04
Puerto Castilla, Honduras	0.31	0.30	0.35	0.37	0.61	0.67	0.91	1.68	1.18	1.28	2.19	8.12
Puerto Limon, Costa Rica	0.24	0.23	0.28	0.30	0.46	0.52	0.77	1.55	0.86	0.99	1.91	7.85
Cristobal, Panama	0.27	0.26	0.31	0.33	0.52	0.59	0.83	1.59	0.99	1.13	2.03	7.97
Belem, Brazil	0.24	0.23	0.28	0.30	0.47	0.53	0.78	1.50	0.88	1.01	1.92	7.46

Table 3. *Standard flood heights derived from the Global Tides and Surge Reanalysis. All values in meters above local Mean Higher High Water. GTSR is known to generally underestimate these flood heights, especially extreme (1% annual chance) flood heights in areas subject to storm surges from tropical cyclones, such as the Caribbean. For reference, 10% chance flood heights listed here may be underestimated by 0.1-0.5 m, and 1% annual chance flood heights are likely to be farther below actual values.*

Tide gauge location	Height of annual flood	Height of 10% annual chance flood	Height of 1% annual chance flood
Virginia Key, Florida	0.12	0.19	0.23
Settlement Point, The Bahamas	0.17	0.25	0.29
Gibara, Cuba	0.14	0.18	0.20
Guantanamo Bay, Cuba	0.09	0.16	0.19
Port Royal, Jamaica	0.00	0.08	0.11
Port Au Prince, Haiti	0.11	0.15	0.17
Puerto Plata, Dominican Republic	0.12	0.16	0.17
Magueyes Island, Puerto Rico	0.05	0.11	0.13
Pointe-A-Pitre, Guadeloupe	0.05	0.07	0.09
Puerto Castilla, Honduras	0.00	0.03	0.04
Puerto Limon, Costa Rica	0.00	0.02	0.02
Cristobal, Panama	0.02	0.04	0.05
Belem, Brazil	0.78	0.89	0.94

Table 4. *Annual percentage risk (0-100%) of coastal flooding above fixed heights, given denoted sea-level rise model and year, for scenario RCP 4.5. 100% likelihoods include the case of sea-level rise exceeding the given height (permanent inundation). Median estimates are shown, with credible intervals for K14 (5th – 95th percentile) but not for K17 because K17 projections are not probabilistic. Credible intervals are based on different sea-level projections. K17 estimates are very similar to K14 estimates in 2050 and thus are not shown; also not shown, K14 median estimates in 2070 and 2100 are all zero for 1m, outside of Belem.* Risk Finder *allows exploration of additional years and scenarios. However, all estimates in* Risk Finder *and this table should be regarded as lower bounds because analysis uses return level curves that underestimate flood risks in the Caribbean.*

Flood height (MHHW):	0.5m	0.5m	0.5m	1m	1m
Model:	K14	K14	K17	K17	K17
Tide gauge location Year:	2050	2070	2070	2070	2100
Virginia Key, Florida	6 (0-82)	88 (0-100)	100	0	100
Settlement Point, The Bahamas	39 (0-93)	95 (9-100)	100	0	100
Gibara, Cuba	0 (0-79)	74 (0-100)	100	0	98
Guantanamo Bay, Cuba	0 (0-53)	58 (0-100)	100	0	92
Port Royal, Jamaica	0 (0-46)	7 (0-100)	20	0	1
Port Au Prince, Haiti	0 (0-97)	70 (0-100)	100	0	98
Puerto Plata, Dominican Republic	0 (0-99)	79 (0-100)	100	0	99
Magueyes Island, Puerto Rico	0 (0-2)	6 (0-100)	88	0	66
Pointe-A-Pitre, Guadeloupe	0 (0-72)	0 (0-100)	89	0	64
Puerto Castilla, Honduras	0 (0-100)	15 (0-100)	100	0	100
Puerto Limon, Costa Rica	0 (0-0)	0 (0-100)	12	0	0
Cristobal, Panama	0 (0-0)	0 (0-100)	100	0	19
Belem, Brazil	100 (100-100)	100 (100-100)	100	99	100

Table 5. *Performance of CoastalDEM compared to SRTM and WorldDEM, referenced against higher accuracy sources. Nassau data provided by IDB.*

