Quantifying the Impact from Climate Change on U.S. Hurricane Risk

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Executive Summary

The purpose of this paper is to explore how climate change may affect hurricane risk in the United States, specifically related to damage to residential and commercial properties. The work follows on from related AIR publications that consider the climatic effects on atmospheric perils responsible for multiple billion-dollar disasters that occur annually around the world.

Climate change is expected to have significant impacts on hurricane activity in the United States, primarily through an increase in sea surface temperatures. While climate change is likely to affect hurricanes in multiple ways, we focus on two aspects: an increase in the frequency of the strongest storms, and additional storm surge flooding due to sea level rise. We assume a “business-as-usual” climate warming by mid-century, corresponding to the Intergovernmental Panel on Climate Change (IPCC) Representative Concentration Pathway (RCP) 8.5 scenario, which assumes little progress in reducing greenhouse gas emissions over the next 30 years.

The analysis relies on the AIR Hurricane Model for the United States, which considers wind, storm surge, and precipitation-induced flooding, and AIR’s database of property exposure. The model features a catalog of simulated hurricane seasons, with each season containing some number of events (frequency) of different strength (severity) at landfall. The baseline catalog is developed to reflect today’s climate, and we describe a technique by which we create a new set of catalogs to reflect the future climate state. From available literature and our own analysis, we assume a target state with an increased frequency of Category 3, 4, and 5 storms of 15%, 25%, and 35%, respectively, with frequencies of other storms held to today’s values.

In the second half of the paper, we explore future hurricane-generated storm surge losses for selected study areas around New York, Houston, and Miami, as indicators of the additional risk created by rising sea levels. In this case we rely on regional projections of sea level rise that incorporate a range of outcomes for each emissions scenario, with estimated probabilities of exceedance for each geographic location. To capture a range of outcomes, we select two sea level estimates corresponding to the RCP 8.5 pathway: one that is almost certain to be surpassed; and one that is less likely but still plausible, based on the current understanding of the ice-sheet loss.

The results of the analysis show that increased event frequency and sea level rise will have a meaningful impact on future damage. The growth in the number of stronger storms, and landfalling storms overall, increases modeled losses by approximately 20%, with slightly larger changes in areas such as the Gulf and Southeast coasts where major landfalls are already more likely today. The loss increases extend to inland areas as well, as stronger storms may penetrate farther from the coast.

The impacts from sea level rise, using the analysis of storm surge for New York, Miami, and Houston suggests that by 2050, sea level rise may increase storm surge losses by anywhere from one-third to almost a factor of two, with larger impacts possible when combined with increases in the number of major storms. The results suggest that an extreme surge event in today's climate may be twice as likely to happen 30 years from now.

The actual loss estimates will undoubtedly be higher; while the analysis holds property exposure constant at today's levels, coastal exposure is currently growing at a 4% annual rate and are likely to continue growing. Higher concentrations of property and wealth along the coast have been and will continue to be a significant factor in U.S. hurricane risk.

With more intense hurricanes making landfall, and storm surges on top of a higher sea level, the results presented here reflect only part of the story. Additional research into a wider range of impacts is necessary to complete what is surely a more complex picture, particularly related to how risk may change geographically. Critical factors include whether the strongest storms become not only more frequent, but also more intense; whether storms could remain stronger at higher latitudes; how much additional rainfall hurricanes might produce, and whether storms are slowing down at landfall and maintaining intensity longer after landfall. Accounting for the full range of impacts for coastal and inland areas is important to identify how populations will be affected and how public policy might adapt to address what is likely to be a widening insurance protection gap.

The modeling tools and data presented here can be extended for additional perils, including inland flooding, wildfires, and convective and extratropical storms. While there is considerable uncertainty in how extreme event risk may evolve in a warmer climate, these models are a practical approach to assessing the potential impacts.

Introduction

According to the National Centers for Environmental Information, tropical cyclone losses have dominated the distribution of billion-dollar weather disasters in the United States since 1980. These events have the highest average event cost at over USD 20 billion per event, and hurricanes are responsible for the 5 largest and 7 of the 10 largest natural disasters during that time (NOAA, 2020).

In 2017, AIR released a comprehensive assessment of the role that climate change may play in shaping future disasters. The goal of the paper, “Climate Change Impacts on Extreme Weather” (Sousounis and Little 2017) was to bring a risk-based mindset to the challenge of climate change’s effects on atmospheric perils responsible for multiple billion-dollar disasters that occur annually around the world. In this paper, we focus on potential hurricane impacts in the United States and quantify the degree to which damage and loss may increase due to climate change.

A series of above-average and costly hurricane seasons in recent years has led to questions about whether climate change is fueling increased hurricane activity in the North Atlantic Ocean Basin. An average of nearly 15 named storms have occurred each year between 2011 and 2019, a 25% increase over the climatological average of the previous 30 years (CPC, 2020). While studies by Klotzbach *et al*. (2018) and others have shown no significant trend in landfalling hurricane frequency or severity over longer time horizons (since 1900), studies focused on more recent periods suggest a shift may be under way (Kossin, et al., 2020). There is no doubt that observed large increases in hurricane damage are due to increased population and wealth along the U.S. coastline, but it is interesting to consider what role increased hurricane activity could play in the future.

This paper considers this question in several ways. Using the AIR Hurricane Model for the United States and a robust estimate of property exposure in hurricane-affected states, we explore the potential effects of climate change on U.S. hurricane risk and the resulting impacts on estimated damage and loss for a fixed set of residential and commercial exposure. By holding exposure constant, we isolate the impacts due to hurricane wind, storm surge, and hurricane-induced precipitation in a mid-century, “business-as-usual” climate scenario. We also consider plausible impacts of sea level rise on storm surge by considering multiple scenarios for three study areas around the cities of Houston, Miami, and New York City.

The analyses are designed to quantify the impacts under the selected scenarios; however, it is important to recognize the uncertainty inherent in the approach. As a result, we focus on one potential impact of climate change on hurricanes (i.e., changes to frequency and severity) and include discussion of the variability in these estimates on the nationwide, regional, and county-level loss estimates. We also include discussion of uncertainty in the sea level rise estimates on the storm surge scenarios for the three study areas. The goal of this paper is to explore the potential contribution of some aspects of climate change on U.S. hurricane damage, recognizing that many pieces of the puzzle remain to be joined to see the whole picture.

Our paper is organized as follows. First, we review the science behind climate change impacts to hurricanes and identify the elements used in this study. Second, we present an overview of the modeling methodology and describe adjustments to the model to simulate the climate change effects. Third, we provide a brief summary of the models and exposure data used to develop the loss estimates. The results are presented in two ways: first for hurricane-affected states considering wind, storm surge, and precipitation; and then for the three selected study areas considering the effects of sea level rise on storm surge. The paper concludes with observations and describes potential areas for future work.

Impacts of Climate Change on Hurricane Frequency and Severity

Climate change is expected to have significant impacts on hurricane activity in the U.S. This section describes what is and is not known about climate change influences and the expected impacts. This section also describes the methodology used to reflect that activity from a catastrophe modeling perspective for the current study.

Background

The primary mechanism through which climate change may influence hurricanes is through an increase in sea surface temperature (SST), adding more energy particularly in the regions of the Atlantic where hurricanes form and travel toward land. In addition, a warmer atmosphere holds more water vapor, which may increase the amount of rain that storms produce.

While the basic driver of hurricane activity is SST, hurricane development also depends on the atmosphere's response to local SST changes. Other ingredients such as vertical wind shear, mid-level moisture, large-scale subsidence, and degree of environmental stability are all important for influencing frequency, intensity, size, forward speed, and trajectory. In the current climate, these influences are demonstrated by the significant interannual variability of hurricane activity both over the Atlantic and for U.S. landfalls. The Atlantic Multidecadal Variability (AMV), or Atlantic Multidecadal Oscillation (AMO), as it is also called, which manifests as anomalous sea surface temperature, the El Niño-Southern Oscillation, Saharan dust, and the Madden Julien Oscillation (MJO) are some of the large-scale drivers that currently influence Atlantic Basin hurricane activity. Understanding the degree to which climate change has already had an impact is therefore challenging, but not impossible.

Some very recent results suggest that there has been a significant increase in intense hurricane activity (e.g., Category 4 and 5 storms) since the late 1970s, which roughly coincides with the beginning of the high-resolution satellite era (Kossin, et al., 2020). This finding is consistent with results from General Circulation Models (GCMs). For years now, GCMs have indicated that climate change would likely have a notable impact on hurricane intensity—not only in terms of *more* Category 4 and 5 storms, but also in terms of the strongest storms becoming *stronger* (the

Lifetime Maximum Intensity or LMI is one such metric); storms remaining stronger for *longer* periods of time; and stronger storms being found *farther north* in the Atlantic Basin. All these projected impacts stem more or less directly from expected continued increase of ocean warming, especially farther north.

Uncertainty in Expected Results

Despite the consensus on the qualitative impact on hurricane intensity, there is a very wide range of expected results in terms of the extent to which (if at all) the frequency of the more severe storms will change. It is important to distinguish between the phrases "an increase in the frequency of," and "an increase in the proportion of." The former indicates an increase in number; the latter reflects an increase in the fraction of storms of a certain strength relative to storms of all strengths. There is more agreement that the latter will occur because there is more agreement that the total number of tropical cyclones will decrease, primarily because the number of weak storms is expected to decrease. Very recently, however, there has been some additional evidence that the total number of tropical cyclones may increase (Lee et al., 2020), and thus there is even more uncertainty regarding how the total number will change.

Other aspects of hurricane activity that are important from a damage perspective in the U.S. include where storms will make landfall; how large their wind field and precipitation shield will be; whether they will move more slowly once they make landfall, as Hurricane Harvey (2017) and Hurricane Florence (2018) did; and whether they will continue to weaken more slowly after landfall as has been shown recently by Li and Chakraborty (2020). Unfortunately, there is even less certainty regarding how these aspects may change (Knutson et al., 2020). Thus, for the purposes of this study, we focus on future hurricane activity for the U.S. considering only the frequency and severity of landfalling hurricanes.

Modeling Methodology

The analysis relies on a well-developed set of catastrophe risk models widely used in the insurance industry to estimate the risk of loss from extreme events. This section describes the basic modeling framework and how the hazard component was adjusted for use in the current study. Later sections provide additional details of the AIR Hurricane Model for the United States, including the wind, storm surge, and precipitation-induced flood components.

Catastrophe Models

An insurer's ability to estimate the potential loss from low frequency, high severity events such as hurricanes and earthquakes is limited by the lack of data associated with these events. Extreme events are, by definition, rare, and changes in exposure over time, regional variations in the building stock, and construction practices make it difficult to rely solely on historical loss experience. For several decades, the insurance industry has addressed the issue through the use of catastrophe models, which combine scientific and physical modeling of hazards with engineering analyses of building behavior to simulate large sets of stochastic events and the damage they cause. The model results effectively augment the information available in the limited historical record.

A standard catastrophe model framework is shown in Figure 1.

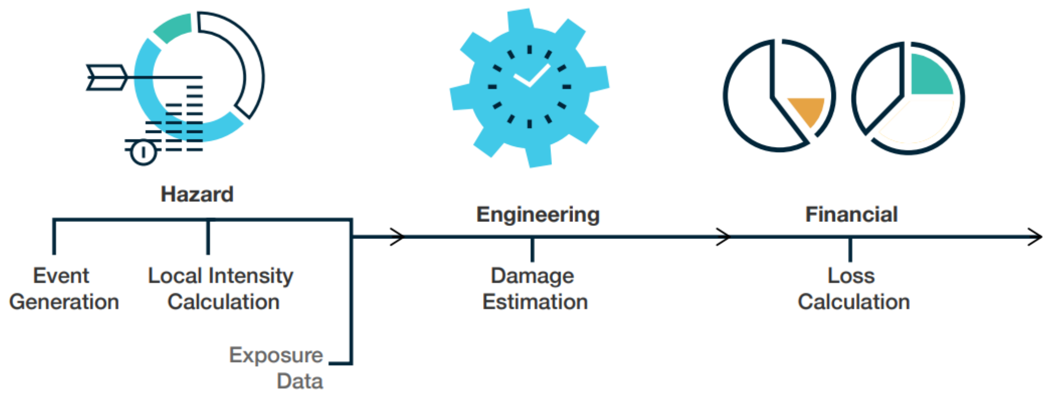

Figure 1. Catastrophe Model Framework.

There are three basic components to the model, each designed to answer a specific set of questions:

- ***Hazard Component.*** The hazard component simulates a "catalog" of events, capturing the full range of plausible events that could impact an area and, for each event, estimates intensity (e.g., wind speed, flood depth) for each affected location. The hazard component considers questions such as "Where are future events likely to occur?" and "How intense are they likely to be?"
- ***Engineering Component.*** The "exposure data" is a database of physical assets at risk, including their location and physical attributes. The engineering component considers the vulnerability of each asset to the modeled intensity, taking into consideration the physical attributes of each location. This component accounts for the difference in vulnerability between a single-family home and a high-rise office building during a hurricane, for example, addressing the question of, "How will each asset react to wind and water?"
- ***Financial Component.*** The financial component computes the monetary loss for each event, combining the damage, building values, and other factors at each location. This component answers the question, "What is the range of potential loss amounts?" The large catalog of events enables users to compute a variety of loss metrics, from the average annual (expected) loss to loss amounts with a specific annual probability—for example, the 1% or 2% annual probability of occurrence (the "100-year" or "50-year" loss, respectively).

Note that while catastrophe models were originally developed for use by the insurance industry, the underlying methodology is applicable to a wide range of uses outside insurance. Catastrophe models can help corporate risk managers estimate damage to physical assets, allow the public sector to develop mitigation and land use plans, and allow rating agencies to assess the credit risk of public and private entities seeking financing from the capital markets.

