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# CBO's Approach to Estimating Expected Hurricane Damage

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## Abstract

This working paper describes how the Congressional Budget Office estimates the effects of climate change and coastal development on hurricane damage. The estimates themselves are presented in a separate report—*Potential Increases in Hurricane Damage in the United States: Implications for the Federal Budget*—for three selected future years: 2025, 2050, and 2075.

Climate change is projected to increase damage in two ways. First, climate change is projected to result in more frequent high-intensity hurricanes. Second, for any given storm, rising sea levels are projected to lead to increased damage from storm surges. CBO generates state-specific estimates of hurricane damage on the basis of existing property exposure (which corresponds to existing vulnerability-weighted populations and per capita income in each state) by using damage functions provided by Risk Management Solutions and estimates of the distributions of hurricane frequencies and state-specific sea levels in future years.

Coastal development is also projected to increase damage simply by putting more people and property in harm's way. In this analysis, coastal development is measured as changes in population and per capita income in areas that are vulnerable to hurricane damage. Specifically, CBO inflates those state-specific damage estimates on the basis of each state's distributions of vulnerability-weighted population and per capita income in future years, as well as on elasticities that translate changes in population and per capita income into changes in the magnitude of damage.

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In its June 2016 report *Potential Increases in Hurricane Damage in the United States: Implications for the Federal Budget*, the Congressional Budget Office estimated hurricane damage in future years. Details on the approach—known as a Monte Carlo method—that CBO used to develop underlying distributions for hurricane frequencies, sea levels, population, and per capita income, along with a more expanded description of how CBO estimated expected damage on the basis of those inputs, are described in this paper.

# Overview of CBO's Estimation Process

CBO estimated a distribution of hurricane damage by simulating damage 5,000 times, with each simulation, $n$ ($n$ = 1 to 5,000), based on a unique set of values for changes in the frequency of hurricanes and for state-specific estimates of sea level, population, and per capita income selected from distributions for a future year.

Twenty-two states—all of which CBO estimated to have a nonzero probability of incurring hurricane damage—were included in the agency's model. Because growth in some regions (along the coast, for example) will have a larger effect on damage than growth in other regions, measures of population and per capita income were weighted on the basis of their relative vulnerability to hurricane damage, with $\ddot{p}$ and $\ddot{y}$ indicating vulnerability-weighted population and per capita income, respectively, and $p$ and $y$ indicating unweighted values.

The values for hurricane frequencies, $f$, sea levels, $s$, vulnerability-weighted population, $\ddot{p}$, and vulnerability-weighted per capita income, $\ddot{y}$, in turn, were each selected from individual distributions in each specific future year: 2025, 2050, or 2075. The shape of CBO's damage distribution in a particular year, such as 2075, depends on the shape of the 2075 distributions for $f$, $s$, $\ddot{p}$, and $\ddot{y}$ and on the relationship between those variables and hurricane damage.

The distributions of hurricane frequencies and sea levels that CBO used were estimated by university or government researchers (or by CBO, using data provided by those researchers). The distributions of vulnerability-weighted population and per capita income were developed by CBO. For each of the three future years ($t$ = 2025, 2050, and 2075), CBO selected hurricane frequencies from 18 sets of expected frequencies, where each set included a value for each hurricane Category $c$, $c$ = 1 (for a Category 1 hurricane) through $c$ = 5 (for a Category 5 hurricane) for each year; the selection probabilities for both hurricane frequencies and sea levels in the simulations are described below. (There are five categories of hurricanes, which are classified on the basis of their peak wind speed, with Category 5 storms being the most intense.) The other variables discussed here ($\ddot{p}$ and $\ddot{y}$) have normal distributions.

CBO compared distributions of expected damage in each future year with an estimate of expected damage in a reference case. For the reference case, hurricane frequencies, $f$, were based on estimates for 2010, and all other variables, $s$, $\ddot{p}$, and $\ddot{y}$, were set at their estimated values for 2015.[1] For notational convenience throughout this paper, the $t$ subscript is suppressed when denoting future years. Subscripts $i$, $j$, and $k$ are used to indicate county, state, and region, respectively; subscript $n$ indicates that the variable takes on a different value in each $n$th simulation; and subscript $R$ indicates that the variable is set at its reference value. Thus, for example, $s_{j,n}$ denotes sea level in state $j$ in the $n$th simulation, and $s_{j,R}$ denotes sea level

[1] This reference case of estimated expected damage under current conditions is a more appropriate comparison to expected future damage than actual damage in any particular year for the following reasons: Actual hurricane damage may be unusually high or low depending on whether the number of hurricanes in each category making landfall in that year was higher or lower than average and whether landfalls occurred in densely or sparsely populated areas. Likewise, the distribution of actual hurricane damage in any selected future year would be wider than the distribution of expected damage that CBO estimates.

in state *j* in the reference case. For general purposes, a damage estimate for state *j* can be described as $D_j(f_x, s_{j,x}, \ddot{p}_{j,x}, \ddot{y}_{j,x})$, where *x* = *R* indicates that $D_j$ was calculated with the variable set at its reference value, and *x* = *n* indicates that $D_j$ was calculated with the variable set at its value selected in the *n*th simulation.

Each simulation of CBO's model begins with a set of draws for all four of the conditions that affect expected hurricane damage (see Figure 1). Each *n*th simulation of the model determines a set of state-specific estimates of expected damage (reflecting only the effects of climate change) based on the draws for hurricane frequency, *f*, and sea levels, *s*, in that simulation; existing property exposure in each state; and a set of damage functions developed by Risk Management Solutions (RMS). Those climate-only damage estimates are then adjusted to reflect the effects of coastal development. That adjustment is based on draws of each county's population and per capita income in 2075—which are weighted to reflect the county's relative vulnerability to damage from wind and storm surges and then aggregated to the state level (creating variables $\ddot{p}$ and $\ddot{y}$)—along with state-specific inflation factors developed by CBO.

For each simulation, *n*, values of the four random variables *f*, *s*, $\ddot{p}$, and $\ddot{y}$ were drawn from their individual distributions, and those variables were used to estimate expected damage for each state *j* (*j* = 1 through 22). The *n*th damage estimate (corresponding to the *n*th simulation) for state *j* is:

$$D_j(f_n, s_{j,n}, \ddot{p}_{j,n}, \ddot{y}_{j,n}) = \sum_{c=1}^{5} f_n\,(c) d_{j,n}(c, s_{j,n}, \ddot{p}_{j,R}, \ddot{y}_{j,R}) g_{j,n}(\ddot{p}_{j,n}, \ddot{y}_{j,n})$$

where:

- $d_{j,n}(c, s_{j,n}, \ddot{p}_{j,R}, \ddot{y}_{j,R})$ is the expected damage in dollars in state *j* , given U.S. landfall of a hurricane of Category *c*, the specific value of sea level for state *j* selected for the *n*th simulation, and state *j*'s population and per capita income in the reference case (reflecting state *j*'s property exposure in 2015); and
- $g_{j,n}(\ddot{p}_{j,n}, \ddot{y}_{j,n})$ is a damage inflation factor. It increases $d_{j,n}(c, s_{j,n}, \ddot{p}_{j,R}, \ddot{y}_{j,R})$ on the basis of the estimates of state *j*'s vulnerability-weighted population and per capita income in year *t* as selected in the *n*th simulation. As described below, each state's population and per capita income can be affected by rising sea levels.

The damage inflation factor, $g_{j,n}$, depends on the change in population and per capita income in each state (relative to 2015) and a set of state-specific population and per capita income elasticities (indicating the percentage change in expected damage given a percentage change in population or per capita income) developed by CBO (see Figure 2). Specifically,

$$g_{j,n}(\ddot{p}_{j,n}, \ddot{y}_{j,n}) = 1 + \Delta\ddot{p}_{j,n}\epsilon_j^p + \Delta\ddot{y}_{j,n}\epsilon_j^y$$

where:

| | | |
|---|---|---|
| $\ddot{p}_{j,n}$ | = | the vulnerability-weighted population of state *j* in the *n*th simulation |
| $\Delta\ddot{p}_{j,n}$ | = | $\frac{\ddot{p}_{j,n}}{\ddot{p}_{j,R}} - 1$ |
| $\ddot{p}_{j,R}$ | = | the vulnerability-weighted population of state *j* in the reference case |

| | | |
|---|---|---|
| $\epsilon_j^p$ | = | the percentage change in expected damage in state *j* given a percentage change in population in state *j* |
| $\ddot{y}_{j,n}$ | = | the vulnerability-weighted per capita income value for state *j* in the *n*th simulation |
| $\Delta\ddot{y}_{j,n}$ | = | $\frac{\ddot{y}_{j,n}}{\ddot{y}_{j,R}} - 1$ |
| $\ddot{y}_{j,R}$ | = | the vulnerability-weighted per capita income of state *j* in the reference case |
| $\epsilon_j^y$ | = | the percentage change in expected damage in state *j* given a percentage change in per capita income in state *j*. |

Total expected damage in the United States corresponding to the *n*th simulation is obtained by aggregating across the 22 state damage estimates for that simulation:

$$D_n = \sum_{j=1}^{22} D_j\left(f_n, s_{j,n}, \ddot{p}_{j,n}, \ddot{y}_{i,n}\right)$$

For each selected year (2025, 2050, and 2075), this process is repeated 5,000 times to generate a distribution of expected hurricane damage in the United States.