Reference DEM data source	Area	Product	Bias (m)	RMSE (m)	LE90 (m)	LE95 (m)
Airborne lidar (continuous coverage)	USA	SRTM 3.0	3.7	5.4	9.1	11.2
		CoastalDEM30 v1.1	0.0	2.4	3.9	5.0
	Australia	SRTM 3.0	2.5	4.2	6.8	9.0
		CoastalDEM30 v1.1	-0.1	2.5	3.9	5.2
	Puerto Rico	SRTM 3.0	2.1	3.5	5.6	6.9
		CoastalDEM30 v1.1	0.1	2.8	4.5	5.6
WorldView-2 stereo images	**Nassau, The Bahamas**	SRTM 3.0	3.1	3.7	5.5	6.5
		CoastalDEM30 v1.1	-0.2	1.8	2.8	3.7
ICESat space lidar (sparse)	**Caribbean**	SRTM 3.0	2.4	*ICESat data do not support robust RMSE or LExx estimates*		
		CoastalDEM30 v1.1	-0.3			
Airbus brochure stated claim	Global	Airbus WorldDEM™ DTM			<10	

Table 6*. Low-lying land area (km^2) within 0.5-4 vertical meters of local Mean Higher High Water. Total (tot) and percentage (pct) of land below each level given.*

Place	National Tot Area	0.5m Tot	Pct	1m Tot	Pct	2m Tot	Pct	4m Tot	Pct
Antigua and Barbuda	427	10	2.3%	17	4.0%	41	9.6%	100	23.4%
The Bahamas	12,514	4,043	32.3%	5,771	46.1%	8,771	70.1%	11,240	89.8%
Barbados	437	-	0.0%	-	0.0%	2	0.5%	11	2.5%
Dominica	757	1	0.1%	1	0.1%	3	0.4%	5	0.7%
Dominican Republic	47,866	779	1.6%	1,006	2.1%	1,417	3.0%	2,168	4.5%
Grenada	360	3	0.8%	4	1.1%	7	1.9%	15	4.2%
Guyana	209,746	3,457	1.6%	4,632	2.2%	6,223	3.0%	7,956	3.8%
Haiti	26,983	126	0.5%	210	0.8%	423	1.6%	794	2.9%
Jamaica	11,013	113	1.0%	160	1.5%	303	2.8%	615	5.6%
Saint Kitts and Nevis	269	-	0.0%	2	0.7%	5	1.9%	10	3.7%
Saint Lucia	617	7	1.1%	9	1.5%	17	2.8%	30	4.9%
Saint Vincent and the Grenadines	399	4	1.0%	5	1.3%	7	1.8%	11	2.8%
Suriname	145,018	4,113	2.8%	5,467	3.8%	7,621	5.3%	10,316	7.1%
Trinidad and Tobago	5,169	78	1.5%	118	2.3%	206	4.0%	379	7.3%

Table 7. *Population (LandScan 2010) on low-lying land.*

Place	National Total Pop.	0.5m Tot	Pct	1m Tot	Pct	2m Tot	Pct	4m Tot	Pct
Antigua and Barbuda	86,710	1,170	1.3%	1,737	2.0%	4,236	4.9%	12,759	14.7%
The Bahamas	310,015	76,993	24.8%	128,328	41.4%	176,398	56.9%	247,435	79.8%
Barbados	285,134	240	0.1%	526	0.2%	5,643	2.0%	25,335	8.9%
Dominica	72,811	737	1.0%	1,277	1.8%	3,284	4.5%	6,316	8.7%
Dominican Republic	9,812,309	99,310	1.0%	127,179	1.3%	232,506	2.4%	574,226	5.9%
Grenada	107,817	1,021	0.9%	2,108	2.0%	4,859	4.5%	8,728	8.1%
Guyana	723,107	101,871	14.1%	191,368	26.5%	446,309	61.7%	558,477	77.2%
Haiti	9,660,438	97,241	1.0%	164,310	1.7%	405,978	4.2%	852,626	8.8%
Jamaica	2,847,231	13,700	0.5%	22,681	0.8%	75,242	2.6%	370,732	13.0%
Saint Kitts and Nevis	49,898	244	0.5%	613	1.2%	1,996	4.0%	4,310	8.6%
Saint Lucia	160,742	2,725	1.7%	8,659	5.4%	22,466	14.0%	31,838	19.8%
Saint Vincent and the Grenadines	104,218	697	0.7%	1,129	1.1%	3,650	3.5%	8,060	7.7%
Suriname	508,340	52,493	10.3%	102,318	20.1%	332,934	65.5%	435,907	85.8%
Trinidad and Tobago	1,228,676	4,426	0.4%	15,384	1.3%	66,640	5.4%	170,167	13.8%