Accounting for Climate Change Impacts

The basic approach employed for this study involves extracting, or subsampling, simulations from an existing AIR U.S. hurricane model catalog containing 100,000 stochastic simulations of individual hurricane seasons.[1] The existing catalog reflects the current climate—each simulated season contains a count of events (frequency) of different strength (severity) at landfall. One simulated year may include 3 events, for example a Category 1 event in Texas, a Category 2 in Florida, and a Category 2 in North Carolina. Another simulated year might include only two events of different types, or 5 events, or zero events. Each simulated year is different, but the collection of simulations is calibrated to be consistent with what has been observed historically.

The goal of subsampling is to create a new collection of simulated hurricane seasons to reflect a future climate. This can be accomplished by extracting seasons from the existing catalog that are likely to occur in a warmer climate. The methodology is suitable especially when the "parent" catalog being sampled (the existing catalog) contains a very large inventory of events and when "target" catalogs do not require events of intensity or landfall location that are not contained in the parent.

For the purposes of this study, we assume a "business-as-usual" climate warming by mid-century as characterized by the Intergovernmental Panel on Climate Change (IPCC) Representative Concentration Pathway (RCP) 8.5 scenario (IPCC, 2014). RCPs are the plausible greenhouse gas concentration trajectories adopted by the IPCC to characterize climate evolution under different management and adaptation strategies. RCP 8.5 is a high-emissions scenario that assumes little progress in reducing greenhouse gas emissions over the next 30 years.

The subsampling process requires that we first define the event frequency and severity for hurricane seasons corresponding to the climate scenario. The frequency-severity target was created by considering most of the available literature. Several sources were particularly useful, including Knutson *et al.* (2019, 2020), the supplemental material contained therein, and a scenario based on a study from the NOAA Geophysical Fluid Dynamics Laboratory (Knutson *et al.*, 2015). A graphic on the GFDL web page on hurricanes and climate change was also used as guidance—to adjust the frequency of major category storms. The graphic has been adapted as Figure 2.

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[1] Because the model aims to estimate hurricane damage (and not overall hurricane activity), it is important to note that the AIR U.S. hurricane model catalog only contains events that make landfall on or bypass the U.S. coastline closely at hurricane strength (i.e., one-minute sustained wind speeds greater than or equal to 74 mph).

The left panel of Figure 2 shows simulation of present-day activity and the right panel shows simulated Category 4/5 activity for late this century under an assumed RCP 4.5. The simulations derive from the Coupled Model Intercomparison Project Phase 5 (CMIP5), a framework that helps scientists study coupled atmosphere-ocean general circulation models used in climate research. While the reference considers an RCP 4.5 scenario for late this century, the corresponding global temperature increase of ~2°C is what would occur in an RCP 8.5 scenario at mid-century. Because tropical cyclone activity is strongly correlated to ocean temperature in general (Evans, 1993), we make the assumption that the result is also valid for hurricane impacts at mid-century from RCP 8.5. This equivalency has been demonstrated in other publications. Ting *et al.* (2015) showed that the maximum potential intensity for Atlantic hurricanes from RCP 8.5 at 2050 was nearly the same as that from RCP 4.5 at 2100.

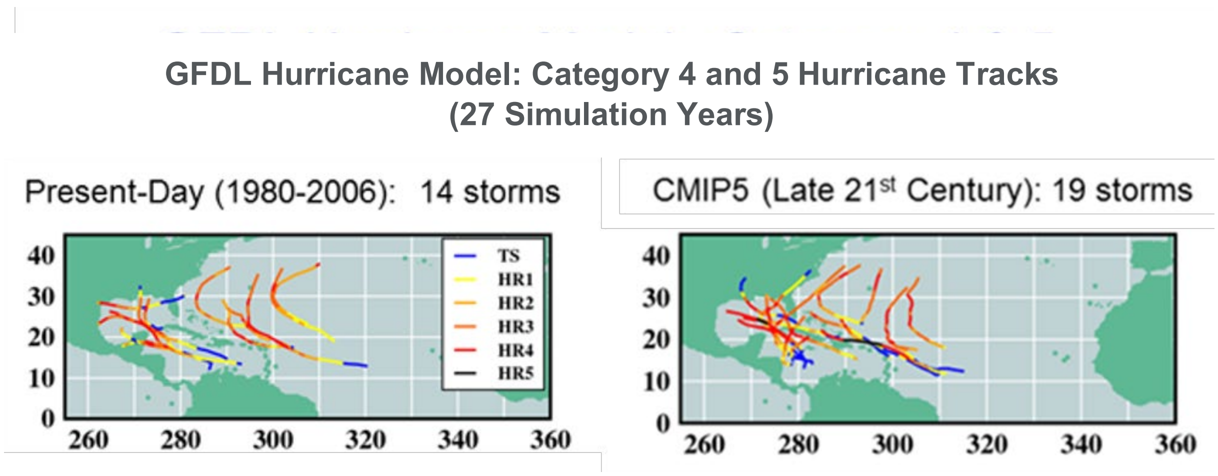

Figure 2. Tracks and intensities of all storms reaching Category 4 or 5 intensity (>59 m/sec) in the GFDL hurricane model downscaling experiments. Results are shown for the control climate (left) and CMIP5/RCP4.5 18-model ensemble late (right) 21st century. All results shown are based on model version GFDL. Track colors indicate the intensity category during the storm's lifetime.

A comparison of the two panels in Figure 2 suggests a 35% increase in Category 4/5 frequency; however, because the graphic focused only on Category 4 and 5 storms during only a 27-year window and because Category 0, 1, and 2 storm frequencies were not going to be changed for the climate change target, the percentage changes for the major categories were made non-uniformly and more conservatively to be consistent with other published results.

Subsampling of the events from our 100,000-year U.S. hurricane model catalog was conducted by extracting the appropriate number of events by Saffir-Simpson category at landfall.[2] In this study, 1,000 distinct catalogs were created based on the climate change target. The primary reason is because subsampling, by its very nature, begins with a random seed, and because

[2] Specifically, the entire catalog of events was partitioned into different Saffir-Simpson categories such that Bin ι contained only storms that made landfall as a Category ι storm (ι = 0, 1, ... 5). Adjusted frequency targets were created for each category and events were drawn at random until the frequency targets for all categories were met. The events were then reassigned into new simulated years, preserving the target overall annual event frequency.

the climate change target was not specified, a 30% increase in Category 4 storms could occur in many different ways. Each catalog that was created met the climate change target but differed slightly in other ways, producing some variation in the modeled loss just due to the sampling process. Generating 1,000 different catalogs provided enough samples that the spread in losses could be accurately obtained, while, at the same time, capturing plausible ranges due to catalog sampling error. The impact of the sampling variability on the modeled results will be considered in the "Analysis and Results" section.

Figure 3 indicates how all categories were adjusted and shows a comparison of annual event frequency from the 100,000-year catalog (the baseline for the current climate) with the climate change target. The non-major[3] categories were intentionally held constant to reflect the increased recent uncertainty as to whether the frequencies of these storms would change. The GFDL result (and many other results) focuses on Category 4 and 5 activity and, in fact, suggests a 35% increase for RCP4.5 by late this century. But the climate change target must be informed for all categories and must reflect impacts from RCP8.5 at mid-century. The resulting increases (15%, 25%, and 35% increases for Category 3, 4, and 5 storms, respectively) factor in much of the information. The decision process was guided by and consistent with published results and well within the expected uncertainty.

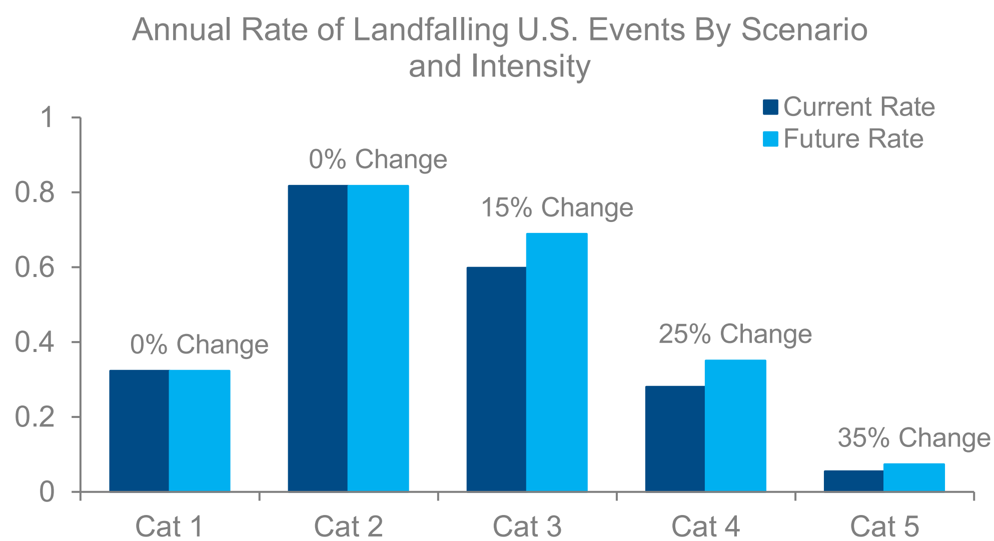

Figure 3. Climate change (future) target annual frequencies for events by Saffir-Simpson category at landfall in the U.S.; frequencies for current climate are shown for perspective.

[3] The small number of Category 0 storms are the combined result of using a hurricane catalog based on wind speed and a subsampling criteria based on equivalent central pressures.

Hurricane Modeling

This section provides additional detail on the AIR Hurricane Model for the United States, including a brief description of the wind, storm surge, and precipitation-induced flooding components. This section also summarizes the methodology for estimating the damage to properties.

The AIR U.S. Hurricane Model

The AIR Hurricane Model for the United States is a fully probabilistic model that captures the effects of tropical storm–force and hurricane-force winds, storm surge, and precipitation-induced flood from hurricanes. The model domain includes 29 states and the District of Columbia, as shown in Figure 4.

Figure 4. AIR U.S. hurricane model domain highlighted in light green.

Wind intensity computations are based on storm intensity, size, location, forward speed, and direction, as well as the underlying terrain and land use in the region. Storm surge estimates are based on the associated hurricane's meteorological parameters, coastal elevation and geometry, tide heights, and bathymetry. The model also simulates hurricane rainfall patterns realistically. Additional details are provided in the following subsections.

Wind Modeling

The stochastic catalog used by AIR's U.S. hurricane model was developed from data collected from more than 1,000 tropical cyclones (i.e., tropical storm intensity or higher) that have formed in the North Atlantic basin since 1900. This information comes from National Weather Service observation stations, the National Hurricane Center's historical hurricane database (HURDAT2), and other sources. AIR scientists use this data to develop basinwide storm tracks, including the hourly track direction, forward speed, and central pressure as the storm moves across the basin as well as inland following landfall. Historical data is also used to derive probability distributions for hurricane landfalls, with additional smoothing techniques to maintain areas of high and low risk while still accounting for the possibility of future landfalls in segments of the coastline where there have been none historically.

The model uses the latitude-dependent central pressure as the primary intensity variable, applying an exponential filling function to estimate central pressure after landfall. Storm decay, or dissipation over land, in the AIR model is based on observational data and standard methodologies adopted from the literature.

After the model probabilistically generates the characteristics of a simulated event, it propagates that event across the affected area and estimates the wind speed at each location within that area. The local intensity at each location is a function of the magnitude of the event, the distance from the source of the event, and local conditions such as wind direction, geological and topographical features at that location, and land use characteristics.

Storm Surge Modeling

Storm surge is estimated for all events in the hurricane catalog using the modeled event tracks. The AIR storm surge module incorporates many aspects of the well-established Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model, developed by the U.S. National Oceanic and Atmospheric Administration (Jelenianski *et al.,* 1992). The model accounts for hurricane parameters, coastal geography, coastline features, tidal rivers, and flood defenses. Tidal effects are included by computing a tidal height for each event, considering the simulated landfall date and time, the landfall location, and other adjustments based on the local geography and seasonality. AIR engineers post-process the SLOSH water elevations using a high-resolution digital terrain model to calculate storm surge depths at a 30-meter resolution.

Precipitation-Induced Flood Modeling

To account for flooding from precipitation during hurricane events, AIR researchers developed a machine learning technique to simulate precipitation patterns along each track in the hurricane catalog. The rainfall patterns for the stochastic catalog were “trained” from numerical weather prediction models of historical hurricanes over the last several decades. The result is a large catalog of events with realistic precipitation fields that evolve throughout the storm’s life, from landfall to extratropical transition and dissipation over land.

After precipitation is simulated for each stochastic hurricane track, it is input into the hydrological model to simulate the corresponding runoff and peak flows for each stream link in the model domain. Output from the hydrological model (river discharge data in the form of hydrographs) is coupled with a hybrid 1D/2D hydraulic model to determine the water surface elevations for locations both on and off the floodplain, at 10-meter resolution. More than 29,000 miles of flood defense systems are included in the model, with each system having a defined standard of protection but also some probability of failure based on the severity of the loading.

Damage Estimation

The relationship between event intensity and building damage varies depending on building characteristics, such as occupancy class, construction type, and building height, as well as regional and temporal variation in the building stock, building codes, and building code enforcement. The model employs different damage functions for wind, surge, and precipitation-induced flood damage, using a component-based engineering approach to assess damage to individual building components (e.g., roof or foundation) to provide a more realistic estimate of the cost to repair than an estimate based on the building as a whole. The model also includes estimates of contents damage, based on building damage and occupancy type, and costs associated with business interruption or *per diem* expenses associated with the expected number of days that the building will be uninhabitable.

Exposure Modeling for the United States

Exposure at Risk

To assess the impacts of climate change on hurricane risk, the simulated hurricane events were modeled against a database of property exposure developed by AIR. The database contains estimates of building counts and replacement values, along with information about the occupancy and physical characteristics of the structures, such as construction types and height classifications.