CBO compared distributions of expected future damage with a reference case, which is the estimate of expected damage obtained by setting all variables at their reference levels (denoted by subscript *R*):

$$D_R = \sum_{j=1}^{22} D_j\left(f_R, s_{j,R}, \ddot{p}_{j,R}, \ddot{y}_{i,R}\right)$$

# Damage Functions

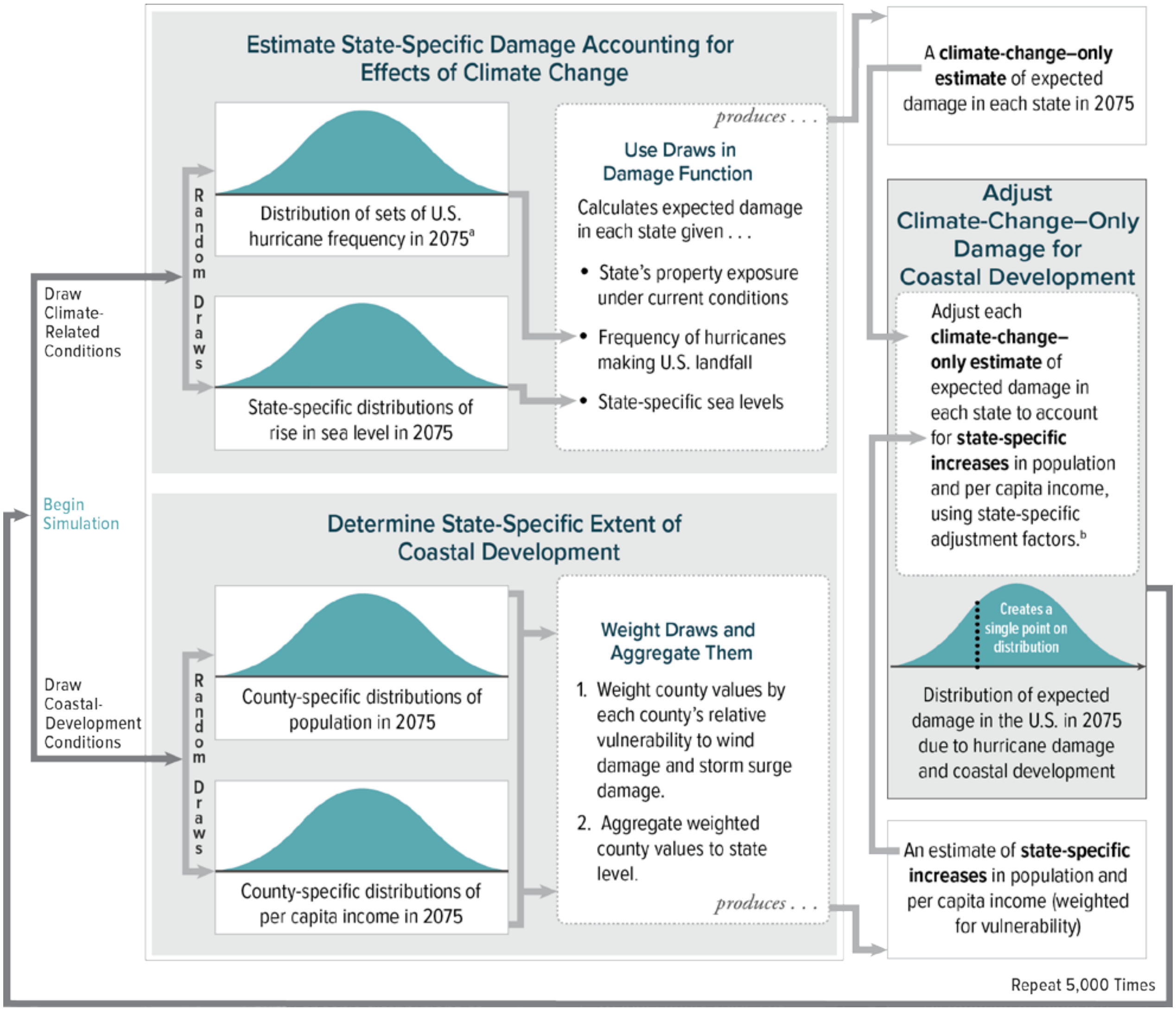
CBO projects the magnitude of expected hurricane damage by using damage functions provided by RMS.[2] Those functions estimate expected damage on a state-specific basis, given:

- Existing exposure of residential and nonresidential property in the state,
- Landfall of a specific category of hurricane (Categories 1 through 5) anywhere in the United States, and
- State-specific estimates of sea levels.

Those estimated losses account for the probability that the state will incur no losses when a hurricane of a particular category makes landfall in the United States. For example, if a Category 5 hurricane was to make landfall in the United States, it would be much more likely to strike the southern section of the United States' eastern coast than the northern section. As a result, the estimated expected damage would be much smaller in New Jersey (roughly $15 million under current conditions) than in Florida (roughly $1.8 billion under current conditions). If a Category 5 hurricane actually made landfall in New Jersey,

[2] For a description of this model, see Michael Delgado and others, "Technical Appendix: Detailed Sectoral Models," in Trevor Houser and others, *American Climate Prospectus: Economic Risks in the United States* (Rhodium Group and Risk Management Solutions, October 2014), p. C-6, http://climateprospectus.org/publications/. Damage estimates include direct damage to property and contents caused by wind and storm surges, as well as indirect damage caused by interrupted business activity.

Figure 1.
Flow of the Model for Estimating the Effects of Climate Change and Coastal Development on Hurricane Damage in Selected Future Years: Example Year, 2075

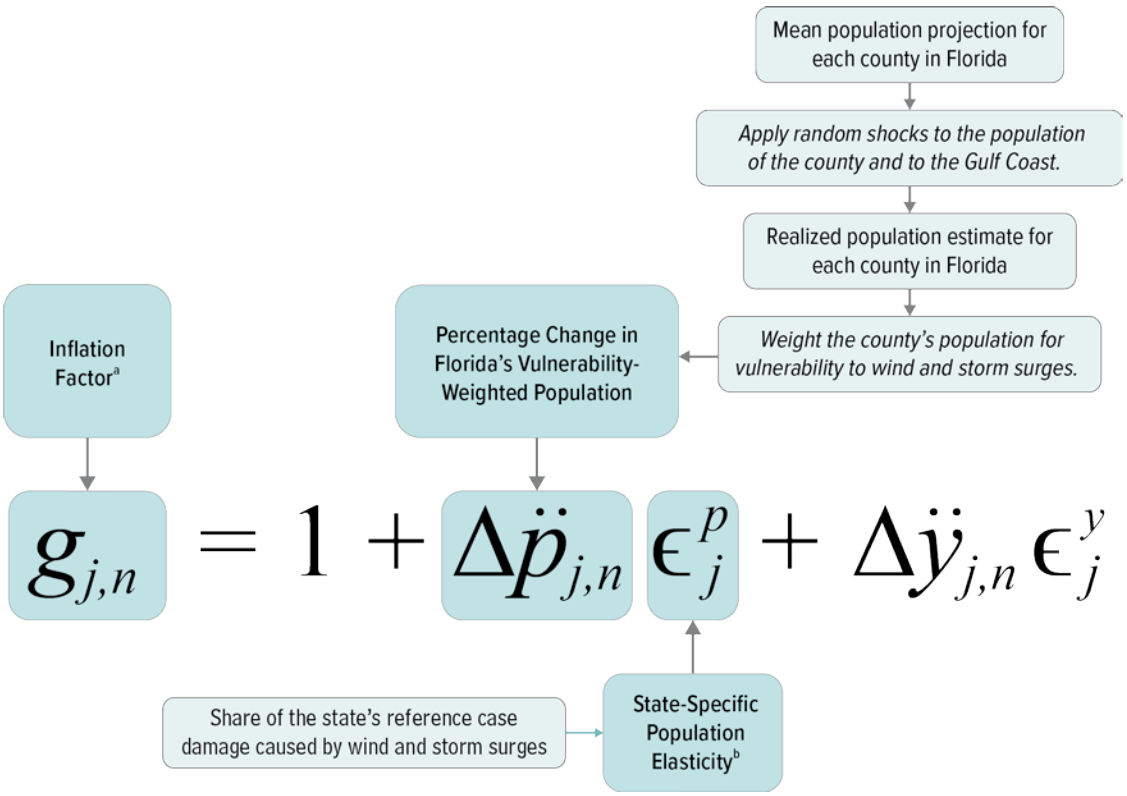



Source: Congressional Budget Office.

a. Each set consists of a projection of frequency for hurricanes in each of five categories. (The five categories of hurricanes are based on peak wind speed. Category 5 storms are the most intense.)

b. Each state's increase in expected damage due to an increase in its population and per capita income is uniquely determined based on the share of the state's expected damage (measured under current conditions) that comes from wind versus storm-surge damage. That unique determination incorporates different responses of wind and storm-surge damage to a given increase in population and per capita income.