Table 8. *Population on low-lying land: Results based on LandScan (1km resolution)* vs. *WorldPop (100m resolution) for places where both are available.*

Place	0.5m LandScan	WorldPop	1m LandScan	WorldPop	2m LandScan	WorldPop	4m LandScan	WorldPop
Antigua and Barbuda	1,170	1,165	1,737	1,689	4,236	4,641	12,759	12,935
Dominican Republic	99,310	80,279	127,179	119,624	232,506	239,877	574,226	556,144
Guyana	101,871	225,307	191,368	332,339	446,309	537,378	558,477	626,494
Haiti	97,241	97,460	164,310	168,663	405,978	439,580	852,626	962,830
Jamaica	13,700	19,128	22,681	29,534	75,242	68,865	370,732	272,043
Suriname	52,493	88,707	102,318	146,774	332,934	334,497	435,907	424,151
Trinidad and Tobago	4,426	12,078	15,384	25,027	66,640	70,927	170,167	173,951

Table 9. Internet access points on low-lying land.

Place	National Total APs	0.5m Tot	Pct	1m Tot	Pct	2m Tot	Pct	4m Tot	Pct
Antigua and Barbuda	45,094	262	0.6%	365	0.8%	2,564	5.7%	13,236	29.4%
The Bahamas	197,748	26,195	13.2%	51,181	25.9%	80,141	40.5%	134,681	68.1%
Barbados	205,483	37	0.0%	118	0.1%	5,878	2.9%	37,763	18.4%
Dominica	29,850	165	0.6%	165	0.6%	659	2.2%	6,384	21.4%
Dominican Republic	2,044,686	11,058	0.5%	20,162	1.0%	48,034	2.3%	138,155	6.8%
Grenada	23,034	198	0.9%	267	1.2%	2,736	11.9%	6,395	27.8%
Guyana	90,703	3,584	4.0%	11,499	12.7%	69,234	76.3%	88,503	97.6%
Haiti	71,468	256	0.4%	281	0.4%	501	0.7%	2,504	3.5%
Jamaica	487,225	3,986	0.8%	9,325	1.9%	36,760	7.5%	132,352	27.2%
Saint Kitts and Nevis	26,651	177	0.7%	293	1.1%	3,131	11.7%	10,523	39.5%
Saint Lucia	55,599	3,448	6.2%	10,613	19.1%	25,498	45.9%	34,860	62.7%
Saint Vincent and the Grenadines	29,650	58	0.2%	58	0.2%	214	0.7%	2,480	8.4%
Suriname	191,974	8,284	4.3%	26,434	13.8%	155,939	81.2%	187,282	97.6%
Trinidad and Tobago	727,614	520	0.1%	5,135	0.7%	30,225	4.2%	103,364	14.2%

Figure 1*. A screenshot from* Surging Seas Risk Zone Map *(ss2.climatecentral.org), showing (in blue) land less than 2m above the local high tide line in Nassau (New Providence), The Bahamas.*