The database has been developed using data obtained from a variety of data sources, including private vendors, government reports and databases, and remotely sensed information. AIR develops similar databases for all modeled regions and has refined the process over many years as data availability has improved, processing power has advanced, and the models have become more detailed. For the United States, the database is developed on a 90-meter grid with underlying data current through 2019.

The exposure database captures single- and multi-family homes, manufactured homes, apartment buildings, and a variety of commercial establishments and industrial facilities, including but not limited to offices, manufacturing, wholesale and retail trade, hotels and restaurants, education, and healthcare.

Because differences in building materials, quality, and design all have a significant impact on building vulnerability, the classification of risks by structural type plays an important role in the damage estimation process. The AIR database explicitly captures the proportion of risks represented by various structural types—such as wood frame, masonry, concrete frame, and steel frame—taking into consideration local engineering and construction practices, building codes, and other factors. The data is further divided into three height categories: low-rise, mid-rise, and high-rise.

Replacement values are derived from a rebuild cost approach, which considers floor area estimates and local construction costs. For residential structures, data on construction type, building height, floor area, year-built, and dwelling size are used in conjunction with a property valuation tool (Verisk's 360Value®) to determine average home replacement values. Contents value is estimated as a percentage of the building replacement cost using insurance industry statistics.

For commercial risks, replacement costs depend on the type of business, the construction type, and local variations in materials and labor prices. Data from the Bureau of Economic Analysis (BEA) and published reports on space per employee along with third-party vendor data are used to develop a floor space estimate for each commercial establishment, which are, in turn, used to model building sizes and height classifications. Contents value is calculated as a percentage of building replacement value; the percentage varies by occupancy and includes variations in fixed equipment, internal fixtures, and inventory.

The estimates for residential and commercial structures factor in an allowance for loss of use of the structure, including business interruption and additional living expenses associated with buildings under repair. The loss of use estimate is proportional to the building and contents replacement values and varies by occupancy for commercial and industrial properties.

AIR corroborates its database against alternative regional and national data sets

Coastal Property Values Continue to Grow

An estimated 50 million people live in counties along the U.S. Atlantic and Gulf coasts. Despite the rising risk of hurricanes, the coastal population has continued to increase every year since 2000, except in 2005 when hurricanes Katrina, Rita, and Wilma struck the U.S., displacing many to inland areas. Increasing population adds to increases in exposure values and, while construction slowed considerably following the recession, housing prices and construction costs have continued to increase in recent years. The figure in this box illustrates this trend. In less than a decade, the value of coastal exposure has increased 27%.

The value of coastal exposure along the Atlantic and Gulf coasts has experienced a compound annual growth rate of about 4% over the past decade. This rate translates into a doubling of 2012's coastal exposure by 2030. The rise in exposure values, although modest compared to pre-recession levels, continues to be the largest factor increasing the hurricane risk facing the United States today.

For more information, see:

https://www.air-worldwide.com/Models/Tropical-Cyclone/The-Coastline-at-Risk/

containing reported building and economic attributes. AIR also benchmarks its national total values against various independent sources, such as gross capital stock and client data aggregates.

The resulting database contains approximately 73 million residential and 7 million commercial/industrial buildings across the hurricane-exposed states, representing nearly USD 40 trillion of building replacement value. Figure 5 shows the distribution of all exposure by ZIP Code for the entire United States in the database.

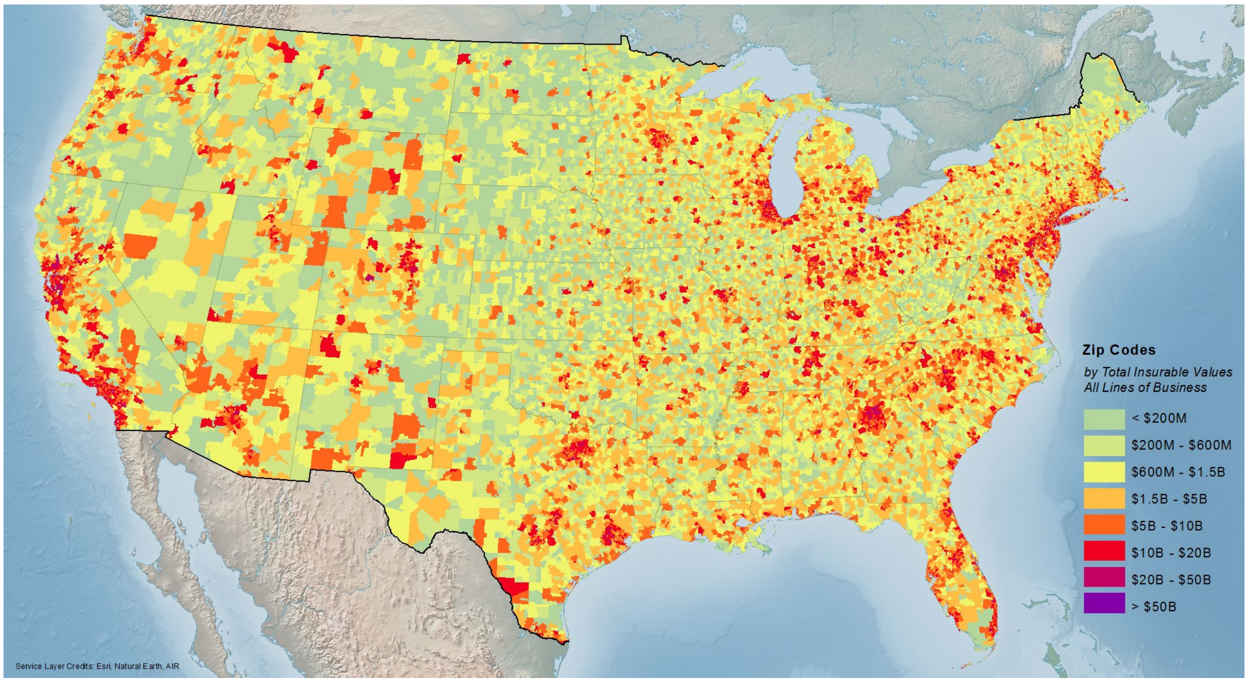

Figure 5. Total combined value by ZIP Code for residential, commercial, and industrial buildings from the AIR database (USD billions).

Economic Versus Insured Loss

In the results that follow, the loss estimates consider the *direct* damage to exposures, such as residential, commercial, and industrial properties, and automobiles, etc., in the AIR database and the temporary loss of use of those exposures caused by that damage; they do *not* include non-modeled exposures such as public infrastructure, marine, or cargo or *indirect* sources of loss, such as lost wages or economic productivity. The total of the direct and indirect sources of loss make up the total *economic* loss. Historically, only about 40% of the economic loss across all perils in North America has been insured; the percentage is even less for underinsured perils such as flood. The sizable difference between insured and economic losses—the protection gap—represents the cost of catastrophes to society, much of which is ultimately borne by individuals, businesses, governments, and taxpayers (AIR, 2020).

The calculated loss results also include the impacts of *demand surge*, a temporary increase in repair costs, which may occur following a large-scale natural disaster (Olsen and Porter, 2010). Modern supply chains generally ensure the availability of materials and labor sufficient to meet a normal level of demand without affecting price. Historical analyses of price changes for materials and labor in the immediate aftermath of an event, however, demonstrate that a sharp, unexpected increase in demand can cause prices to inflate temporarily and may extend the time required to repair and rebuild damaged property, which can be days, weeks, or months depending on the severity of the event. For the purposes of this analysis, the impacts of demand surge were assumed to be identical in the baseline and climate change scenarios.

Analysis and Results

This section presents the potential climate change impacts on future hurricane losses. First, we examine the effects of increasing landfall frequency and intensity on the combined losses of the hurricane sub-perils of wind, storm surge, and precipitation-induced flood for the U.S. The sections that follow present loss changes at a regional level and spatially by county, for hurricane-affected states.

The second half of this section focuses on sea level rise impacts on hurricane storm surge, using a novel approach for adjusting modeled storm surge footprints. The analysis focuses on three small study areas around Houston, Miami, and New York City. The goal of this analysis is to highlight how the effects of sea level rise, storm surge, and changes in hurricane frequency and severity may combine to exacerbate the risk in vulnerable areas.

Note that the nationwide, regional, and county-level results address changes in hurricane damage with respect to the increases in event frequency and intensity only; no other changes in future storm characteristics are included. Furthermore, storm surge is included in the nationwide, regional, and county-level estimates without the additional impacts from sea level rise.

Nationwide Change in Hurricane Losses

The results of the nationwide analysis with respect to climate change were generated using the direct damage from the AIR exposure database and the 2020 version of the AIR Hurricane Model for the United States. The baseline scenario was established using these losses as derived from the 100,000-year catalog, reflecting current climate conditions. The climate change scenario losses were derived from the 1,000 subsampled catalogs, each of which contains 10,000 simulated events.

Baseline Scenario

The baseline scenario was developed to reflect losses in today’s climate and provides a baseline against which future losses could be compared. Wind, surge, and precipitation-induced flood losses were combined by event to generate event-level losses. We then generated an exceedance probability (EP) curve from the resulting event-level losses to determine the baseline scenario results.

The exceedance probability curve is created by ranking the total losses in each simulated year from largest to smallest to identify the probability of a given loss being equaled or exceeded in any year. For example, the largest loss in a 10,000-year stochastic catalog is the 1 in 10,000-year loss, or a loss that has a 0.01% chance of being equaled or exceeded in a given year or has a 10,000-year return period in the common parlance. Similarly, the second-largest loss in a 10,000-year stochastic catalog is the 1 in 5,000-year loss, or one that has a 0.02% probability of exceedance each year or has a 5,000-year return period. In this study, we focus on four loss points: the average annual loss (AAL), which is the average loss across all years or expected loss per year averaged over many years, and the 25-, 50- and 100-year return period losses representing the 4%, 2%, and 1% annual probability of a given loss being equaled or exceeded, respectively.

Future Climate Conditions

As described in the discussion ahead of Figure 3, we sampled events from the existing 100,000-year catalog to create 1,000 unique 10,000-year catalogs containing the proportion of major hurricane landfalls (Category 3, 4, and 5 hurricane events) defined by the climate change target. These catalogs were then run through the AIR model to compute the climate change scenario losses.

Note that each of the 1,000 unique catalogs will produce a different result when modeled against the countrywide exposure. Further, since there was no additional specification in the climate change target of how landfall frequencies might change geographically (e.g., a higher percentage

Quick Guide to Terms and Acronyms

AAL: AAL stands for average annual loss, which is the average loss across all years in a stochastic catalog, or the **expected loss per year** averaged over many years. It is technically the mean of a fully probabilistic loss distribution output from a catastrophe model. AAL is a loss statistic that is widely used and has a diverse range of applications in catastrophe risk management.

Catalog/Stochastic Catalog: AIR catastrophe model catalogs contain **years of simulated activity** that reflect our best scientific understanding of potential future events. In each simulated year of our U.S. hurricane catalog, for example, there may be zero, one, or multiple hurricanes.

Exceedance Probability Loss/ Exceedance Probability Curve: An exceedance probability (EP) curve is created by ranking the total losses in each simulated year from largest to smallest to identify the probability of a given loss being equaled or exceeded in any year. For example, the largest loss in a 10,000-year stochastic catalog is the **1 in 10,000-year loss, or a loss that has a 0.01% chance of being equaled or exceeded in a given year, or has a 10,000-year return period** in the common parlance. Similarly, the second-largest loss in a 10,000-year stochastic catalog is the 1 in 5,000-year loss, or one that has a 0.02% probability of being equaled or exceeded each year or has a 5,000-year return period, etc.

Return period loss: An alternative, and common, way of rendering EP losses. For example, 25-, 50- and 100-year return period losses represent the 4%, 2%, and 1% EP losses, or the 4%, 2%, and 1 % chance that a loss has of being equaled or exceeded, respectively.

increase in landfalling major hurricanes in the Northeast than in the Gulf States), the changes in hurricane landfalls in the subsampled catalogs are also subject to some variability, although the changes are mostly regionally homogeneous.

For this reason, we include measures of the variability for the climate change results presented in the next paragraphs. It is important to note that the spread in loss is the result of the sampling variability associated with achieving the climate change target, not a reflection of the scientific uncertainty associated with the climate change impact.

Figure 6 compares the baseline and climate change scenario losses from the model simulations. The baseline scenario AAL along with the 4% (25-year), 2% (50-year), and 1% (100-year) EP losses are plotted in orange, and the *mean* climate change scenario losses assembled from the subsampled catalogs are in blue. The upper and lower bounds of the error bars on the climate change scenario losses represent the maximum and minimum losses, respectively, at their respective exceedance probability. The percentage increases of the baseline to the mean, minimum, and maximum (as a range) climate change scenario losses are stated in the text boxes.