Figure 2.
Estimating Effects of Climate Change and Coastal Development in 2075: Example, Florida




Source: Congressional Budget Office.

CBO constructed a measure of the percentage change in each state's vulnerability-weighted per capita income, $\Delta\ddot{y}_{j,n}$, by using the same method presented in this figure for the percentage change in vulnerability-weighted population. The agency also constructed a state-specific per capita income elasticity, $\epsilon_j^y$, which indicates the percentage change in damage given a percentage change in per capita income.

a. Inflation factor is used to adjust the estimate of expected climate-only damage for the effects of coastal development.

b. Population elasticity indicates the percentage change in damage given a percentage change in population.

the losses would be very large; however, the relatively small *expected* loss reflects the small probability of that occurring.

Estimating the probability that a hurricane of a particular category will make landfall at any given location is difficult given the infrequency with which hurricanes occur, particularly the most damaging Category 4 and 5 storms. RMS addressed that problem by using more than 100,000 simulations of hurricane seasons under current conditions (with frequencies of simulated hurricanes constrained to the frequencies observed over the past 100 years and with hurricanes following physically realistic pathways).[3]

[3] See Michael Delgado and others, "Technical Appendix: Detailed Sectoral Models," in Trevor Houser and others, *American Climate Prospectus: Economic Risks in the United States* (Rhodium Group and Risk Management Solutions, October 2014), p. C-6, http://climateprospectus.org/publications/.

CBO assessed the validity of using damage functions provided by RMS in this analysis by comparing RMS's damage estimates for actual hurricanes that have occurred since 2002 with estimates generated by the National Oceanic and Atmospheric Administration (NOAA).[4] For this purpose, RMS modeled the specific storms by using estimates of property exposure at the time the hurricane occurred. RMS estimated exposure in previous years by adjusting downward the monetary value of current property exposure in its model to account for trends in development between the time of landfall and the present.[5]

For individual storms, some of RMS's estimates were higher than NOAA's (most significantly for Hurricane Katrina); however, on average, RMS's estimates were lower—equal to 80 percent of NOAA's estimates. Excluding Hurricane Katrina from the calculation, RMS's estimates were, on average, 2 percent higher than NOAA's. In the case of Katrina, RMS's method for adjusting property exposure is not able to replicate the significant changes in exposure in New Orleans as a direct result of Hurricane Katrina itself, and consequently the downward adjustment underestimates property exposure in New Orleans in 2005.[6]

## Frequency of Hurricanes

The estimated effects of climate change on the frequency of various categories of hurricanes depend on changes in the climatic conditions affecting hurricane formation (changes in sea surface temperatures, for example) as well as the relationship between those conditions and the occurrence of hurricanes. CBO uses 18 different sets of predictions about the frequency of hurricanes—with each set providing a prediction of the annual frequency of each of the five categories of hurricanes. Those 18 sets include predictions that are based on the following: different concentrations of greenhouse gases in the atmosphere that correspond to different emission scenarios and land-use patterns, different models that link such concentrations to changes in the conditions that cause hurricanes, and different models that predict hurricanes on the basis of changes in those conditions.[7]

The 18 sets of frequency projections that CBO uses include 11 sets that were constructed using a downscaling model developed by Thomas Knutson and 7 sets constructed using a downscaling model constructed by Kerry Emanuel.[8] (The downscaling models estimate regional effects on the basis of output from global climate models.) To avoid having the 11 sets of hurricane frequencies produced by Knutson be more influential than the 7 sets produced by Emanuel—simply because there are more of them—CBO drew from each researcher's hurricane frequencies with a probability of 0.5 for its simulations. Specifically, the probabilities are about 4.5 percent (0.5/11) for each of Knutson's sets and about 7 percent (0.5/7) for each of Emanuel's sets.

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[4] NOAA's method of estimating damage is described in Adam B. Smith and Richard W. Katz, "U.S. Billion-Dollar Weather and Climate Disasters: Data Sources, Trends, Accuracy, and Biases," *Natural Hazards*, vol. 67, no. 2 (June 2013), Table 3, pp. 387–410, http://dx.doi.org/10.1007/s11069-013-0566-5.

[5] This information was provided to CBO by RMS for the purpose of making this comparison. These comparisons were made using RMS's estimate of "ground-up wind and full surge losses," which is the measure that CBO used in its analysis.

[6] Paul Wilson, Risk Management Solutions, personal communication (March 29, 2015).

[7] Land use affects the stock of carbon stored in vegetation. For example, turning forestland into cropland releases carbon that had been stored in the trees and the soil.

[8] See Kerry A. Emanuel, "Downscaling CMIP5 Climate Models Shows Increased Tropical Cyclone Activity Over the 21st Century," *Proceedings of the National Academy of Sciences*, vol. 110, no. 30 (July 2013), pp. 12219–12224, www.pnas.org/content/110/30/12219; and Thomas R. Knutson and others, "Dynamical Downscaling Projections of Twenty-First-Century Atlantic Hurricane Activity: CMIP3 and CMIP5 Model-Based Scenarios," *Journal of Climate*, vol. 26, no. 17 (September 2013), pp. 6591–6617, http://journals.ametsoc.org/doi/abs/10.1175/JCLI-D-12-00539.1.

Knutson and Emanuel both predict hurricane frequencies in future years on the basis of projections of factors that influence storms (such as sea surface temperature and wind shear in the Atlantic Basin). Those projections are derived from a number of different coupled atmosphere-ocean general circulation models (AOGCMs). Those AOGCMs were used in the Coupled Model Intercomparison Project (CMIP), an undertaking in which all models were run using the same set of analyses (for example, making projections on the basis of a specific concentration of greenhouse gases in the atmosphere and reporting results over the same time frames). As a result, CMIP isolates differences in climate outcomes resulting from differences in the models that project such outcomes, rather than differences in the scenarios that the researchers modeled.

Emanuel projected landfalls of hurricanes in the United States on the basis of the results of six individual AOGCMs that were used in the fifth (most recent) CMIP (CMIP5) as well as the "CMIP5 ensemble," which projects landfalls on the basis of hurricane-influencing factors that are obtained by averaging the results of each AOGCM.[9] Knutson estimated hurricane occurrences in the North Atlantic by using projections from the CMIP5 ensemble as well as results from 10 individual AOGCMs used in an earlier phase of the CMIP.[10] CBO translated Knutson's basin-level hurricane projections into U.S. landfalls on the basis of a matrix provided by RMS. For example, that matrix indicates the probability that a Category 4 hurricane that forms in the North Atlantic Basin will make landfall in the United States as a Category 4, 3, 2, or 1 hurricane or that it will diminish to a tropical storm.

Emanuel and Knutson's hurricane projections were derived using different assumptions about concentrations of greenhouse gases in the atmosphere. Specifically, Emanuel used AOGCM results that were based on an assumption of higher concentrations of greenhouse gases in the atmosphere than the model results that Knutson used. Emanuel's landfall projections were based on Representative Concentration Pathway (RCP) 8.5—a concentration of greenhouse gases in the atmosphere projected under a scenario in which both emissions and the conversion of terrain to cropland or pastureland continues to increase over the next century.[11] The global surface temperature, averaged between 2081 and 2100, is projected to increase under the RCP8.5 scenario by 6.7°F (in relation to the average preindustrial temperature).[12] Knutson's projections were based on RCP4.5, which is a concentration that could occur if emissions were to peak in 2040 and then begin to decline after that, and if less terrain was converted to cropland and pastureland than under the RCP8.5 scenario. Researchers estimate that, averaged between 2081 and 2100, global surface temperature would increase by 3.24°F under the RCP4.5 scenario.[13]

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[9] The hurricane projections that Emanuel based on the CMIP5 ensemble results are shown in Kerry A. Emanuel, "Downscaling CMIP5 Climate Models Shows Increased Tropical Cyclone Activity Over the 21st Century," *Proceedings of the National Academy of Sciences*, vol. 110, no. 30 (July 2013), pp. 12219–12224, www.pnas.org/content/110/30/12219. The results from the downscaling of individual AOGCM models were obtained directly from the author and have not yet been published.