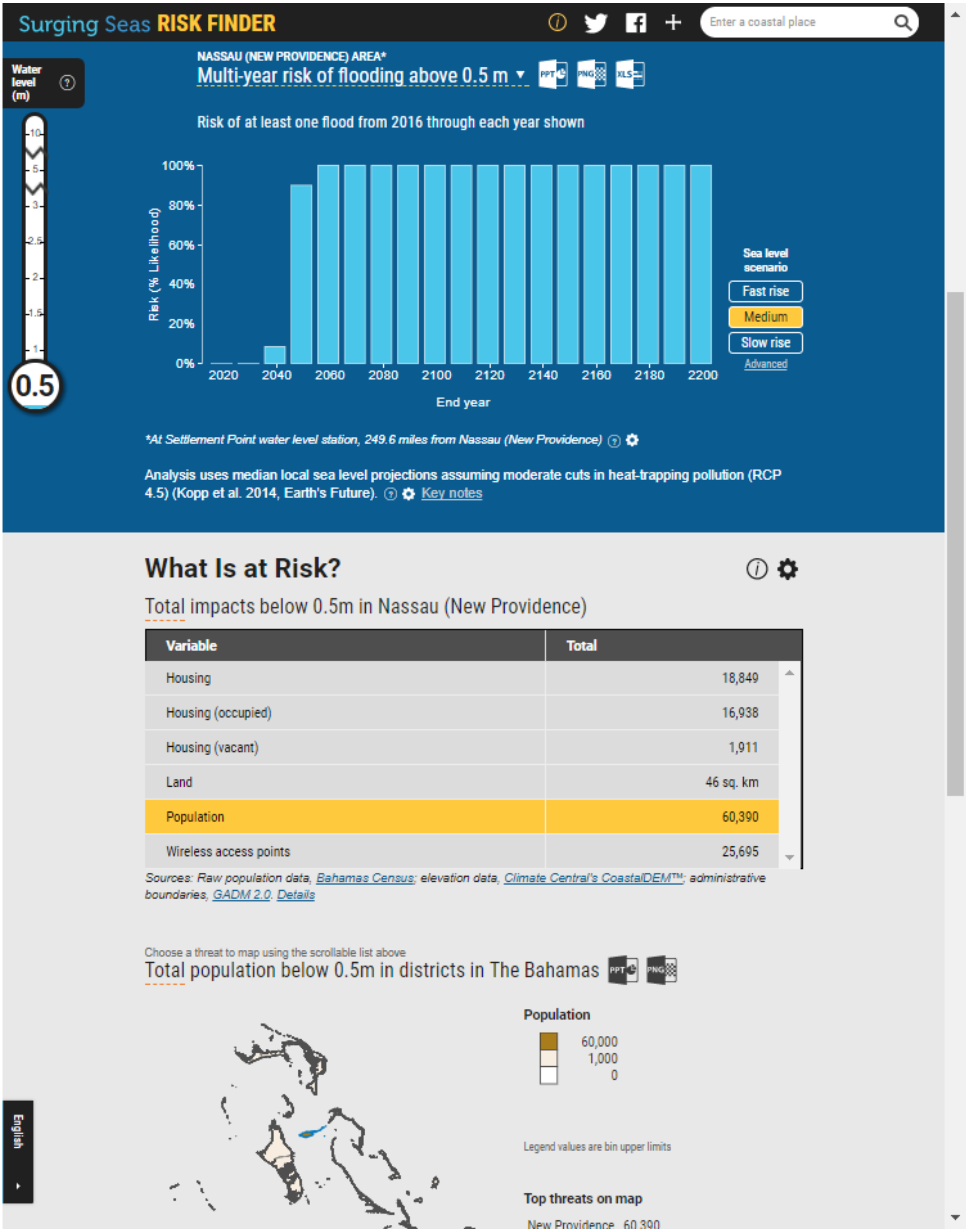

Figure 2. A partial screenshot from Surging Seas Risk Finder *(riskfinder.org/Caribbean) showing a portion of the landing page for Nassau, The Bahamas.*