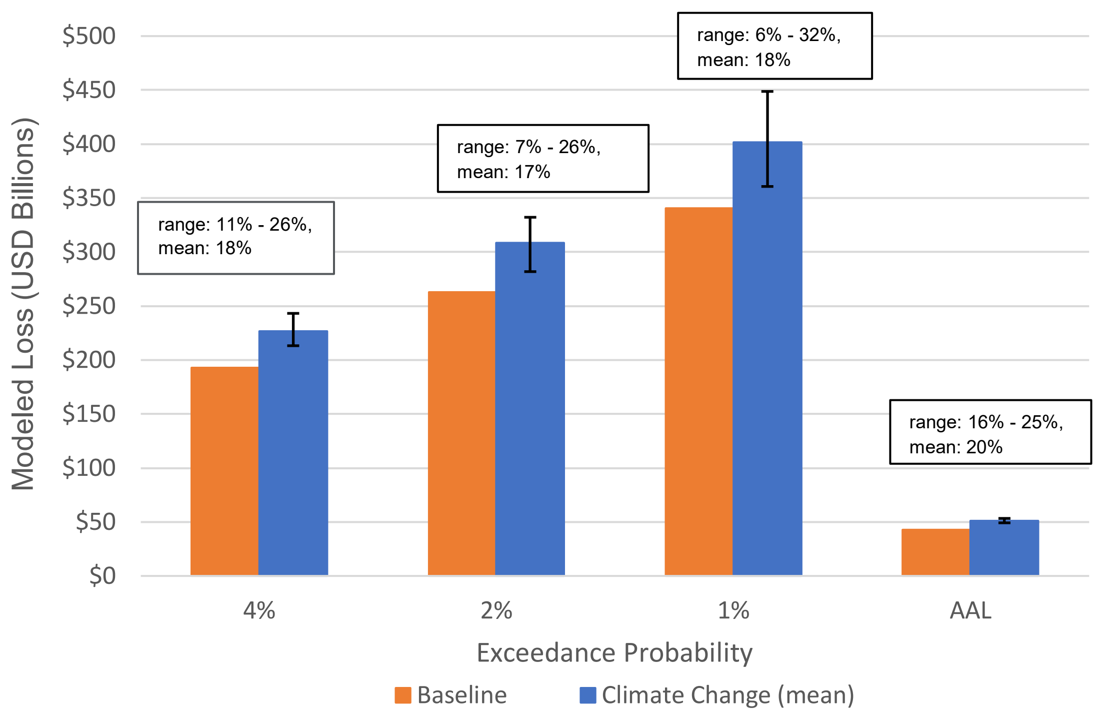

Figure 6. Increase from baseline (orange) to climate change (blue) scenario EP loss using the 1,000 subsampled 10,000-year catalogs. The range represents the sampling variability in losses for the given climate change scenario. The annual exceedance probabilities correspond to return periods of 25 years (4%), 50 years (2%) and 100 years (1%). The AAL is the annual expected loss.

The climate change target results in approximately a 20% increase in the average annual loss (AAL) compared to the current range of expected losses. As noted, climate change reflected in the subsampled catalogs assumes an RCP8.5 ("business-as-usual") climate scenario projected to the year 2050. Note also that we are keeping the exposure database constant to isolate the effects of changes in hurricane frequency and severity but that continued coastal population growth is likely and would exacerbate potential losses due to an increase in hurricane activity.

The increase from baseline to the *mean* climate change scenario loss is consistent across each exceedance probability (EP) and the AAL (approximately 17% to 20%). An increase in loss is on par with the expectation of more intense hurricanes making landfall in the U.S. The variation in potential loss between the newly generated subsampled catalogs is reflected in the range of values shown in Figure 6.

As mentioned above, the estimates in Figure 6 reflect the direct damage to the full database of exposure—not the insured portion. The insured portion will be significantly lower particularly for the surge and flooding components, which are significantly underinsured.

Regional Loss Changes

As might be expected, the loss changes vary with geography within the U.S. Figure 7 shows the domain of AIR's U.S. hurricane model, with the hurricane-affected states subdivided into seven modeled regions

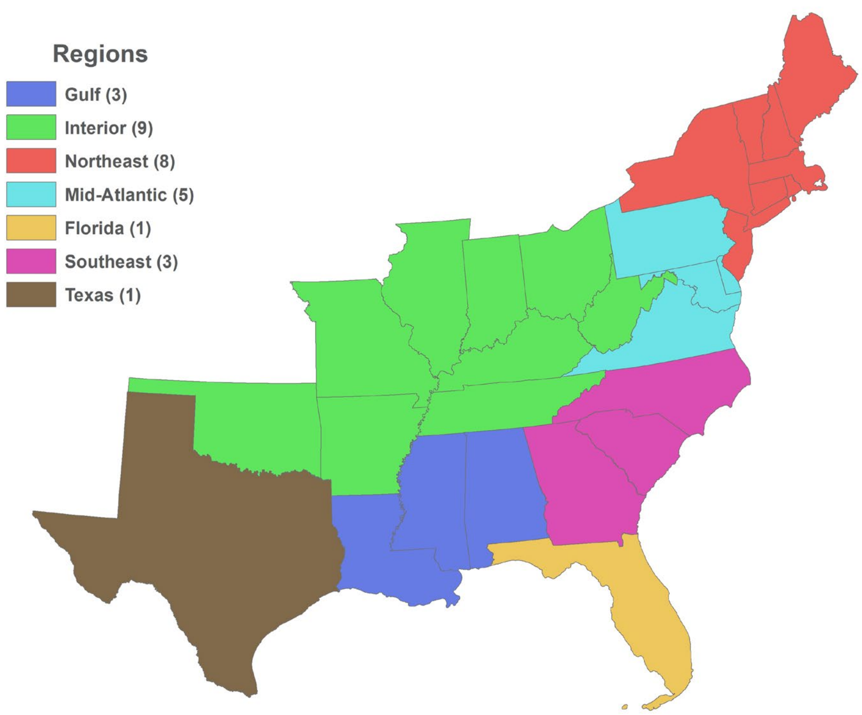

Figure 7. Grouping of states into modeled regions.

Separate exceedance probability (EP) curves were computed for each region by accumulating the state-level results for each event and aggregating to a regional total by event. As in Figure

6, the AAL and the 4%, 2%, and 1% EP losses were computed for the baseline and climate change scenarios.

The results of the regional comparisons are shown in Figure 8, using the mean climate change result for comparison. The largest increases in AAL (>20%) are seen in the Texas, Gulf, Florida, and Southeast modeled regions. These regions experience a higher annual frequency of hurricane events relative to the rest of the country in today's climate and can be expected to experience the greatest impact from the increasing frequency and intensity of hurricanes in a warmer climate. Southern states already experience more intense storms and that trend will continue.

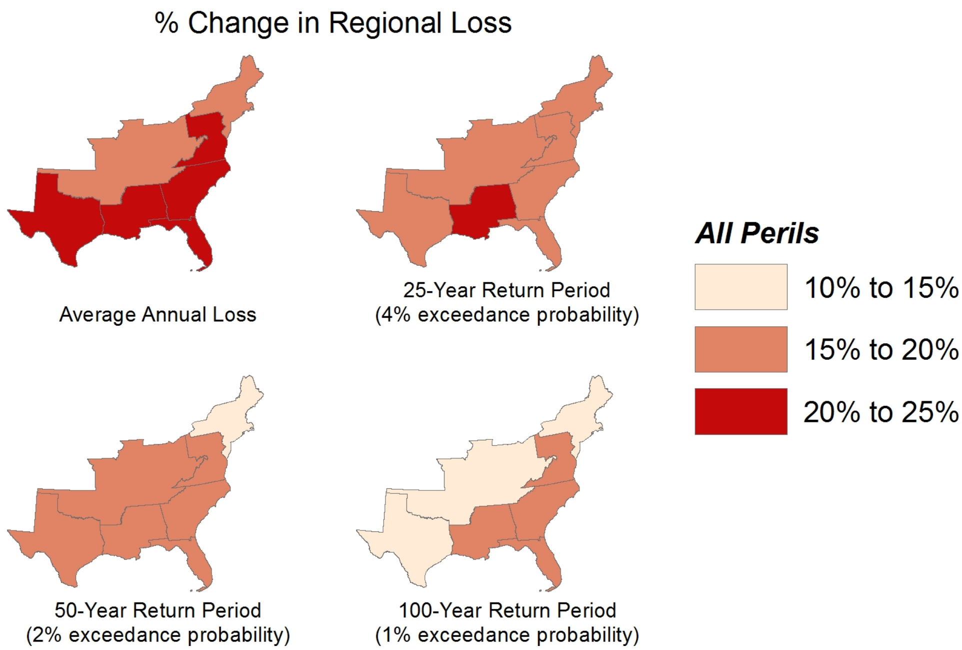

Figure 8. Percentage increase in the AAL, 25-, 50-, and 100-year return period loss by each region. All regions experience some increase in loss (beige) with the largest increases in the Gulf Coast (dark red).

The results shown in Figure 8 also indicate that all hurricane states are affected, not just those along the coast. For example, the Northeast and Interior modeled regions may also experience an increase in anticipated hurricane loss due to climate change. Although the percentage increases in AAL (and losses overall) are not as great as for the Gulf and Southeast, the change in risk is still significant (15%to 20%), as the annual frequency of hurricane events in these modelled regions is still expected to increase. Furthermore, with a higher percentage of stronger hurricanes making landfall, a portion of these storms will penetrate farther inland to states in the Interior region, causing many more people to experience the disruptions brought about by these events.

The results suggest that hurricane-exposed regions of the United States, including states in the Interior region, can expect moderate (>15%) increases in loss at the more frequent return periods. The exception is the states in the Gulf region, which are predicted to experience significant loss increases (>20%) at the 25-year return period as major hurricane landfalls increase.

Interestingly, the areas expected to see the biggest increases in the most severe losses are concentrated along coasts of the Gulf, Southeast, and Mid-Atlantic regions, where even at the 100-year return period loss (1% exceedance probability), a moderate (15% to 20%) increase is expected. The Mid-Atlantic region stands out, as this part of the country is not known to be frequently impacted by hurricane events. Note that because baseline losses are low in the Mid-Atlantic, the increase appears more pronounced on a percentage basis.

County-Level Loss Changes

Additional insight into the geographical changes in hurricane risk is available by considering results by county. For this analysis, we present a normalized view of the average annual loss by dividing it by the exposure value to present a loss per unit of exposure, or loss cost. Normalizing in this way provides a clearer picture of the loss and loss changes, as all areas are presented on the same basis.

As a point of reference, the baseline loss cost by county is displayed in Figure 9. As expected, modeled losses are highest along the coasts and generally decrease farther inland.

Figure 10 depicts the county-level change in normalized loss. Increasing event frequency and intensity will have the largest impact on the areas already at highest risk for hurricane activity. The impact of stronger, more frequent hurricanes traveling farther inland is expected to drive the increase in inland states of the country as well.

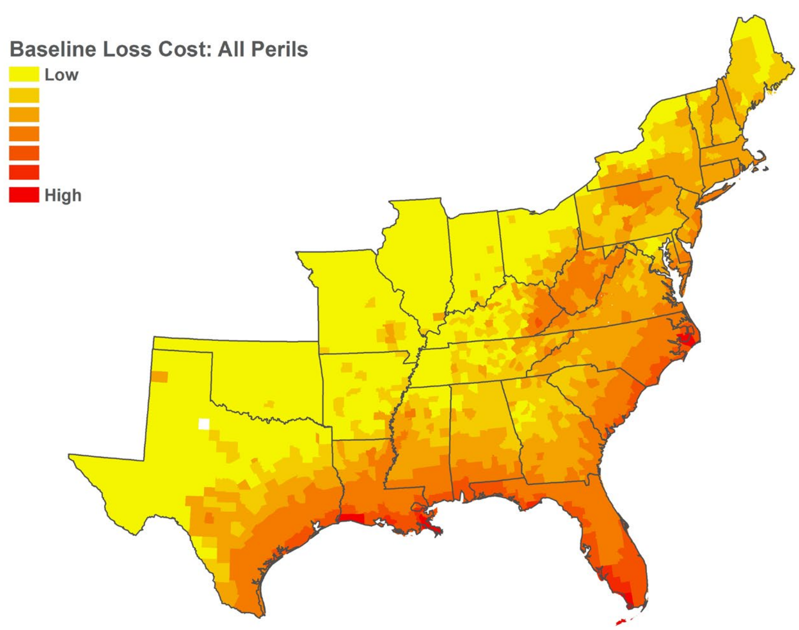

Figure 9. Normalized loss from combined wind, surge, and precipitation-induced flooding.

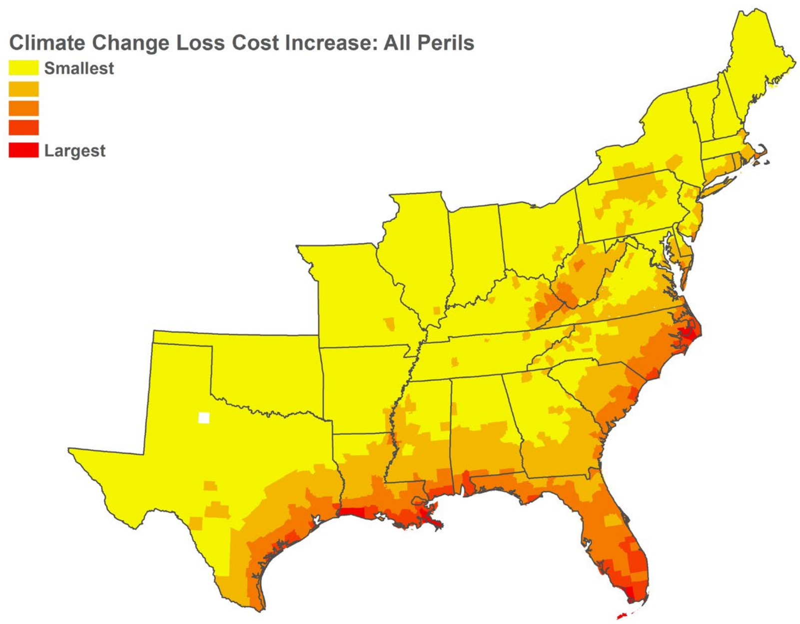

Figure 10. Change in normalized loss from combined wind, surge, and precipitation-induced flooding.

The largest increases can be found across Texas and the Southeast, in addition to pockets of the Interior. With hurricanes tending to be stronger in Texas and the Southeast, a more pronounced increase in loss can be expected there than farther up in the Northeast , as the number of strong storms in these two regions rises.