[10] Knutson's method and the CMIP5 ensemble results are shown in Thomas R. Knutson and others, "Dynamical Downscaling Projections of Twenty-First-Century Atlantic Hurricane Activity: CMIP3 and CMIP5 Model-Based Scenarios," *Journal of Climate*, vol. 26, no. 17 (September 2013), http://journals.ametsoc.org/doi/abs/10.1175/JCLI-D-12-00539.1. Although Knutson did not project hurricane occurrences on the basis of the output of the individual AOGCM models used in CMIP5, he did so for 10 individual models used in CMIP3 (the third phase of the CMIP). On the basis of advice provided by Knutson, CBO used the percentage variations found between the downscaling of *individual* CMIP3 model results and downscaling CMIP3 *ensemble* results to build an equivalent amount of variation around the CMIP5 ensemble.

[11] See Detlef P. van Vuuren and others, "The Representative Concentration Pathways: An Overview," *Climatic Change*, vol. 109, no. 1 (November 2011), pp. 5–31, http://link.springer.com/article/10.1007%2Fs10584-011-0148-z.

[12] See Intergovernmental Panel on Climate Change, "Summary for Policymakers," in T.F. Stocker and others, eds., *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the IPCC* (Cambridge University Press, 2013), Table SPM.2, p. 23, www.ipcc.ch/report/ar5/wg1/.

[13] Ibid.

## Rising Sea Levels

As the global climate warms, sea levels rise because of the thermal expansion of seawater and the melting of ice sheets in Greenland and Antarctica. The most recent report by the Intergovernmental Panel on Climate Change (IPCC) concluded that sea levels are rising globally, that the rate at which they are rising has increased since preindustrial times, and that the rate will accelerate in this century.[14] Rising sea levels increase damage caused by storm surges; thus, estimated damage from any given category of hurricane increases as sea levels rise. CBO's analysis takes that effect into account by using state-specific predictions of changes in sea level for the three selected future years (2025, 2050, and 2075).

The predictions CBO used were based on data provided by RMS. Specifically, RMS provided estimates at nine specified percentiles of the distributions of rising sea levels for each state and for each decade; CBO interpolated to obtain values for sea level values for 2025 and 2075.[15] (The estimates differ for different states for several reasons, including nonuniform changes in ocean dynamics, heat content, and salinity, as well as variation in the rates of vertical land motion attributable to factors such as tectonics and the withdrawal of local groundwater and hydrocarbons.)[16] The probabilities CBO attached to each of the nine percentiles are shown in Table 1; for example, the 66.7th percentile was chosen with a probability of 0.172, or 17.2 percent of the time. For each simulation, the same percentile was used for all the states.

In turn, RMS based its percentile distributions of rising sea levels by state and decade on predictions provided by climate scientist Robert Kopp.[17] Those predictions were based on alternative assumptions about the concentration of greenhouse gases in the atmosphere (known as representative concentration pathways, or RCPs)—and about changes in rising sea levels for any RCP.[18] For example, the percentiles for rising sea levels combine potential outcomes associated with each of three different RCPs used by the IPCC: RCPs 2.6, 4.5, and 8.5.[19] (As described above, each scenario corresponds to a unique set of assumptions about emissions and land-use patterns.)

[14] See Intergovernmental Panel on Climate Change, "Sea Level Change," Chapter 13 in T.F. Stocker and others, eds., *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the IPCC* (Cambridge University Press, 2013), Figure 13.27, p. 1204, www.ipcc.ch/report/ar5/wg1/.

[15] RMS provided 11 percentiles but had damage functions corresponding to only nine of the percentiles.

[16] See Robert E. Kopp and others, "Probabilistic 21st and 22nd Century Sea-Level Projections at a Global Network of Tide-Gauge Sites," *Earth's Future*, vol. 2, no. 8 (August 2014; corrected, October 2014), pp. 383–406, http://onlinelibrary.wiley.com/doi/10.1002/2014EF000239/full; and National Oceanic and Atmospheric Administration, Tides & Currents, "Frequently Asked Questions" (October 15, 2013), http://tidesandcurrents.noaa.gov/sltrends/faq.htm.

[17] In particular, Kopp provided decade-specific percentile estimates for 79 locations defined by latitude and longitude. RMS then identified the states corresponding to those values. (Paul Wilson, Risk Management Solutions, personal communication, August 30, 2015). The analysis by Kopp and others combines potential outcomes associated with three scenarios about the concentration of greenhouse gases, called representative concentration pathways (RCPs), used by the IPCC: RCPs 2.6, 4.5, and 8.5. Global sea level rise through 2050 is caused primarily by thermal expansion of the ocean and does not differ greatly in the three scenarios. Differences in the RCPs are more important in the second half of the century, when the melting of global ice sheets plays a more significant role.

[18] Global sea level rise through 2050 is caused primarily by thermal expansion of the ocean and is relatively insensitive to changes in emissions. Differences in RCPs begin to be more important in the second half of the century, when the melting of global ice sheets plays a more significant role. See Robert E. Kopp and others, "Probabilistic 21st and 22nd Century Sea-Level Projections at a Global Network of Tide-Gauge Sites," *Earth's Future*, vol. 2, no. 8 (August 2014; corrected, October 2014), pp. 383–406, http://onlinelibrary.wiley.com/doi/10.1002/2014EF000239/full.

[19] For RCPs 2.6, 4.5, and 8.5, the IPCC predicts an increase in global surface temperature, averaged between 2081 and 2100 (and measured relative to pre-industrial levels), of 1°C, 1.8°C, and 3.7°C, respectively. See Intergovernmental Panel on Climate Change, "Summary for Policymakers," in T.F. Stocker and others, eds., *Climate Change 2013: The Physical Science Basis.*

Table 1.
Percentiles and Corresponding Probabilities of Rising Sea Levels

| Percentile Observation for Rising Sea Levels | Probability of Drawing the Percentile Observation |
|---|---|
| 0.5 | 0.017 |
| 5.0 | 0.078 |
| 16.7 | 0.146 |
| 33.3 | 0.172 |
| 50.0 | 0.171 |
| 66.7 | 0.172 |
| 83.3 | 0.146 |
| 95.0 | 0.078 |
| 99.5 | 0.017 |

Source: Congressional Budget Office.

On a global scale, the predictions from Kopp and his colleagues are similar to those found in other assessments. For example, 90 percent of the projections by Kopp and others for the global rise in sea levels by 2100 are between 1 ft. and 4 ft. Similarly, the IPCC's *Fifth Assessment Report* finds that 90 percent of the projections for 2100 lie between 1.2 ft. and 3.2 ft.[20]

# Vulnerability-Weighted Population Estimates for Each State

In its analysis, CBO used projections of population and per capita income as a proxy for property exposure, a method that is consistent with previous research on hurricane damage.[21] CBO first estimated population at the county level. Because growth in some counties (those along the coast, for example) will have a larger effect on the state's expected damage than growth in others (inland ones, for example), CBO weighted each county on the basis of its relative vulnerability to hurricane damage. Those vulnerability-weighted county estimates were then aggregated to the state level. CBO also allows for increases in sea level that substantially increase hurricane damage to slow growth in population (and per capita income, as discussed below).