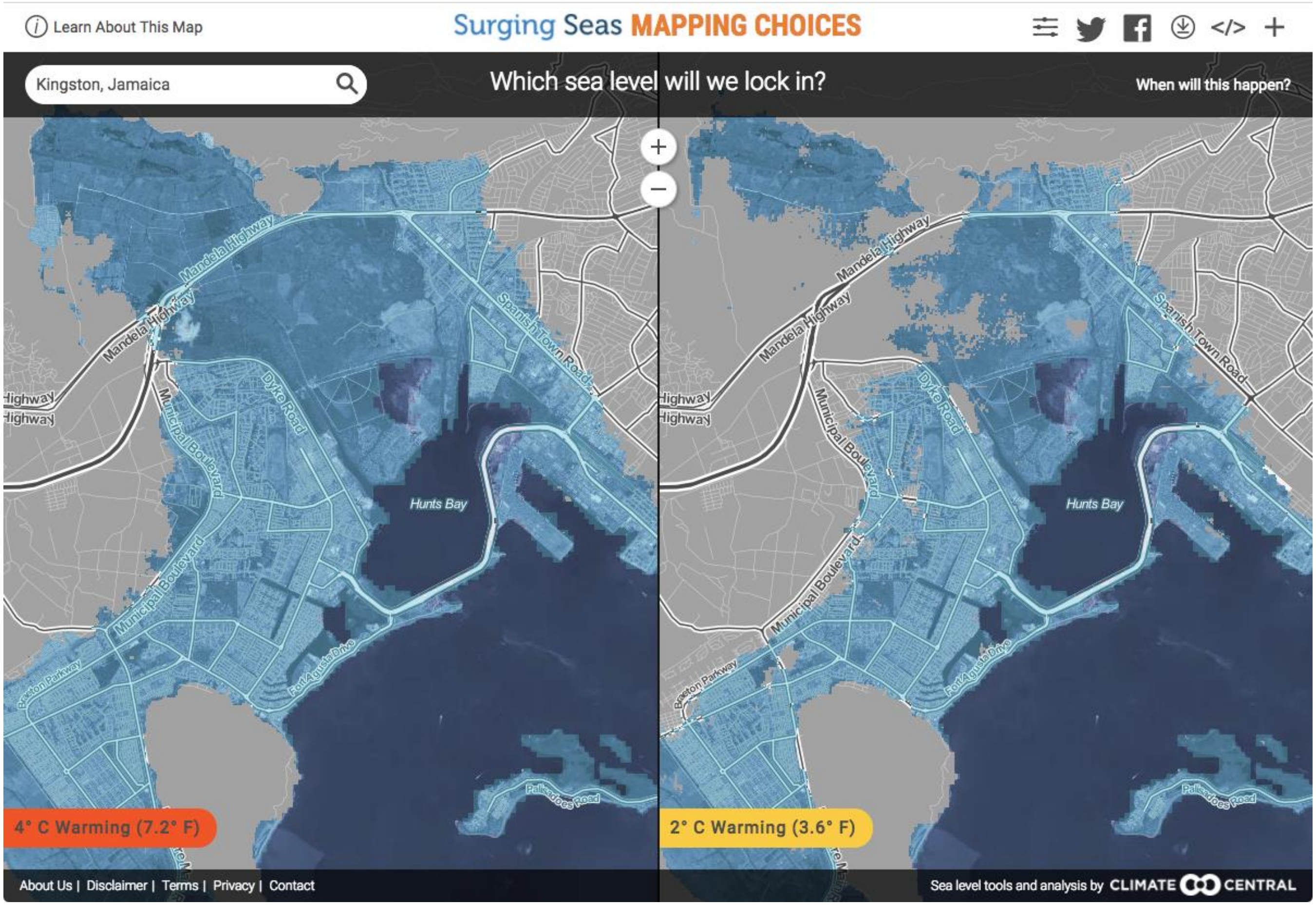

Figure 3. *A screenshot from* Mapping Choices *(choices.climatecentral.org) showing multi-century sea-level rise just west of Kingston, Jamaica, as projected to lock in after carbon emissions causing 4℃ vs 2℃ warming.*

KINGSTON, JAMAICA

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Figure 4. *Photorealistic illustration of different locked-in sea levels in Kingston, Jamaica.*