While the changes are generally smaller, states in the Interior region are expected to see increases in hurricane risk in line with the regional changes shown in Figure 8. Pockets of larger changes may be observed in some inland locations, for example in parts of West Virginia and Kentucky, that can experience flooding from hurricane events. It is important to note that the pattern in Figure 10 reflects only changes related to the frequency and severity of landfalling hurricanes. No regional assumptions were applied with respect to anticipated changes in landfall frequency—event counts were increased based on the severity of hurricanes and not their track or landfall location. Furthermore, no adjustments were made to account for other ways in which storms may change, for example, their size, forward speed, or precipitation potential. As a result, while it is possible to break down the results further by geography and sub-peril, any such view is necessarily incomplete.

To illustrate the point, Figure 11 shows the proportion of loss driven by wind and precipitation-induced flooding.

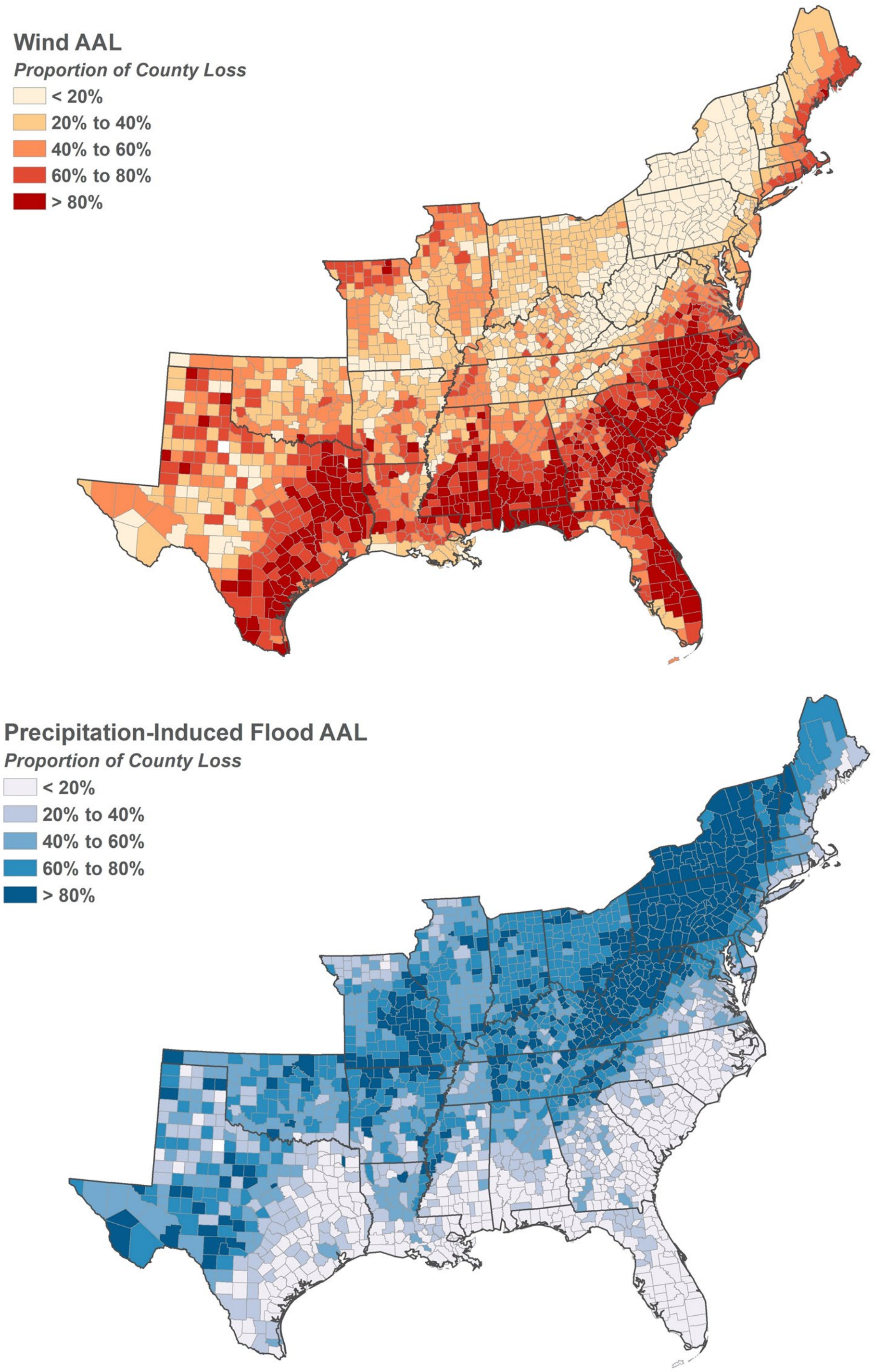

Figure 11. Proportion of modeled hurricane loss driven by wind (top) and precipitation-induced flooding (bottom). Results shown for baseline case.

The figures above show that wind makes the largest contribution to the total damage in areas closest to the coast, with flooding producing the largest impacts for inland locations. The pattern holds in most areas of the country, with the exception of a few coastal counties, where storm surge (not included in Figure 11) makes a significant contribution, and parts of the Northeast where wind and flooding cause damage in similar proportions. While the results shown are for the baseline condition—current climate—the climate change scenarios look very similar. This is perhaps not too surprising, as an increase in the kinds of events that are already occurring will increase loss overall, but not change the proportion of losses by sub-peril component.

Figure 11 leads to two observations. First, the results show the greatest impact of hurricanes for inland areas comes from flooding—losses that are largely uninsured today except for those covered under the National Flood Insurance Program (NFIP) and private (mostly commercial) insurance. An increase in hurricanes overall will lead to more uninsured loss and further stress the NFIP. Second, the analysis of increased frequency of hurricanes, while useful, is not sufficient to quantify the full effect of climate change on hurricanes. Our results show plausible changes, directionally and geographically, but a more comprehensive accounting requires consideration of the full range of impacts.

Future Storm Surge Loss with Sea Level Rise

The analysis in the previous section considers storm surge impacts without including the effects of sea level rise. In this section, we explore future hurricane-generated storm surge losses for selected study areas as indicators of the additional risk created by rising sea levels.

Sea level rise (SLR) is among the most evident and well understood aspects of climate change. Data compiled for AIR's 2017 report shows that global mean sea level has risen about 21–24 centimeters (8–9 inches) from 1880 through the 2010s, with about a third of that occurring in just the last 25 years. The rising water originates from a combination of melting glaciers and ice sheets and thermal expansion of warming seawater. A primary concern with sea level rise is the impact on coastal storm surges, as it increases not only the depth of flooding but also the inland extent, potentially exposing much larger populations to deadly floods. Without coastal protection, adaptation, or retreat, rising sea levels will impact a larger proportion of land area, population, and global assets in the years ahead (Kirezci *et al.,* 2020).

Sea Level Rise Scenarios

The regional projections of sea level rise for this study were obtained from NOAA (2017). This source is used because it provides very detailed information for a variety of sea level rise scenarios, incorporating different plausible emissions futures (RCPs) and geographic locations. The report provides six different scenarios for each location, labeled as Low, Intermediate-Low, Intermediate, Intermediate-High, High, and Extreme. Figure 12 shows the global mean sea level rise scenarios and their correspondence to the RCP scenarios.

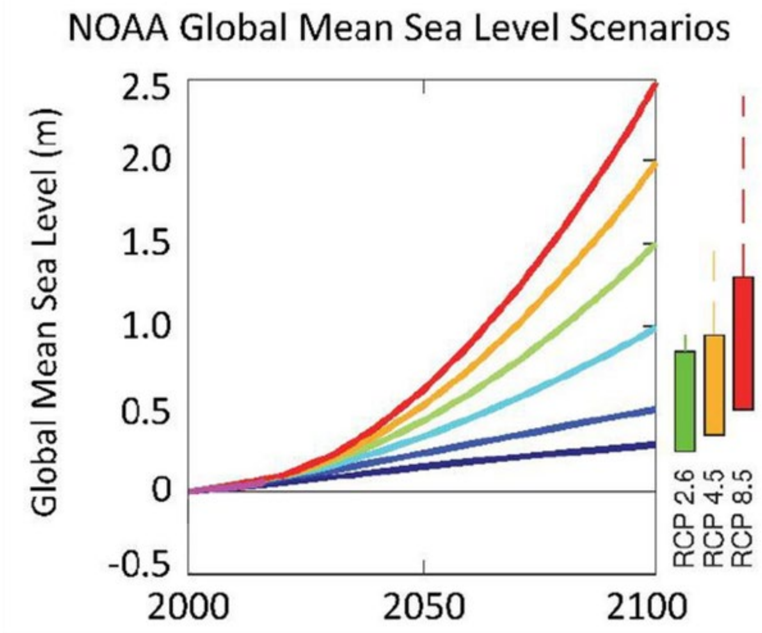

Figure 12. Representative Global Mean Sea Level (GMSL) rise scenarios for 2100 (6 colored lines) relative to historical geological, tide gage, and satellite altimeter GMSL reconstructions from 1800–2015 and central 90% conditional probability ranges (colored boxes) of RCP-based GMSL projections from recent studies. Source: Figure 8 in Global and Regional Sea Level Rise Scenarios for the United States. NOAA Technical Report NOS CO-OPS 083, Silver Spring, MD. (2017)

Table 1 further describes the connection between the NOAA and RCP scenarios. Although the time horizon of interest for this study is 2050, the probabilities of the RCP scenarios exceeding the NOAA scenarios are the same as they are at 2100.

Table 1. Probability of exceeding Global Mean Sea Level (median value) scenarios in 2100 based upon Kopp et al. (2014).

GMSL rise Scenario	RCP2.6	RCP4.5	RCP8.5
Low (0.3 m)	94%	98%	100%
Intermediate-Low (0.5 m)	49%	73%	96%
Intermediate (1.0 m)	2%	3%	17%
Intermediate-High (1.5 m)	0.4%	0.5%	1.3%
High (2.0 m)	0.1%	0.1%	0.3%
Extreme (2.5 m)	0.05%	0.05%	0.1%

The probabilities in the rightmost column of Table 1 reflect the likelihood of exceeding the corresponding GMSL rise scenario if the RCP8.5 scenario materializes. The Intermediate-Low scenario is almost certain to be surpassed (96% probability), but the Intermediate-High scenario is much less likely (1.3%)—although recent studies of observed ice-sheet losses suggest estimates may approach the upper range of the IPCC sea-level predictions (Slater *et al.,* 2020). So, these two NOAA scenarios bound the range of increases in sea level projected to occur under RCP8.5, and we chose the Intermediate-Low and Intermediate-High scenarios to cover the range of projected outcomes.

Study Area Selection

Three study areas covering limited geographical areas were selected to illustrate the impacts of rising seas on future hurricane risk. Because the exposure is constantly growing, the objective is not to project future damage in absolute terms. Rather, the goal is to understand how the risk may increase on a percentage basis using a subset of exposure from three representative locations, which are highlighted in Figure 13: Metro NYC, Miami-Dade, and Houston/Galveston. In each region, we limited the analysis to include selected counties from the AIR industry exposure database. For Metro NYC, we consider the five New York City Boroughs and Hudson, Union, Essex, and Bergen counties in New Jersey. For Houston/Galveston, we include Harris, Fort Bend, Montgomery, Brazoria, Galveston, Liberty, Waller, Chambers, and Austin counties. For Miami-Dade we consider Miami-Dade County.

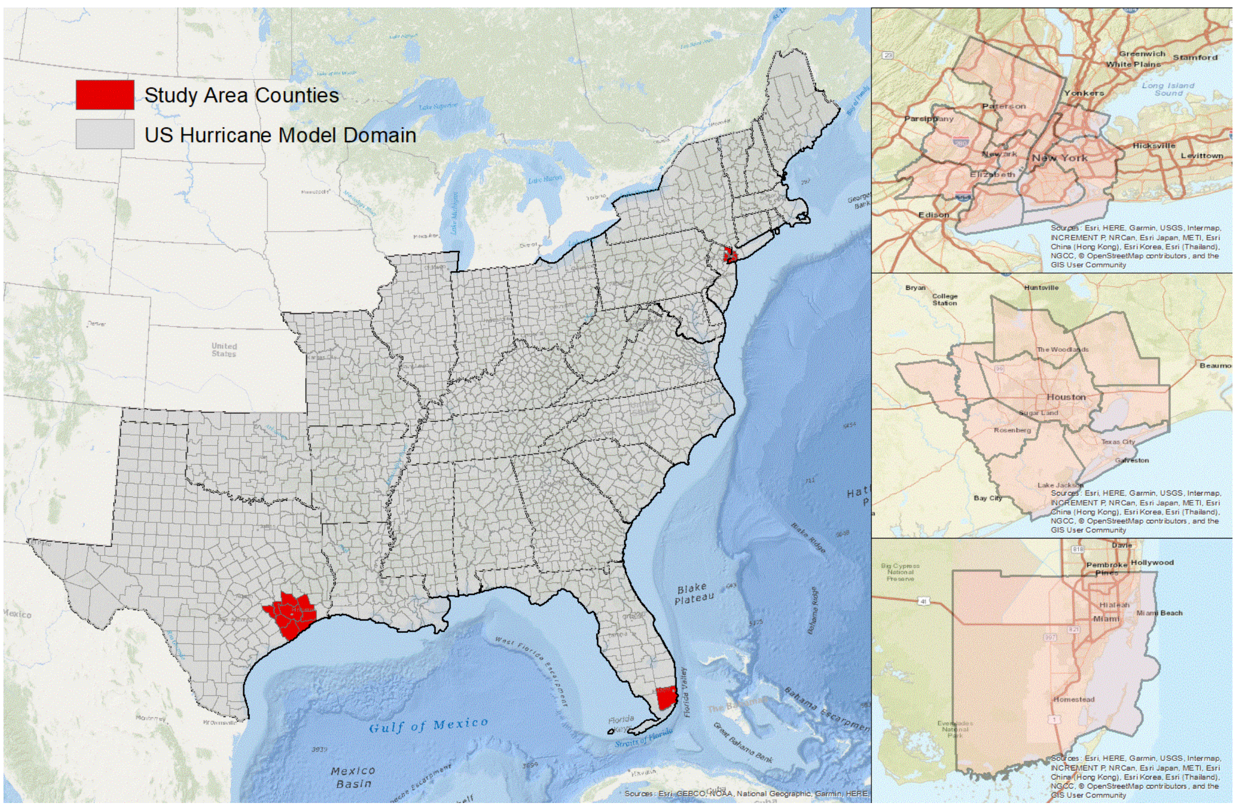

Figure 13. The storm surge SLR analysis was conducted in three study regions: Metro NYC, Miami-Dade, and Houston/Galveston (regions range from one to nine counties).