## Estimates of County Population

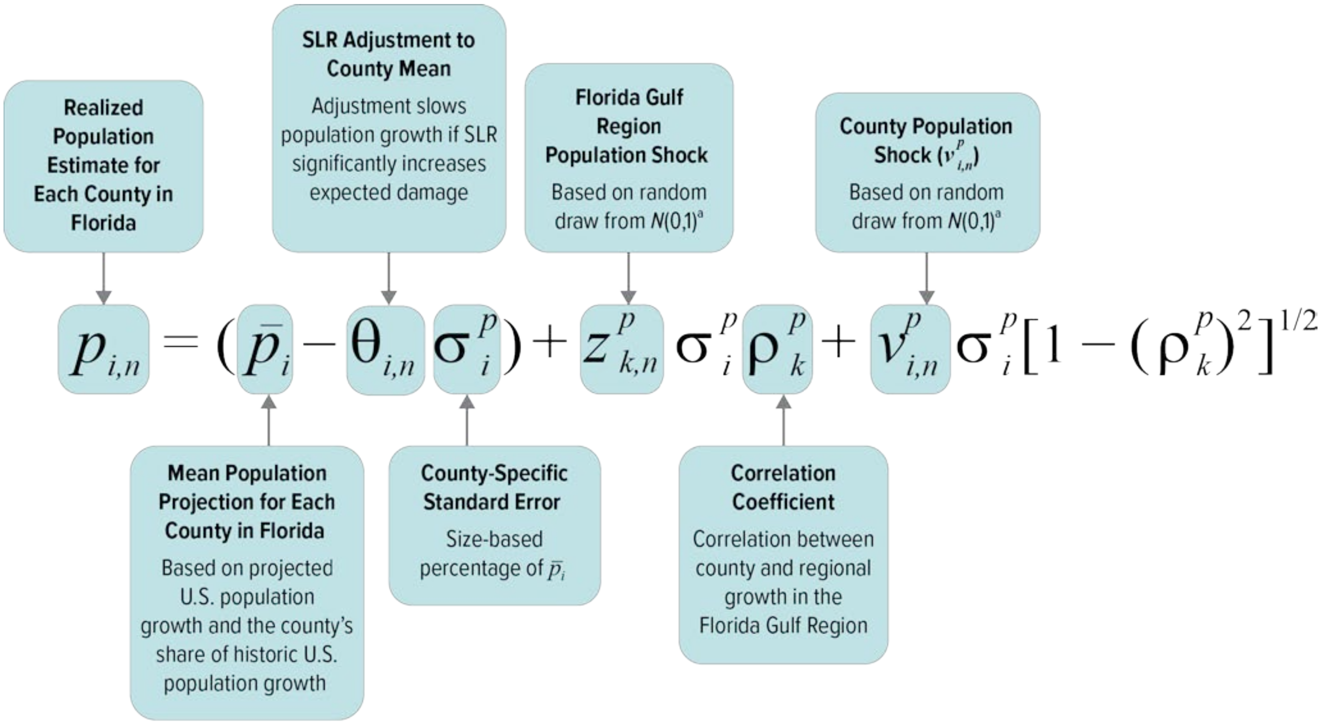
CBO's model incorporated 777 counties, including all counties that were found to have a nonzero probability of incurring hurricane damage (described below). For each simulation, CBO used a county population estimate that was based on a mean projection and on both a regional shock and a county shock, such that the shocks affecting counties within a region had a joint normal distribution (see Figure 3). CBO

*Contribution of Working Group 1 to the Fifth Assessment Report of the IPCC* (Cambridge University Press, 2013), Table SPM.2, p. 23, www.ipcc.ch/report/ar5/wg1/.

[20] The IPCC's "likely" range for sea level rise encompasses 90 percent of the distribution and is compared with the "very likely" range estimated by Kopp and others, which also encompasses 90 percent of the distribution. Although the IPCC projects sea level rise for ranges of years, CBO has used the IPCC's projections of global mean sea level rise in 2100 to best compare with Kopp's results. See Intergovernmental Panel on Climate Change, "Sea Level Change," chap. 13 in T.F. Stocker and others, eds., *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the IPCC* (Cambridge University Press, 2013), Table 13.5, p. 1182, www.ipcc.ch/report/ar5/wg1/.

[21] For further discussion, see Laura A. Bakkensen and Robert O. Mendelsohn, "Risk and Adaptation: Evidence From Global Tropical Cyclone Damages and Fatalities," *Journal of the Association of Environmental and Resource Economics* (forthcoming).

Figure 3.
Applying Random Shocks to Generate County Population Estimates for Each Simulation: Example, Florida




Source: Congressional Budget Office.

SLR = sea level rise.

a. $N(0,1)$ is a standard normal distribution, with a mean of zero and a standard deviation of 1.

adjusted county means on the basis of potential increases in damage in a given state resulting from rising sea levels (allowing significant increases in sea levels) and the associated hurricane damage in that state (to slow the county's population growth):

$$p_{i,n}(\theta_{i,n}, z^p_{k,n}, v^p_{i,n}) = (\bar{p}_i - \theta_{i,n}\sigma^p_i) + z^p_{k,n}\sigma^p_i\rho^p_k + v^p_{i,n}\sigma^p_i[1 - (\rho^p_k)^2]^{1/2}$$

where:

$p_{i,n}$ = county *i*'s estimated population projection in the *n*th simulation

$\theta_{i,n}$ = an adjustment to county *i*'s mean population projection on the basis of the extent to which rising sea levels in the *n*th simulation are estimated to increase damage in the state in which county *i* resides (see a more detailed description of $\theta_{i,n}$ below)

$z^p_{k,n}$ = the draw for the population shock for region *k* (in which county *i* resides) in the *n*th simulation (the shock is obtained from a standard normal distribution)

$v^p_{i,n}$ = the draw for the population shock for county *i* in the *n*th simulation, obtained from a standard normal distribution

$\bar{p}_i$ = county *i*'s mean population projection (a fixed value estimated by CBO, as described below)

$\sigma_i^p$ = the standard deviation of county *i*'s population distribution (a fixed value that is equal to $x\bar{p}_i$, where $x$ = 0.1, 0.11, or 0.12, as described below)

$\rho_k^p$ = the correlation between the historical population growth rate of region *k* and the population-weighted growth rates for the individual counties within the region (a fixed value estimated by CBO, as described below).

**Projections of Mean County Population Growth (Estimates of $\bar{p}_i$).** For all but 26 of the 777 counties, CBO projected their population growth between 2010 and 2040 on the basis of their historic population growth between 2000 and 2010 relative to that of the total U.S. population over the same period. For example, if a county accounted for 1 percent of the growth in the total U.S. population between 2000 and 2010, then CBO estimated that the county would account for 1 percent of the growth in the U.S. population over the forecast period. The total U.S. population growth is based on CBO's macroeconomic forecast.[22] That method preserves the underlying variation in counties' growth rates while ensuring that the county-specific projections are consistent with CBO's aggregate population projection.[23]

CBO chose to project counties' populations on the basis of their growth rates between 2000 and 2010 rather than over a longer historical period because the 777 counties grew very rapidly (relative to the U.S. population as a whole) in the second half of the 20th century, and CBO judged that such a trend was unlikely to continue.[24] Measured between 1950 and 2000, the population-weighted growth rate of the 777 counties in this analysis was more than three times higher than the growth rate of the U.S. population as a whole. Measured over the decade from 2000 to 2010, the populations of the 777 counties still grew faster than that of the United States as a whole, but only 22 percent faster. The relatively rapid population growth of the 777 counties between 1950 and 2000 was fueled, in part, by a significant southern migration prompted by the increased availability of air conditioning; consequently, that growth is unlikely to continue.

For the other 26 counties, CBO instead used county-specific population projections that were made for regional planning purposes.[25] Those projections were made by county or city planning departments, state governments, or state universities. Those 26 counties include:

- The 20 counties with the largest populations in 2010. Specific projections were obtained for those counties since the most populated counties tend to make up a relatively large share of their state's estimated damage.

[22] See Congressional Budget Office, *The 2015 Long-Term Budget Outlook* (June 2015), www.cbo.gov/publication/50250.

[23] This method is called the "share of growth, apportionment method"; see Stanley K. Smith, Jeff Tayman, and David A. Swanson, *State and Local Population Projections: Methodology and Analysis* (Kluwer Publications, 2002), p. 179, www.springer.com/us/book/9780306464928.

[24] Although counties' population growth rates between 2000 and 2010 were influenced by the downturn in the economy during that period, the selection of that decade is unlikely to bias projections made through 2040. In particular, the use of the 2000–2010 growth rates would bias CBO's projections of county growth only if the downturn systematically reduced growth in the 777 counties more, or less, than it reduced population growth in the United States as a whole.

[25] CBO identified sources for county-specific projections from the Census Bureau's list of state-level offices that manage population estimates. See Census Bureau, Federal–State Cooperative for Population Estimates, "FSCPE Contacts," www.census.gov/popest/fscpe/coop.html.

- Six counties that had populations of more than 100,000 and had a difference of two or more percentage points between the average annual growth over the 1950–2010 period and the 2000–2010 period. Those two criteria captured counties, such as the parishes surrounding New Orleans, that had unusual circumstances between 2000 and 2010. (New Orleans experienced a sharp decline in population after Hurricane Katrina in 2005.)

Given the difficulty of knowing whether each coastal county will continue to grow faster or slower than the U.S. total population over the long run, CBO estimates that for 2040 and beyond all 777 counties will grow at the same rate that CBO projects for the United States as a whole.