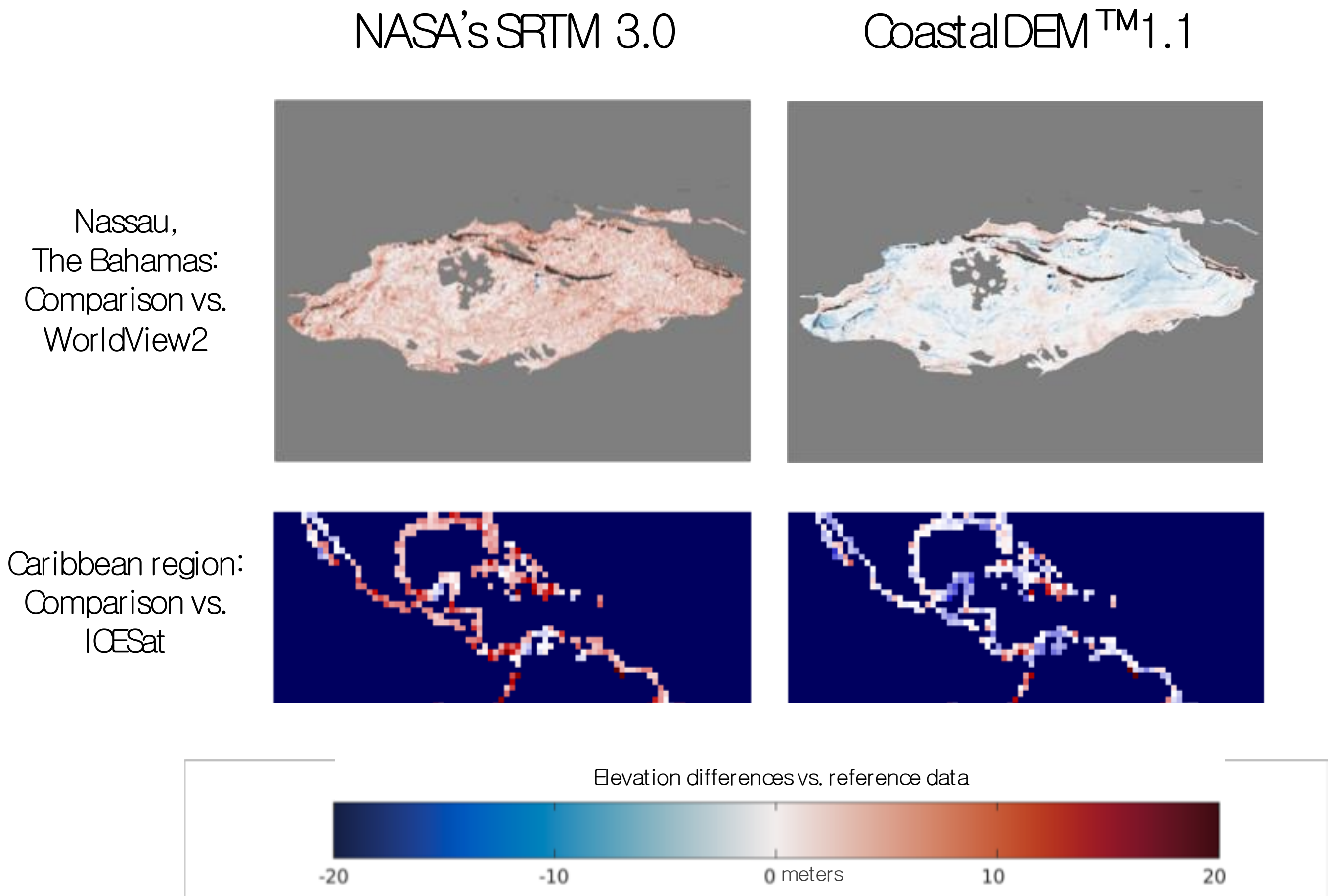

***Figure 5**. Images showing the performance of CoastalDEM vs. SRTM at different scales, as measured against reference datasets believed to have more accurate elevations. Red tones indicate that SRTM or CoastalDEM is overestimating elevation compared to reference and thus underestimating exposure to sea-level rise and coastal flooding; blue tones indicate underestimation of elevation and thus overestimation of risk. Darker reds and blues indicate larger absolute errors, and lighter/whiter tones indicate smaller ones. In the first row, medium gray denotes water, and dark gray covers land areas >20m in elevation according to SRTM, which were not modeled in CoastalDEM. In the second row, the darkest blue represents water or land not included in CoastalDEM. Second-row error is computed as the median of all errors within 1-degree cells, because of the sparseness and noise in ICESat data. **Table 5** provides error statistics corresponding to all four images.*