The sea level rise scenarios were derived from the NOAA (2017) projections for the closest tide gauge to each study area. The scenarios correspond to the Intermediate-Low and Intermediate-High estimates as shown in Table 1.

Storm Surge Modeling

We consider the impacts of sea level rise in two steps. First, for the Intermediate-Low (IntLow) and Intermediate-High (IntHigh) scenarios, we adjust the SLOSH-based storm surge footprints for every event in a 50,000-year catalog from the AIR U.S. hurricane model and compare the losses to the baseline scenario . In a following section, we then include the changes in hurricane frequency and severity to account for the full climate change impact.

In the baseline scenario , the surge footprints reflect sea levels (NAVD 88) corresponding to the present-day climate. To create footprints for the IntLow and IntHigh sea level rise scenarios, AIR developed a novel algorithm. The algorithm involves adjusting the storm surge footprint for each modeled event; recomputing the surge height within each grid cell to account for increased depth and additional landward inundation. The approach follows a methodology described by McInnes *et al.* (2013), with modifications to account for frictional effects.

Sea Level Rise (SLR) Impact on Storm Surge Losses

The change in the average annual loss (AAL) storm surge losses from the baseline to IntLow and IntHigh scenarios are shown in Figure 14 for the three study areas.

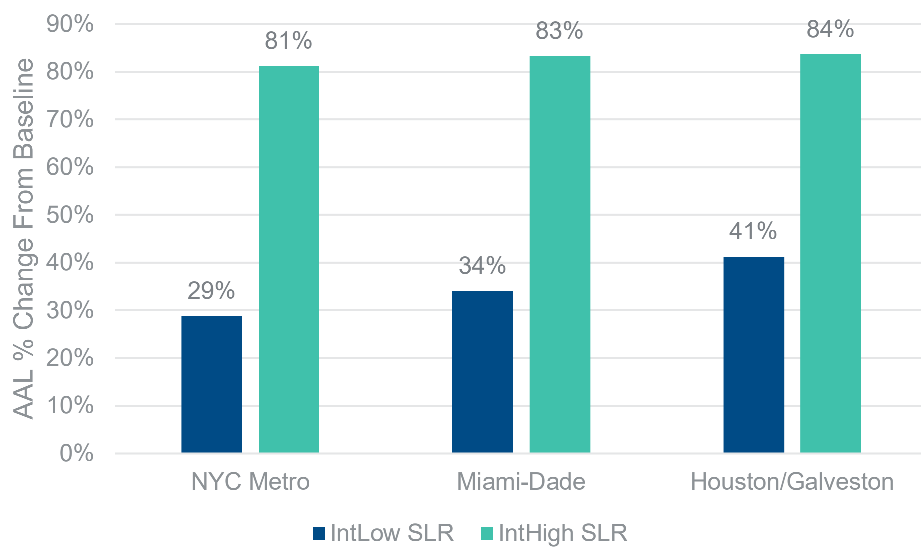

Figure 14. The expected percent increase in storm surge AAL from the baseline to the IntLow and IntHigh SLR scenarios, not accounting for changes in landfall frequency.

The IntLow scenario for the NYC Metro area represents approximately 8.3 inches of sea level rise, resulting in a 29% increase of the average annual loss (AAL) by mid-century. The IntHigh projection corresponds to 24.4 inches of sea level rise, producing an increase of approximately 80% in AAL by the year 2050.

In Miami-Dade County, the IntLow and IntHigh projections for the year 2050 are 7.5 inches and 20.1 inches, respectively, which correspond to AAL increases of between approximately 30% and 80% from the baseline scenario. Results for the Houston/Galveston area are slightly higher—with sea levels projected to increase by between 14.2 and 25.6 inches by the year 2050, the AAL may increase by 40% to over 80%.

The results suggest that sea level rise alone may increase the average annual storm surge loss by anywhere from one-third to nearly a factor of two. Loss changes for individual events may be more pronounced, for example, as shown in the 4%, 2% and 1% exceedance probability (EP), or 25-, 50-, and 100-year return period, losses presented in Figures 15, 16, and 17, respectively.

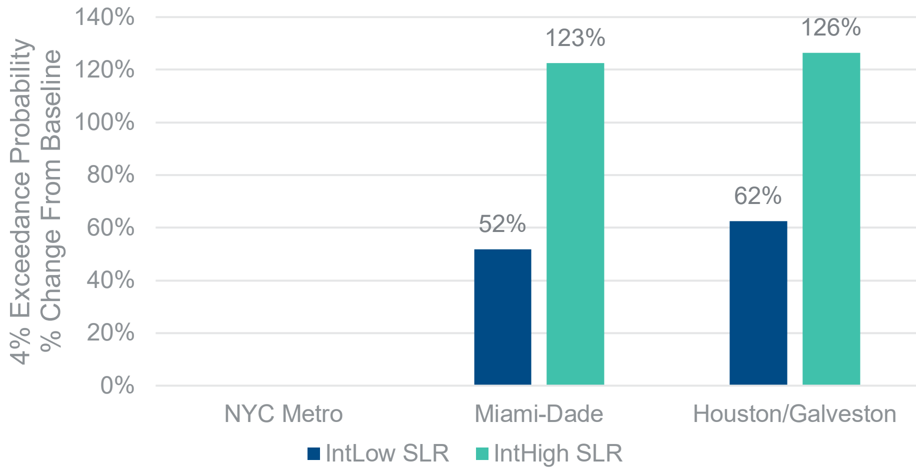

Figure 15. The expected percentage increase in storm surge 4% EP loss from the baseline to the IntLow and IntHigh SLR scenarios, not accounting for changes in landfall frequency.

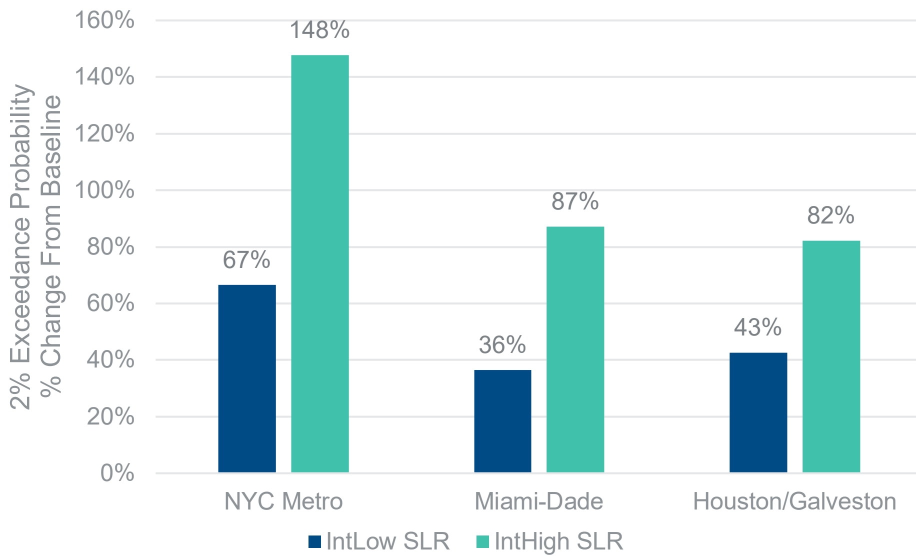

Figure 16. The expected percentage increase in storm surge 2% EP loss from the baseline to the IntLow and IntHigh SLR scenarios, not accounting for changes in landfall frequency.

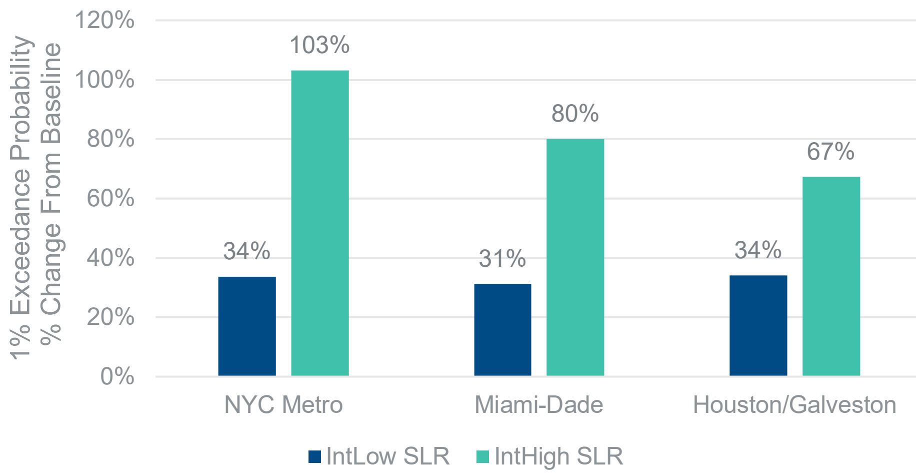

Figure 17. The expected percentage increase in storm surge 1% EP loss from the baseline to the IntLow and IntHigh SLR scenarios, not accounting for changes in landfall frequency.

At the 4% EP, future storm surge losses are expected to increase by approximately 50% and 125% in Miami-Dade under the IntLow and IntHigh scenarios, respectively. Future storm surge losses in the Houston/Galveston region at the same EP, or 25-year return period, are expected to increase by similar margins. Given the low frequency of landfalling hurricanes in NYC Metro generally, and the low incidence of surge-producing events, the 4% EP, or 25-year return period, event is omitted for this region.

The loss increase at the 2% EP for each region is less than those at the 4% EP. In the NYC Metro region, the 2% storm surge loss is expected to increase by roughly 70% and 150% under the IntLow and IntHigh scenarios, respectively. The increases in Miami-Dade and the Houston/Galveston area under each SLR scenario at the 2% EP are slightly lower, ranging from over 30 to nearly 90%.

Finally, at the 1% EP, future storm surge losses are expected to increase by over 30% to 100% in the NYC Metro area, from 30% to 80% in Miami-Dade, and from 34% to nearly 70% in the Houston/Galveston area under the IntLow and IntHigh SLR scenarios, respectively.

The loss increases at the more frequent return period (4% EP) is greater than that of the more extreme (1% EP) across all three regions. With additional seawater, not only do events become much more intense, but their footprint also expands and damages a greater number of structures. The additional number of structures, and the degree to which they are inundated at the 4% EP, is much greater than that of the 1% EP.

Accounting for Changes in Event Frequency

Sea level rise will not be the sole driver of increased storm surge risk when considering climate change. As demonstrated in the national and regional analyses described in earlier sections of this report, increasing the frequency of major hurricane events can have significant impacts on the AAL and EP losses. Therefore, it is important to see how increasing event frequency will compound future storm surge losses after accounting for sea level rise.

The process begins with the 1,000 unique 10,000-year catalogs described earlier, except that now the storm surge loss for each event is replaced with IntLow and IntHigh surge losses to reflect the sea level rise impact. This method thus captures impacts from increases in both landfall frequency and sea level rise.

Accounting for increased hurricane activity generated an additional 19% to 22% storm surge AAL in each of the three regions, relative to future losses with just sea level rise. Figure 18 shows the combined effects of sea level rise and increased hurricane frequency and intensity on expected losses in the three study areas.

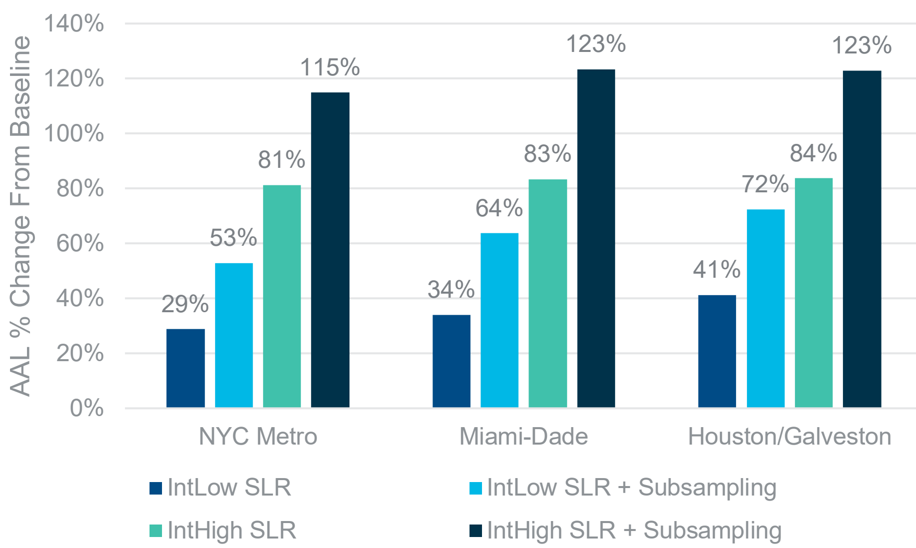

Figure 18. Incorporating the effects of increasing hurricane landfall into that of SLR boosts the percentage increase in AAL from the baseline scenario.

Relative to the baseline scenario, average annual loss (AAL) is expected to increase by more than half under the likely IntLow sea level rise case, and more than double in the more extreme IntHigh sea level rise scenario.

A similar pattern is observed when considering the effects of increased hurricane activity combined with sea level rise on the 4%, 2% and 1% EP, or 25-, 50-, and 100-year return period, losses relative to the baseline scenario (Figures 19, 20, and 21, respectively).