**Uncertainty About Projections of County Population (Estimates of $\sigma_{i,n}^{p}$).** Given the uncertainty about population growth, CBO estimated each county's future population as a normal distribution with a mean estimated by the process described above and a standard deviation equal to a percentage of its population. Specifically, CBO estimated standard deviations equal to:

- 10 percent of the population for counties with populations greater than 100,000
- 11 percent of the population for counties with populations of 50,000 to 100,000
- 12 percent of the population for counties with populations less than 50,000

Those estimates of standard deviations are based on a study conducted by Stanley K. Smith and others.[26] Standard deviations are likely to be larger for smaller cities because a given change in population (for example, if the opening of a new manufacturing plant attracted 5,000 new residents) corresponds to a larger share of the existing population of a small city than of a larger one.

**Correlation in Growth Between Counties and the Region in Which They Reside (Estimates of $\rho_{k}^{p}$).** CBO's estimates of each county's population include its own population shock and a regional shock, each of which are determined by random draws from a standard normal distribution. That method was chosen after exploring the extent to which adjoining counties' decade-specific growth rates—that is, growth during each decade from 1950 to 2010—were correlated, and whether growth rates in adjoining states were correlated. (CBO's examination of correlation between adjoining counties focused primarily on Florida, which accounted for more than half of estimated damage in the reference case.) That analysis revealed no clear pattern of correlation in growth between adjoining counties within a state but indicated distinct patterns of correlation between growth for clusters of states along the Gulf and East Coasts.

On the basis of that analysis, CBO defined four regions for the purpose of projecting population growth and estimated a correlation coefficient, $\rho_{k}^{p}$, for each region:[27]

- Florida Gulf (Alabama, Florida, Louisiana, Mississippi, and Texas)—$\rho^{p}$ = 0.287
- Southern Coastal (Georgia, North Carolina, and South Carolina)—$\rho^{p}$ = 0.184
- Mid-Atlantic and Northern (Connecticut, Delaware, Maryland, Massachusetts, New Jersey, New York, Pennsylvania, Rhode Island, Virginia, and West Virginia, as well as Washington, D.C.)—$\rho^{p}$ = 0.149
- Far Northern (Maine, New Hampshire, and Vermont)—$\rho^{p}$ = 0.469.

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[26] See Stanley K. Smith, Jeff Tayman, and David A. Swanson, *State and Local Population Projections: Methodology and Analysis* (Kluwer Academic Publishers, 2002), Table 13.3, p. 317, www.springer.com/us/book/9780306464928.

[27] The values for $\rho_{k}^{p}$ were obtained by regressing each county's decade-specific population growth rate (for each decade between 1950 and 2010) against the decade-specific population growth rate for the region in which the county resides. Each county's decade-specific growth rate was weighted by its population in that decade.

**Adjustment to County Population Means on the Basis of Rising Sea Levels (Estimates of $\theta_{j,n}$).** CBO accounts for the potential for rising sea levels—and the resulting rise in expected hurricane damage from storm surges—to slow population growth in vulnerable states. Specifically, CBO adjusted each county's estimated mean population on the basis of the estimated increase in expected damage from storm surges for the state in which that county resides. The quantitative effect of expected damage associated with rising sea levels (or even of actual hurricane damage) on population growth is unknown. The adjustment used here incorporates a threshold effect: A rise in sea level must increase the state's expected hurricane damage by at least 25 percent before its counties' population means are adjusted. The adjustment also has an upper bound: It cannot reduce mean population estimates by more than a specified amount, set here at 1 standard deviation from the unadjusted mean.

The adjustment factor, $\theta_{j,n}$, reduces the county's mean population estimate, $\bar{p}_i$, if the rise in sea level in the state *j* (in which county *i* resides) increases state *j*'s damage in the *n*th simulation by more than 25 percent relative to its damage in the reference case. For each state *j*:

$$\theta_{j,n}$$

$$= 0; \text{ if } \Delta\hat{d}_{j,n} \leq 0.25,$$

$$= \min(1, \Delta\hat{d}_{j,n}); \text{ if } \Delta\hat{d}_{j,n} > 0.25,$$

where:

$$\Delta\hat{d}_{j,n} = \frac{D_j\left(f_R, s_{j,n}, p_{j,R}, y_{j,R}\right)}{D_j\left(f_R, s_{j,R}, p_{j,R}, y_{j,R}\right)} - 1$$

For example:

$$\text{if } \Delta\hat{d}_{j,n} = 0.5, \text{ then } \theta_{j,n} = 0.5$$

$$\text{if } \Delta\hat{d}_{j,n} = 1.2, \text{ then } \theta_{j,n} = 1.$$

On the basis of that adjustment factor, county *i*'s mean population, $\bar{p}_i$, would be set at 1 standard deviation below the unadjusted mean if the sea level draw in the *n*th simulation (holding all other variables at their reference levels) led to at least a doubling of estimated damage in the state in which county *i* is located. For example, if the draw for sea levels in the *n*th simulation increased expected damage in Florida by at least 25 percent (relative to Florida's expected damage in the reference case), then the mean population estimates of all the counties in Florida would be reduced in that *n*th simulation.

## Estimates of Vulnerability-Weighted County Populations

Development in each state will probably increase the damage caused by a given storm; however, the effect on hurricane damage depends on where the development occurs. Development in counties that are relatively vulnerable to hurricane damage will increase their state's damage estimate more than development in counties that are relatively invulnerable to such damage. To measure the effect of each county's development on its state's estimated damage, CBO weighted each county's growth in population and per capita income on the basis of its vulnerability to damage from storm surges and wind damage:

$$\ddot{p}_{i,n} = p_{i,n}[\lambda_i(1 - w_j) + \gamma_i w_j]$$

where:

$\ddot{p}_{i,n}$ = vulnerability-weighted population of county *i* in the *n*th simulation

$\lambda_i$ = the weight used to indicate vulnerability of county *i* (in state *j*) to storm surge damage relative to all other counties in state *j*

$(1 - w_j)$ = share of damage in state *j* that comes from storm surges (as opposed to wind)

$\gamma_i$ = the weight used to indicate vulnerability of county *i* (in state *j*) to wind damage relative to all other counties in state *j*

$w_j$ = share of state *j*'s damage that comes from wind (as opposed to storm surges).

**Surge Damage Weights.** CBO's surge damage weight for each county $i$, in state $j$, is equal to the probability-weighted loss ratio from storm surges in county $i$, relative to the total of such probability-weighted losses, summed across all counties in state $j$ (in which county $i$ resides):

$$\lambda_i = \frac{\sum_{c=1}^{5} m_i(c) q_j(c)}{\sum_{i=1}^{I_j} \sum_{c=1}^{5} [m_i(c) q_j(c)]}$$

where:

$m_i(c)$ = storm-surge loss ratio in county *i* (in state *j*), given that a hurricane of Category *c* imposes losses on state *j*

$q_j(c)$ = probability that a hurricane of Category *c* occurs and imposes losses on state *j*. CBO used estimates of $q_j(c)$ generated by RMS's Hurricane Model (see above description)

$I_j$ = the number of counties in state *j*.

The maximum potential total building losses in county $i$—given an occurrence of a Category $c$ hurricane—divided by estimates of the total value of the buildings in the county is equal to $m_i(c)$. CBO calculated each county's loss ratio by using data from the Federal Emergency Management Agency's (FEMA) Coastal Flood Loss Atlas (CFLA), version 3.0, which FEMA developed using the Hazus loss estimation model.[28]

In essence, the weight $\lambda_i$ is county $i$'s share of the total increase in probability-weighted damage from storm surges that state $j$ would experience if an additional $1 of property was added to each county in the state. For example, the weight for Rockingham, New Hampshire, is 0.79, indicating that it accounts for 79 percent of the total additional expected storm-surge damage that New Hampshire would incur if $1 of additional property was added to each county in the state. In contrast, Hillsborough, New Hampshire (which is land-locked), has a zero weight, indicating that adding more property to Hillsborough would not increase expected storm-surge damage in New Hampshire. Surge weights for all the counties in any given state sum to one; that is, $\sum_{i=1}^{I_j} \lambda_i = 1$.