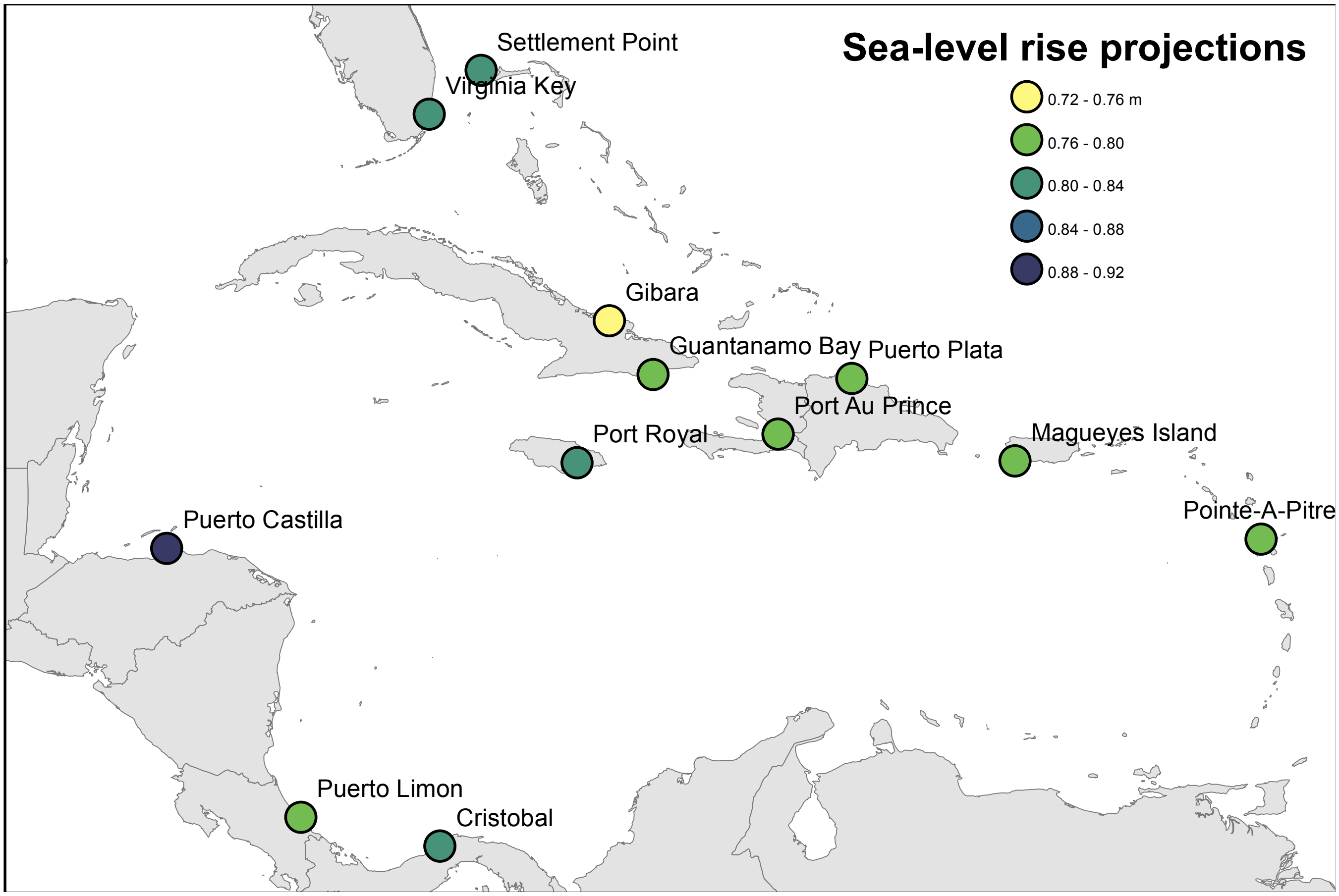

Figure 6. *Median sea-level projections around the Caribbean basin for the year 2100 assuming unabated climate pollution (RCP 8.5), according to Kopp et al. 2014. Omits the study tide gauge at Belem, Brazil.*