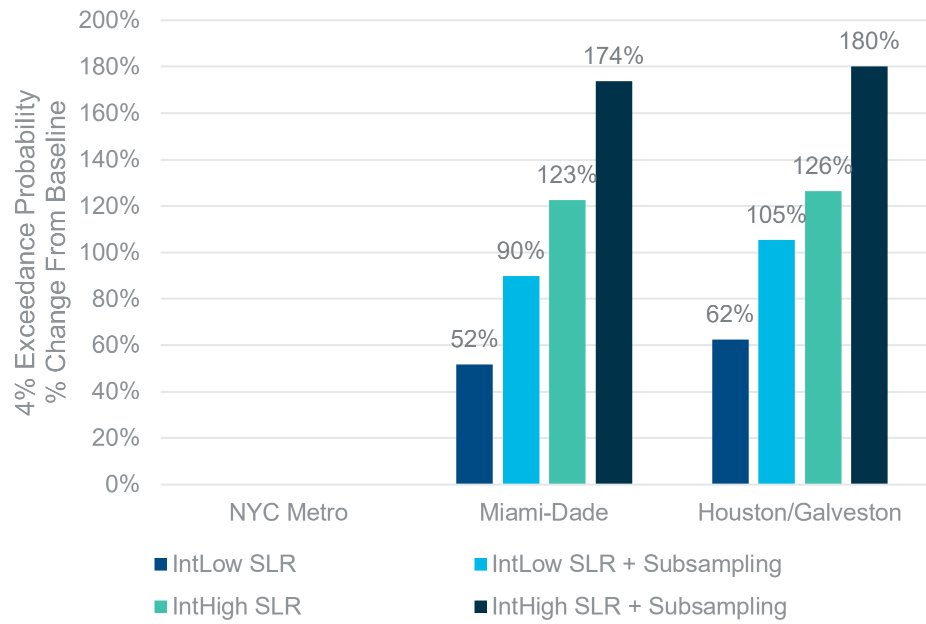

Figure 19. Incorporating the effects of increasing hurricane landfall into that of SLR boosts the percentage increase in the 4% EP loss from the baseline scenario.

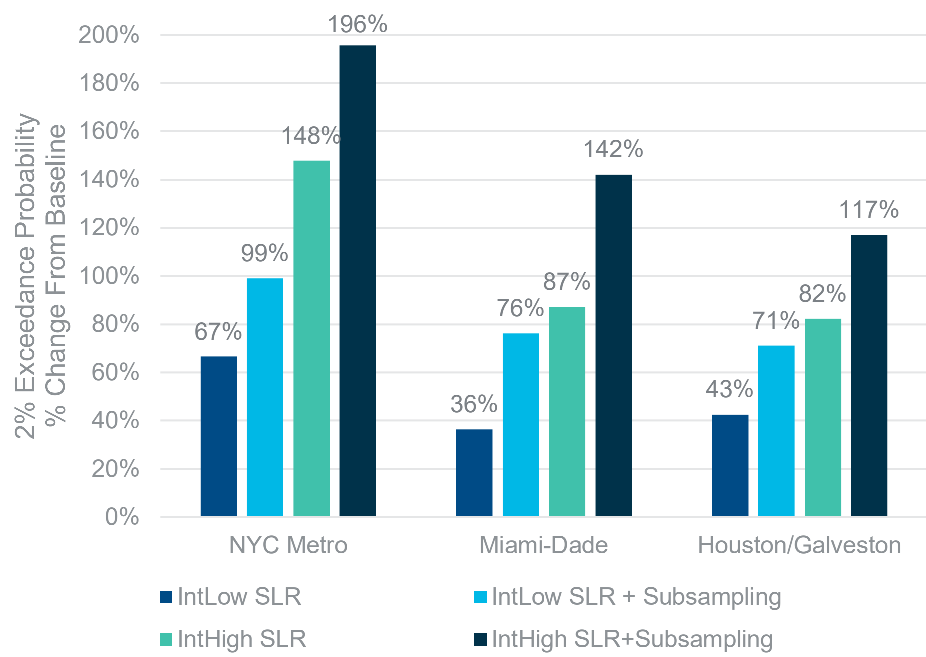

Figure 20. Incorporating the effects of increasing hurricane landfall into that of SLR boosts the percentage increase in the 2% EP loss from the baseline scenario.

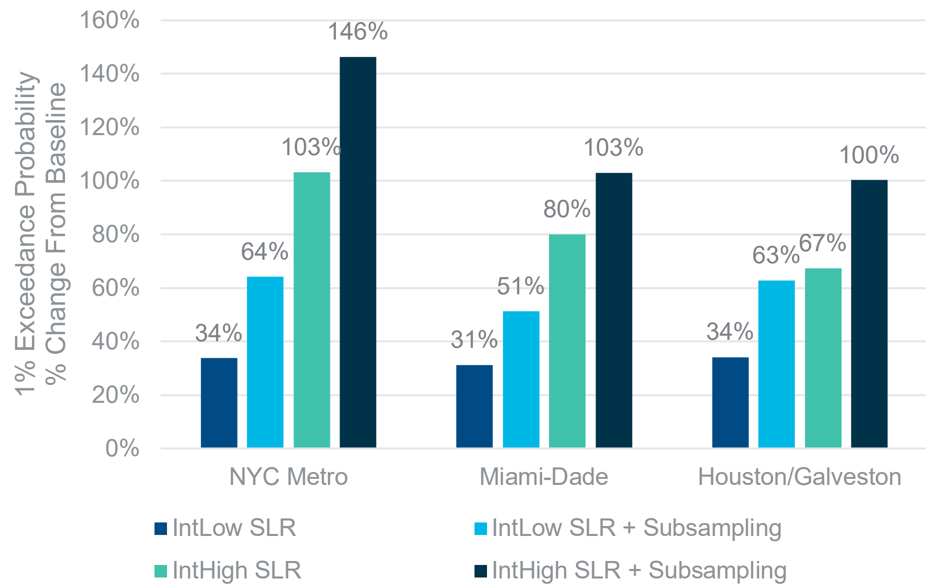

Figure 21. Incorporating the effects of increasing hurricane landfall into that of SLR boosts the percentage increase in the 1% EP loss from the baseline scenario.

To summarize the results, the combined effect of sea level rise and more intense hurricanes is likely to cause a significant increase in storm surge losses by a factor of two or more. Without adaptation and improvements in insurance penetration, an increase in surge losses is likely to exacerbate the insurance protection gap, stressing homeowners, businesses, and economies at all levels.

The Increasing Likelihood of Large Storm Surge Loss Events

In addition to considering how losses might increase, a related question is how the likelihood of large loss events might change in the future, and by how much. As larger storm surge events become more frequent, the probability of today's 50-year return period event, for example, is likely to increase.

Using a similar methodology to the one we employed to estimate changes in loss, we can calculate the maximum storm surge elevations (in feet above the NAVD 88 datum) for each event in the baseline and in the sea level rise scenarios to compute changes in *the level of hazard*. This allows us to consider the exceedance probability of a specified flood elevation in each region under the current and future climate conditions.

In this case, the maximum storm surge elevation was selected from each event, across the entire modeled domain, and thus represents a hazard estimate for the study area. The surge elevations for the selected EPs for the baseline condition are presented in Table 2.

Table 2. The 4%, 2%, and 1% EPs maximum storm surge elevations for the NYC Metro, Miami-Dade, and Houston/Galveston study areas (baseline scenario).

Study Area	Return Period (Years)	Exceedance Probability (%)	Baseline Scenario Storm Surge Elevation (feet)
NYC Metro	25	4	N/A
	50	2	6.9
	100	1	8.8
Miami-Dade	25	4	9.9
	50	2	11.5
	100	1	13.0
Houston/ Galveston	25	4	18.3
	50	2	22.9
	100	1	27.3

The question we are considering is: What is the exceedance probability for these elevations for the climate change scenarios? In other words, if an elevation of 11.5 feet is expected with 2% annual probability for Miami today (i.e., it is a 50-year event), how frequently might a similar elevation be exceeded in the future?

To make this estimate, the maximum surge elevations were calculated from the augmented flood footprints under the IntLow and IntHigh scenarios, and an exceedance probability curve was generated for each study area and scenario. The new EPs, or return periods, when considering only the impact of sea level rise were determined by finding where the baseline scenario surge elevations fell on the future climate exceedance probability curves.

As before, we also include the increased frequency of events, to capture the combined effects. The results are presented in Table 3.

Table 3. The effects of sea level rise and increased hurricane activity is expected to increase the likelihood of surge events.

Region	Baseline Return Period (Years)	New Return Period - IntLow Scenario with Sea Level Rise	New Return Period - IntLow Scenario with Sea Level Rise and Increased Frequency	New Return Period - IntHigh Scenario with Sea Level Rise	New Return Period - IntHigh Scenario with Sea Level Rise and Increased Frequency
NYC Metro	25	NA			
	50	43	38	31	28
	100	76	68	49	44
Miami-Dade	25	20	18	15	13
	50	37	32	25	22
	100	76	65	46	40
Houston/ Galveston	25	21	18	18	16
	50	43	37	37	32
	100	83	71	69	60

Incorporating sea level rise and future hurricane activity shifts the exceedance probability curve as more extreme surge events are added, thereby increasing the probability that smaller surge events will occur. The effects of this shift can be fairly significant, where under the more extreme sea level rise scenario (IntHigh) the probability of large surge events (100-year return period) increases by anywhere from one-third (Houston/Galveston study area) to more than double (NYC Metro and Miami-Dade study areas). Even if sea levels rise by the amounts projected under just the IntLow scenario, the moderate surge events (50-year return period) could become a 30-year event.

As a specific example of the sea level rise impact by itself, consider a recent historical event like Hurricane Sandy. We estimate that the storm surge elevation for an event like Hurricane Sandy is approximately a 185-year event for the NYC Metro region in the baseline scenario. Using the IntHigh sea level rise condition, a Sandy-like surge scenario becomes much more frequent, or an approximately 90-year event. A rare event still to be sure, but more likely as a result of sea level rise.

Example Storm Surge Scenario with Sea Level Rise

Storm surge footprint maps were developed as illustrative examples to complement the expected loss increases. The baseline and IntHigh sea level rise scenario storm surge footprints are provided as Figure 22 (NYC Metro) and Figure 23 (Miami-Dade), with additional discussion later in this section.

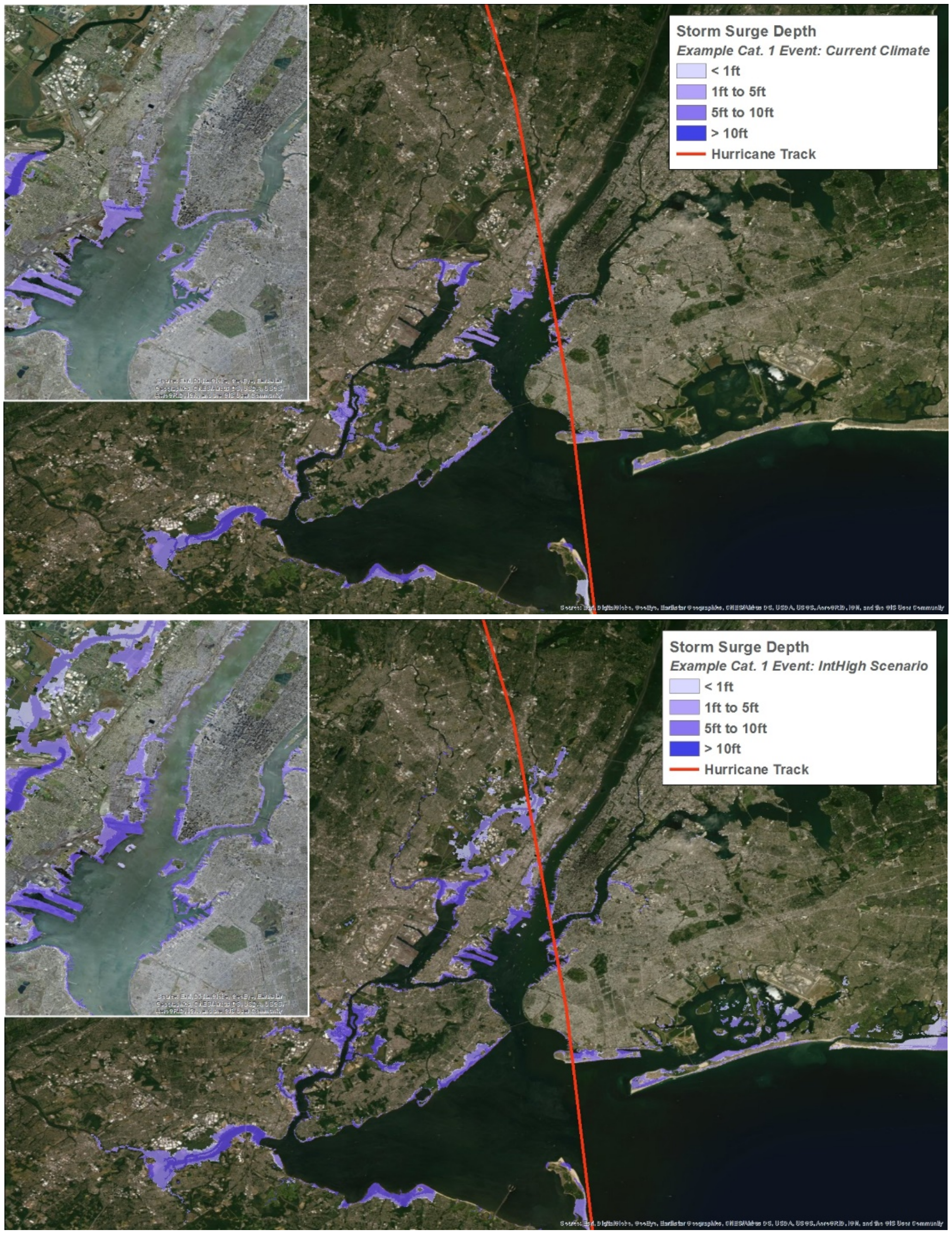

Figure 22. Storm surge depth footprints for the NYC Metro area in today's climate (baseline scenario, top) and with sea level rise (IntHigh scenario, bottom) for a Category 1 event example. (Source: AIR)