[28] Version 3.0 of FEMA's CFLA combines the National Hurricane Center's SLOSH model, which models storm-surge heights, with FEMA's Hazus model, which is a regional multihazard loss-estimation model. CBO used an output attribute (C#_BLDG_LR) from the CFLA for building loss ratios. Those loss ratios represent total damage to buildings divided by actual building valuations for each county modeled in a worst-case "maximum of maximums" storm-surge scenario. Although those loss ratios are based on worst-case scenarios, they are useful for identifying each county's relative contribution to the potential damage that could occur in its state. For more information on the CFLA and the Hazus-MH Coastal Flood Model, see H.E. Longenecker and others, "Hazus-MH Coastal Flood Model: FEMA Region IV Standard Operating Procedure for Coastal Flood Hazard and Loss Analysis" (FEMA Region IV, updated August 2012), http://tinyurl.com/zde3hos (PDF, 13.4 MB).

State $j$'s share of damage that comes from storm surges, as opposed to wind—$(1 - w_j)$—is calculated on the basis of data provided by RMS that indicates the breakdowns of state-specific damage in the reference case. Each state's total damage is attributed either to storm-surge damage or to wind damage.

**Wind Damage Weights.** CBO's wind damage weight for each county $i$, in state $j$, is equal to the probability-weighted wind loss ratio in county $i$, relative to the total of such probability-weighted losses, summed across all counties in state $j$:

$$\gamma_i = \frac{\sum_{c=1}^{5} h_i(c) q_j(c)}{\sum_{i=1}^{I_j} \sum_{c=1}^{5} [h_i(c) q_j(c)]}$$

where:

| | | |
|---|---|---|
| $h_i(c)$ | = | loss ratio due to wind damage in county *i* of state *j*, given U.S. landfall of a hurricane of Category *c*. |

CBO used two sources in generating estimates of $h_i(c)$. Maps of sustained surface wind speeds produced by the National Hurricane Center (NHC) were used to identify the maximum winds each county would be expected to experience if a hurricane in Category *c* made landfall along its state's coastline.[29] (To calculate that maximum, CBO assumed that the hurricane made landfall at the section of the coast closest to the county.) Relationships between wind speed and damage were derived from FEMA's Hazus loss-estimation model. Those relationships, termed wind loss ratios, indicate a county's maximum building damage as a share of its total building valuations for a given wind speed.[30] The estimated ratios indicate that losses increase more than proportionately as wind speeds increase; for example, Category 3 wind speeds, averaging 120 mph, resulted in an average loss ratio of 0.13; Category 4 wind speeds, averaging 143 mph, resulted in an average loss ratio of 0.44.

As was the case for the surge weight, the wind weight calculated for county $i$, $\gamma_i$, is equal to $i$'s share of the total increase in state $j$'s probability-weighted wind damage that would occur if $1 of additional property was added to each county in the state. For example, Rockingham, New Hampshire, had a wind weight of 0.35, indicating that it would account for 35 percent of the total increase in expected wind damage that New Hampshire would experience under those circumstances. Wind weights for all the counties in any given state sum to 1; that is, $\sum_{i=1}^{I_j} \gamma_i = 1$.

## Aggregating Vulnerability-Weighted County Population Estimates to the State Level

Each state's vulnerability-weighted population is simply the sum of the vulnerability-weighted populations of the counties within it:

$$\ddot{p}_{j,n} = \sum_{i=1}^{I_j} \ddot{p}_{i,n}$$

[29] NHC's maps of sustained surface wind speeds are available online at National Oceanic and Atmospheric Administration, National Hurricane Center, "The Inland Wind Model and the Maximum Envelope of Winds," (January 20, 2016), www.nhc.noaa.gov/aboutmeow.shtml.

[30] CBO used building loss ratios generated by running the Hazus Hurricane Model and selecting only for wind damage. The loss ratios sustained in a particular location were correlated with the maximum wind speeds experienced at that location to produce a wind-speed-to-damage curve. For more information on the Hazus Hurricane Model and wind damage curves, see Department of Homeland Security, Federal Emergency Management Agency, "Hurricane Model Technical Manual," *Hazus—MH 2.1: Technical Manual* (January 2015), www.fema.gov/media-library/assets/documents/24609.

where:

| | | |
|---|---|---|
| $\ddot{p}_{j,n}$ | = | the vulnerability-weighted population of state *j* in the *n*th simulation. |

# Estimates of Vulnerability-Weighted State per Capita Income

CBO projected each state's per capita income by using the same method that was used to project the state's population. Counties' per capita incomes were projected on the basis of a mean projection and both regional- and county-level shocks, such that the shocks affecting counties within a region have a joint normal distribution. Mean per capita income estimates were adjusted on the basis of increases in hurricane damage, and county estimates were weighted on the basis of their relative vulnerability to wind and storm-surge damage as well as the state's share of damage from wind and storm surges. County estimates were aggregated to obtain state totals.

## Estimates of County per Capita Income

For each simulation, CBO calculated a unique estimate of per capita income for each county:

$$y_{i,n}\left(\theta_{i,n}, z^{y}_{k,n}, v^{y}_{i,n}\right) = (\bar{y}_i - \theta_{i,n}\sigma^{y}_{i}) + z^{y}_{k,n}\sigma^{y}_{i}\rho^{y}_{k} + v^{y}_{i,n}\,\sigma^{y}_{i}[1 - (\rho^{y}_{k})^2]^{1/2}$$

where:

| | | |
|---|---|---|
| $y_{i,n}$ | = | county *i*'s estimated per capita income projection in the *n*th simulation |
| $\theta_{i,n}$ | = | an adjustment to the projection of county *i*'s mean per capita income on the basis of the extent to which sea level rise in the *n*th simulation is estimated to increase damage (same factor used for $p_{i,n}$) |
| $z^{y}_{k,n}$ | = | the draw for the per capita income shock to region *k* (containing county *i*) for the *n*th simulation of the model, obtained from a standard normal distribution |
| $v^{y}_{i,n}$ | = | the draw for the per capita income shock for county *i* in the *n*th simulation, obtained from a standard normal distribution |
| $\bar{y}_i$ | = | county *i*'s mean population projection |
| $\sigma^{y}_{i}$ | = | the standard deviation of county *i*'s per capita income distribution (a fixed value equal to $0.11\bar{y}_i$, as described below) |
| $\rho^{y}_{k}$ | = | the correlation between the historical per capita income growth rate of region *k* and the population-weighted population growth rates for the individual counties within the region *R*. |

**Mean Projections (Estimates of $\bar{y}_{i,n}$).** Because county-level projections of per capita income growth through 2075 are not available, CBO modeled each county's mean per capita income as growing (through 2040) at a weighted average of:

- Its growth rate between 1990 and 2000 (the decade preceding the recession),
- Its growth rate between 2000 and 2010, which reflects the effects of the recession and is the most recent decade for which census data are available, and
- The growth rate CBO projected for the United States as a whole.

Specifically, each of the county's two historic growth rates was assigned a weight of 0.1, and the U.S. growth rate was assigned a weight of 0.8. That method allows each county's historic growth to influence its future growth but also ensures a degree of consistency between the growth rates of the counties included in this analysis and the rate of growth that CBO projects for the United States as a whole. As was the case with estimates of population growth, CBO projected that, after 2040, each county's per capita income would grow at the same rate as that projected for the United States as a whole.

**Uncertainty About Projections of per Capita Income (Estimates of $\sigma^{y}_{i,n}$).** CBO estimated a distribution of county-level per capita income by using a standard deviation set at 11 percent of each county's mean per capita income; that is, $\sigma_{i,n} = 0.11\overline{y_{i,n}}$. Because the economic literature does not provide estimates of the uncertainty surrounding county-level income projections, CBO chose to use the same standard deviation that was used for estimates of the population growth of midsized counties (those with populations of 50,000 to 100,000).

**Correlation in Growth Between Counties and the Region in Which They Reside (Estimates of $\rho^{y}_{k}$).** CBO estimated correlation coefficients between the growth in counties' per capita income and growth in the per capita income of the region in which they reside. That correlation was estimated for the same four regions used in estimating population growth (described above). Specifically, CBO estimated $\rho^{y}_{k}$ for each region:[31]

- Florida Gulf—$\rho^{y}$ = 0.727
- Southern Coastal—$\rho^{y}$ = 0.794
- Mid-Atlantic and Northern—$\rho^{y}$ = 0.504
- Far-Northern—$\rho^{y}$ = 0.810.

**Adjustment to Counties' Mean per Capita Income on the Basis of Rising Sea Levels.** CBO adjusted each county's mean per capita income by using the same adjustment variable, $\theta_{j,n}$, that was used to adjust its mean population. As described above, that adjustment incorporates a threshold effect: A rise in sea level must increase a state's hurricane damage by at least 25 percent before its counties' mean per capita incomes are affected. The adjustment also has an upper limit: If the draw for rising sea levels in the *n*th simulation causes a state's damage to double (or more than double), its counties' mean per capita incomes used in the *n*th simulation will be decreased by only 1 standard deviation.