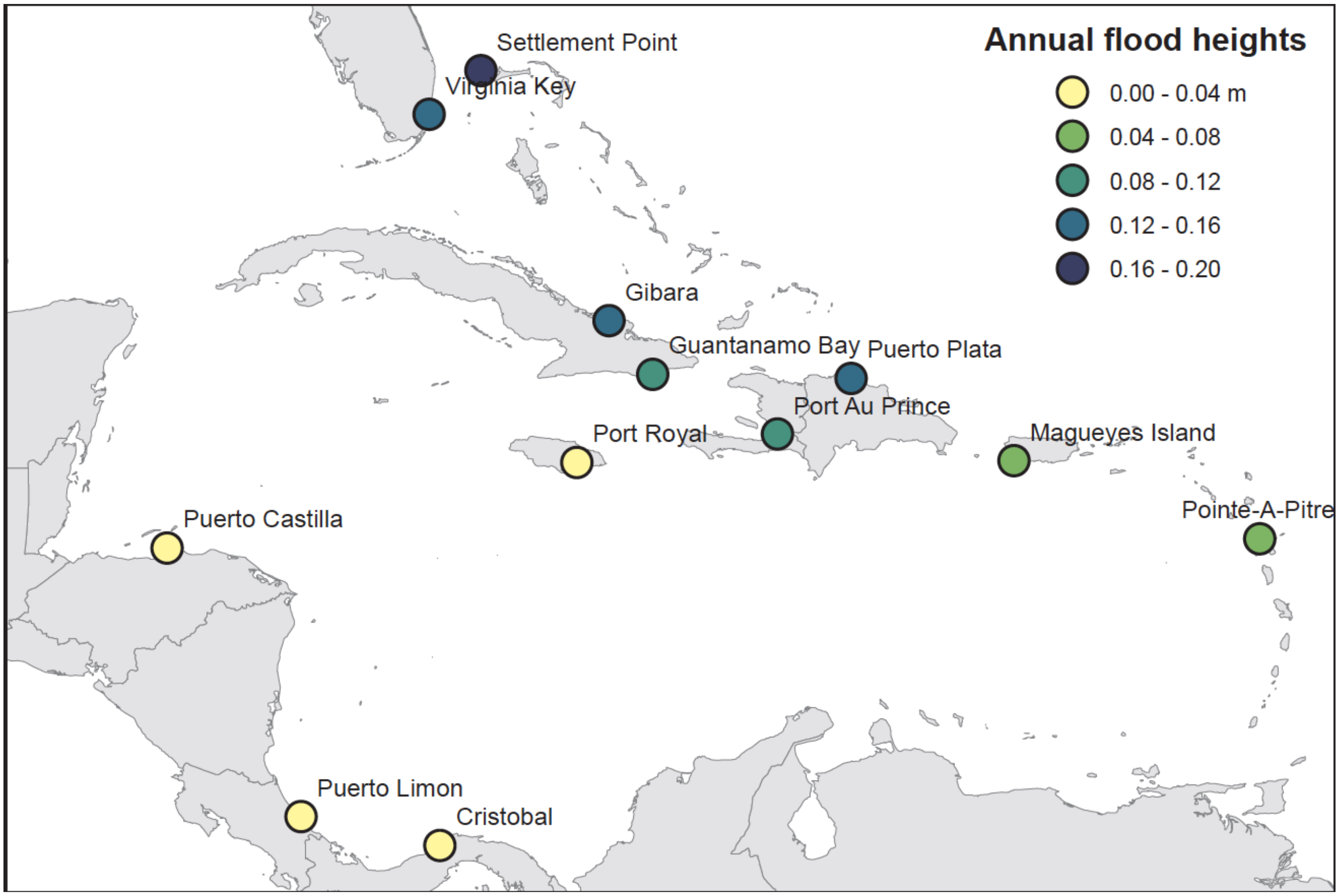

Figure 7. *The heights of "annual" floods (heights exceeded on average once per year) around the Caribbean basin, relative to local high tide lines (Mean Higher High Water), according to the Global Tides and Surge Reanalysis. GTSR generally underestimates flood heights in the Caribbean. Figure omits the study tide gauge at Belem, Brazil.*

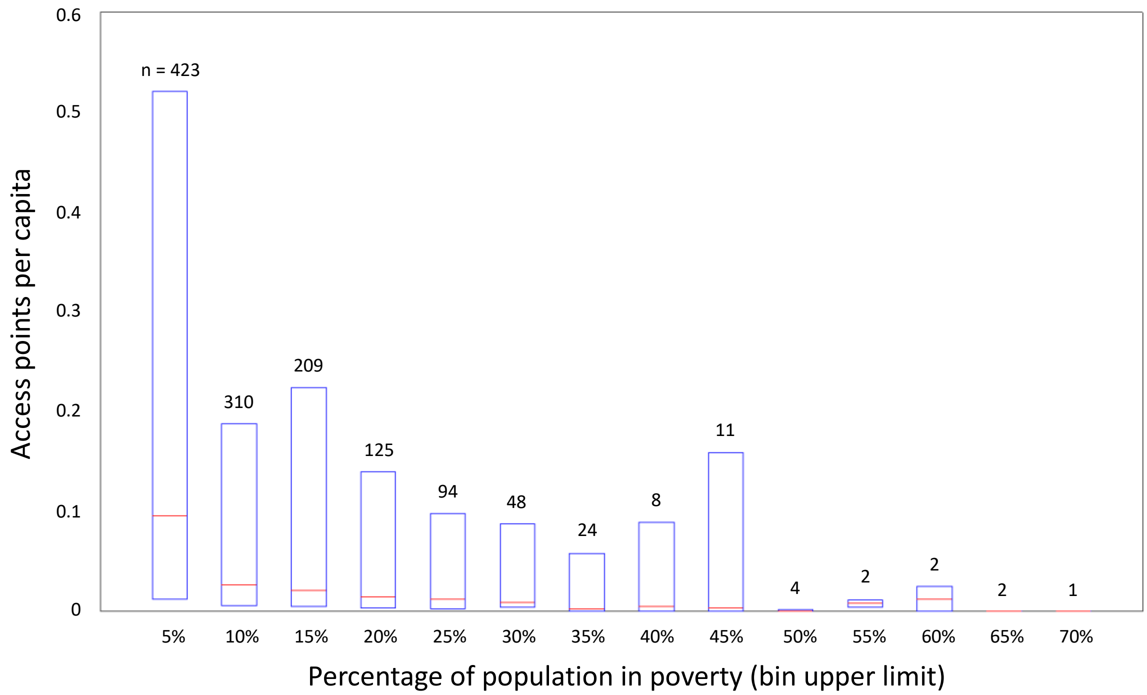

Figure 8. *Bars indicate 25th percentile (lower edge), median (red line), and 75th percentile (upper edge) Internet access points per capita for Census districts in Kingston and St Andrew's parishes, Jamaica, with different poverty levels. Most areas with more than 0.1 APs per capita have low rates of poverty, whereas areas with fewer APs per capita are more weighted toward greater poverty.*