## Estimate of Vulnerability-Weighted per Capita Income for Each County

As was the case with estimates of county population, CBO weighted each county's per capita income to reflect the county's relative vulnerability to damage from storm surges and from wind, as well as the fraction of the state's total damage that is attributed to storm surges versus wind. Specifically, CBO estimated each county's vulnerability-weighted per capita income as:

$$\ddot{y}_{i,n} = y_{i,n}[\lambda_i(1 - w_j) + \gamma_i w_j]$$

[31] The values for $\rho^{y}_{k}$ were obtained by regressing each county's decade-specific per capita income growth rate (for each decade between 1960 and 2000) against the decade-specific per capita income growth rate for the region in which the county resides. Each county's decade-specific growth rate was weighted by its population in that decade.

where:

| | | |
|---|---|---|
| $\ddot{y}_{i,n}$ | = | vulnerability-weighted per capita income of county *i* in the *n*th simulation |
| $\lambda_i, \gamma_i, w_j$ | = | the same weights that are used to estimate vulnerability-weighted population of county *i* in the *n*th simulation. |

### Aggregating Estimates of Counties' Vulnerability-Weighted per Capita Income to the State Level

Projections of vulnerability-weighted per capita income for each state $j$ are calculated as the sum of the estimates of population- and vulnerability-weighted county per capita income:

$$\ddot{y}_{j,n} = \sum_{i=1}^{I_j} \frac{\ddot{p}_{i,n}}{\ddot{p}_{j,n}} \ddot{y}_{i,n}$$

where:

| | | |
|---|---|---|
| $\ddot{y}_{j,n}$ | = | the vulnerability-weighted per capita income in state *j* in the *n*th simulation. |

## Elasticities

Estimates of hurricane damage are sensitive to assumptions about how much hurricane damage will increase in response to increases in population and per capita income in vulnerable areas. Information on the elasticity of hurricane damage with respect to socioeconomic variables—that is, the percentage change in damage given a percentage change in population or per capita income—is limited.[32] Some studies, such as one conducted by Roger A. Pielke and others, assume an elasticity of 1, implying that a doubling of both income and population would lead to a quadrupling of damage. Similarly, in a study published in 2010, William Nordhaus assumed that damage is proportionate to gross domestic product.[33] In contrast, Robert Mendelsohn and others estimated the global income elasticity of damage as 0.42 and the population damage elasticity as –0.2.[34] More recent work by Laura Bakkensen and Robert Mendelsohn found that the United States had significantly different elasticities from those of other countries:[35]

- *Responses to Increases in Population*. Bakkensen and Mendelsohn found no evidence that increases in population led to increases in wind damage in the United States (an elasticity of 0). In contrast, they found evidence of adaptation by countries in the Organization for Economic Co-operation and Development (OECD; excluding the United States) with respect to population growth (a statistically significant elasticity of less than 1).

[32] See Laurens Bouwer, "Projections of Future Extreme Weather Losses Under Changes in Climate and Exposure," *Risk Analysis*, vol. 33, no. 5 (May 2013), pp. 915–930, www.ncbi.nlm.nih.gov/pubmed/22958147.

[33] See Roger A. Pielke Jr. and others, "Normalized Hurricane Damage in the United States: 1900–2005," *Natural Hazards Review*, vol. 9, no. 1 (February 2008), www.nhc.noaa.gov/pdf/NormalizedHurricane2008.pdf (1.75 MB); and William D. Nordhaus, "The Economics of Hurricanes and Implications of Global Warming," *Climate Change Economics*, vol. 1, no. 1 (May 2010), www.worldscientific.com/doi/abs/10.1142/S2010007810000054.

[34] See Robert Mendelsohn and others, "The Impact of Climate Change on Global Tropical Cyclone Damage," *Nature Climate Change*, vol. 2 (2012), pp. 205–209, www.nature.com/nclimate/journal/v2/n3/abs/nclimate1357.html.

[35] See Laura A. Bakkensen and Robert O. Mendelsohn, "Risk and Adaptation: Evidence From Global Tropical Cyclone Damages and Fatalities," *Journal of the Association of Environmental and Resource Economics* (forthcoming).

- *Responses to Increases in Per Capita Income*. Bakkensen and Mendelsohn estimated that hurricane damage in the United States increased more than proportionately to increases in per capita income (an elasticity estimate of 1.15). In contrast, they found a statistically significant per capita income elasticity of less than 1 for non-OECD countries.

The elasticities estimated in the studies described above reflect both intentional and unintentional changes in the vulnerability of communities to damage as population and per capita income increase. For example, as population increases, buildings may be constructed closer to each other (reducing vulnerability to wind damage) or the use of multistory housing may increase (reducing the vulnerability to storm surges). Likewise, as per capita income increases, buildings may be better built, owners may take measures to reduce vulnerability, or communities may invest in coastal protection by constructing levees.[36]

CBO allowed wind and storm-surge damage to each have unique responses to changes in population and per capita income. CBO's elasticity estimates were informed by the estimates of Bakkensen and Mendelsohn (the only study that estimated elasticities explicitly for the United States). However, CBO modified Bakkensen and Mendelsohn's elasticities because the reliability of their estimates is likely to be limited by the size of their data set: They had 110 observations for the United States.[37] As described in this working paper's companion report, CBO examined the sensitivity of its damage estimates to the elasticities used in this analysis.

- *Storm-Surge Damage*. CBO estimated that storm-surge damage would increase less than proportionately to increases in per capita income (an elasticity of 0.75) and to increases in population (an elasticity of 0.5).
- *Wind Damage*. CBO estimated that wind damage would increase proportionately with increases in per capita income (an elasticity of 1) and less than proportionately with increases in population (an elasticity of 0.25).

CBO anticipates that damage from storm surges would increase less in response to increases in per capita income (an elasticity of 0.75) than would damage from wind (an elasticity of 1.0) because higher per capita income could motivate either public or private entities to invest in infrastructure (such as seawalls) that is designed to limit damage from storm surges. In contrast, CBO expects that damage from storm surges would respond more to increases in population (an elasticity of 0.5) than would wind damage (an elasticity of 0.25). Unlike with wind damage, increases in population density would not necessarily provide protection from storm-surge damage: Increasing the number of single-story buildings in a given area would probably result in a proportional increase in the amount of damage from storm surges. However, increases in damage from storm surges would be less than proportional to increases in population to the extent that increased population led to the construction of taller buildings or of public infrastructure designed to limit damage from storm surges. To reflect the fact that potential differences in

[36] One study concludes that the global cost of flooding caused by rising sea levels is likely to be greater than the cost of building levees to avoid such damage. Further, the authors find that flood damage by the end of the century is more sensitive to the applied protection strategy than it is to variations in climate and socioeconomic scenarios. See Jochen Hinkel and others, "Coastal Flood Damage and Adaptation Costs Under 21st Century Sea-Level Rise," in *Proceedings of the National Academy of Sciences*, vol. 111, no. 9 (March 2014), www.pnas.org/content/111/9/3292.abstract. Even when measures are cost-effective, some researchers suggest that they may not be undertaken because they address low-level risks that may be overshadowed by other issues. Moreover, some researchers suggest that adaptive measures, such as the construction of seawalls, may inadvertently increase damage from extreme events. For example, by offering protection from less damaging (but more frequent) hurricanes they may encourage development and thus increase damage from less frequent but stronger Category 4 and 5 storms. (For a discussion of those points, see a literature review by Carolyn Kousky, "Informing Climate Adaptation: A Review of the Economic Costs of Natural Disasters," *Energy Economics*, vol. 46 (November 2014), pp. 576–592, www.sciencedirect.com/science/article/pii/S0140988313002247.

[37] Based on personal communication with Laura Bakkensen.

storm damage would depend on whether population growth led to the construction of more single-story homes or taller buildings, CBO used an elasticity of 0.5.

According to the elasticities described above, doubling both population and per capita income would result in a 125 percent increase in damage from both wind and storm surges. A specific set of elasticities is calculated for each state on the basis of the shares of today's estimated damage that are caused by wind and storm surges. Thus,

$$\epsilon_j^p = 0.5(1 - w_j) + 0.25 w_j$$

$$\epsilon_j^y = 0.75(1 - w_j) + w_j$$

where:

| | | |
|---|---|---|
| $\epsilon_j^p$ | = | percentage increase in damage in state *j*, given a percentage increase population |
| $\epsilon_j^y$ | = | percentage increase in damage in state *j*, given a percentage increase in per capita income |
| $(1 - w_j)$ | = | the share of total damage in state *j* that comes from storm surges |
| $w_j$ | = | the share of total damage in state *j* that comes from wind. |