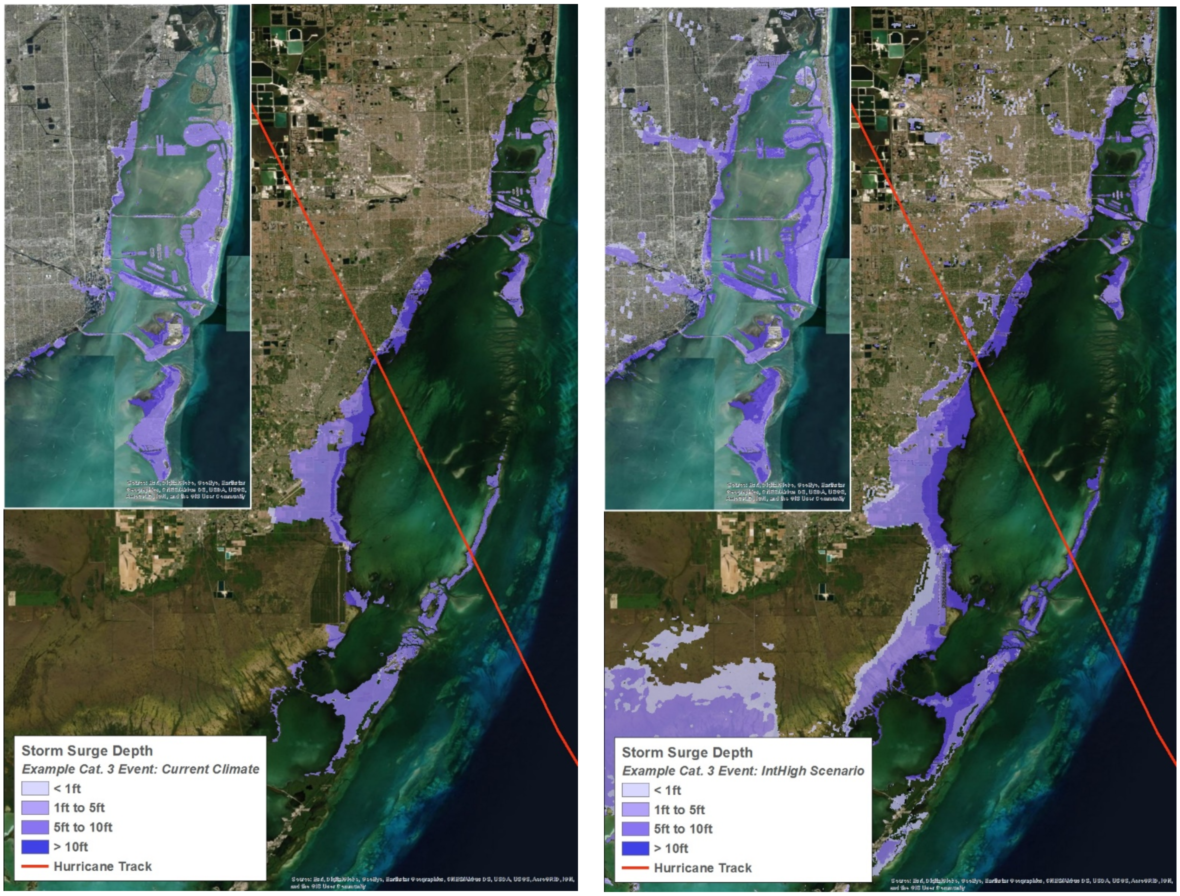

Figure 23. Storm surge depth footprints for the Miami-Dade region in today's climate (baseline scenario, top) and with sea level rise (IntHigh scenario, bottom) for a Category 3 event example. (Source: AIR)

In these examples, we are focused not on the most extreme events but rather on a more frequent, or "typical" event. A single event was selected for the NYC Metro and Miami-Dade regions to demonstrate the effects of sea level rise on storm surge in the respective regions. The examples depict a Category 1 event in the NYC Metro area and a Category 3 event for Miami-Dade, for the baseline and IntHigh sea level rise scenarios. While the tracks for these specific events are more conducive to storm surge, events of this intensity have occurred frequently in the historical record for these areas.

The effects of sea level rise on storm surge were described in the previous section: that the flood intensity (depth) and areal expanse (additional buildings and people affected) will increase. Both are highlighted in Figure 22. Note the lighter purple colors in Jersey City, southern Manhattan, and coastal neighborhoods of Brooklyn, which become darker in the IntHigh scenario, indicating that these areas, which are likely to flood during a surge event in today's climate, will experience greater flood depths with sea level rise. In addition, areas upstream of Newark Bay along the banks of the Passaic and Hackensack rivers that do not flood today (top panel, inset) are inundated when sea level rise is added. The flood wave generated by a surge event that starts at a higher elevation (i.e., with sea level rise) is able to penetrate farther upstream, inundating the low-lying regions along the banks of these rivers and their tributaries.

Similar phenomena can be observed in Miami-Dade (Figure 23). The islands of Miami Beach, Key Biscayne, and Virginia Key, which are more likely to flood in today's climate, are impacted even more so with sea level rise (inset). It is also apparent that storm surge will inundate a significant number of additional buildings, especially along the Miami River and in low-lying areas to the west of Downtown Miami.

To emphasize that sea level rise may significantly increase storm surge risk in these regions, AIR estimated the population impacted using LandScan™, a publicly available global population data set created by the Oak Ridge National Laboratory. A unique feature of the LandScan data set is that it presents an "ambient" population per grid cell, or the average number of people over a 24-hour period. By overlaying the surge footprints on this data set, AIR estimated the number of people impacted, accounting for those directly (i.e., flood damage to first floor, unable to enter or exit a high-rise building, etc.) and indirectly (i.e., unable to commute to work because a road is impassable) affected.

The analysis indicates a significant increase in the affected population for both regions. Holding the population estimates constant, the total number of people affected by surge in the NYC Metro example increases from approximately 115,000 in the baseline scenario to just under 245,000 in the IntHigh scenario, while the estimates for Miami-Dade increase from approximately 94,000 in the baseline scenario to more than 250,000 in the IntHigh scenario. It is important to note that these are illustrative examples only, as there is uncertainty in both the projections and in the population estimates; however, they can be viewed as plausible indications of how even modest events might affect significantly more people.

Discussion and Future Work

This paper explores future changes to hurricane risk for residential and commercial properties in the Unites States. While climate change is likely to affect hurricanes in multiple ways, we focus on only two: an increase in the frequency of the strongest storms, and additional storm surge flooding due to sea level rise. The analysis uses the AIR Hurricane Model for the United States and plausible assumptions about how the risk will change in a warmer climate.

The first set of analyses considered changes to hurricane frequency and severity, specifically an increase in the number of major (Category 3, 4, and 5) hurricanes. A second set of analyses, focused on three study areas, evaluated the additional risk from sea level rise. The analyses considered a "business-as-usual" climate scenario (RCP8.5) at mid-century and were conducted holding exposure constant at today's level.

The analysis shows that increased hurricane activity and SLR will both have a meaningful impact on future damage. The growth in the number of stronger storms and of landfalling storms overall increases modeled losses throughout the hurricane-affected states. The expected annual hurricane losses increase by approximately 20%, with slightly larger changes in areas such as the Gulf and Southeast coasts where major landfalls are already more likely today. The loss increases extend to inland areas as well, as stronger storms may penetrate farther inland, exposing a larger segment of the U.S. population to more frequent damage and disruption.

With sea level rise, the analysis of storm surge for areas of New York, Miami, and Houston suggests that from the present day (2020) to 2050, sea level rise may increase storm surge losses by anywhere from one-third to almost a factor of two, with larger impacts possible when combined with increases in the number of major storms. The results suggest that an extreme surge event in today's climate may be twice as likely to happen 30 years from now. The actual loss estimates will undoubtedly be higher if coastal exposure (currently growing at a 4% annual rate) continues to increase. Higher concentrations of property and wealth along the coast have been and will continue to be a significant factor in U.S. hurricane risk.

In many ways, the results are expected. More hurricanes making landfall and storm surges on top of a higher sea level will certainly increase damage and place many more people at risk. The changes presented here, however, represent an initial view of how risk may evolve. With additional research into a wider range of impacts, many of which were briefly mentioned in this paper, a more complicated picture is likely to emerge.

For example, additional work is needed to identify how risk may change geographically. The results presented here suggest mostly proportional increases in today's geographic risk profile, with more wind and surge damage along the Gulf and Southeast coasts, lower risk farther north, and inland areas affected by flooding. A better understanding of how storms may change in the future will provide greater insight.

Several factors could have a significant impact on the geographic distribution of risk. The first is whether the strongest storms not only become more frequent, but also become *stronger*. This might have a disproportional impact, for example, on wind and surge damage in Florida and the other Gulf Coast states most likely to be impacted by the strongest events. A related issue is whether storms could remain stronger for longer periods of time, which might lead to storms advancing further north and threatening large population centers in the Northeast. Both issues are plausible outcomes of higher sea surface temperatures, especially if it creates more favorable conditions for storms to retain strength at higher latitudes. Increased atmospheric temperature will also allow hurricanes to produce more rainfall, which will exacerbate flooding, particularly if storms are also slowing down at landfall, as hurricanes Harvey (2017) and Irma (2017) seemed to do.

The results of this study show a modest increase in damage potential for inland states, mostly caused by rainfall from more frequent events. The prospect of stronger and wetter storms, coupled with potential changes in forward speed and the geographic distribution of landfalls, however, raises at least the possibility that inland states could experience even more damage. Accounting for the full range of impacts for inland areas is important not only to identify increases in affected populations but also to quantify the additional burden on the National

Flood Insurance Program and the widening insurance protection gap. Hurricanes may evolve such that they are no longer considered to be a largely coastal phenomenon.

While there is considerable uncertainty in assessing these additional hurricane factors, the modeling approach described in this paper presents a logical path forward. The sampling methodology can be improved by simulating a wider range of storm parameters, increasing the inventory of events that could become more likely in a warmer climate. Furthermore, the catalog-based catastrophe modeling framework can be extended to consider climate change impacts for additional perils, including inland flooding, wildfires, severe thunderstorms (hail, tornadoes, and straight-line winds) and winter storms.

While this effort was focused on understanding potential impacts on property damage, similar analyses could be designed to help address a more targeted set of questions. For example, how will floods impact the economy in a warming climate across multiple dimensions (mortgage risk, real estate values, municipal bond ratings)? Or, what infrastructure assets might be at greatest risk from increased storm surge as a result of sea level rise?

The importance of these questions is clear. On the current emission trajectory, hurricane damage will continue to increase, in some cases significantly, placing not only homes and businesses but also public infrastructure and financial assets, at greater risk.

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References

AIR, 2020. *Global Modeled Catastrophe Losses Report* https://www.air-worldwide.com/siteassets/Publications/Brochures/documents/2019-AIR-Global-Modeled-Catastrophe-Losses

Climate Prediction Center, 2020. *NOAA 2020 Atlantic Hurricane Season Outlook*. Link accessed September 1, 2020

Evans, J. L., 1993: Sensitivity of Tropical Cyclone Intensity to Sea Surface Temperature. *J. Climate*, 6, 1133–1140, https://doi.org/10.1175/1520-0442(1993)006<1133:SOTCIT>2.0.CO;2

Insurance Information Institute, 2020. “Spotlight on: Flood insurance”, page accessed at https://www.iii.org/article/spotlight-on-flood-insurance on September 9, 2020.

Jelenianski, C.P., Chen, J., W.A. Shaffer, 1992. SLOSH: Sea, Lake, and Overland Surges from Hurricanes; NOAA Technical Report NWS 48; National Oceanic and Atmospheric Administration, U.S. Department of Commerce: Silver Spring, MD, U.S.A; pp. 1–71

Kirezci, E., Young, I.R., Ranasinghe, R. et al. 2020. Projections of global-scale extreme sea levels and resulting episodic coastal flooding over the 21st Century. Sci Rep 10, 11629. https://doi.org/10.1038/s41598-020-67736-6

Klotzbach, P.J., Bowen, S.G, Pielke, R. Jr., and M. Bell, 2018. Continental U.S. Hurricane Landfall Frequency and Associated Damage. *Bulletin of the American Meteorological Society* 99 (7): 1359–1376, DOI:10.1175/BAMS-D-17-0184.1

Knutson, T.R., Sirutis, J.J., Zhao, M, Tuleya, R.E., Bender, M.A., Vecchi, G.A., Villarini, G and D. Chavas, 2015. *Global Projections of Intense Tropical Cyclone Activity for the Late Twenty-First Century from Dynamical Downscaling of CMIP5/RCP4.5 Scenarios.* J. Climate, 28(18), DOI:10.1175/JCLI-D-15-0129.1

Kossin, J. P., Knapp, K R., Olander, T. L. and C.S. Velden, 2020: Global increase in major tropical cyclone exceedance probability over the past four decades, *PNAS*, 117 (22): 11975-11980. DOI: 10.1073/pnas.1920849117

Knutson, T., Camargo, S.J., Chan, J.C.L., Emanuel, K., Ho, C., Kossin, J., Mohapatra, M., Satoh, M., Sugi, M., Walsh, K., and L.Wu, 2019. Tropical Cyclones and Climate Change Assessment: Part I. Detection and Attribution. *Bulletin of the American Meteorological Society*, 100(10), DOI:10.1175/BAMS-D-18-0189.1.

Knutson, T., Camargo, S.J., Chan, J.C.L., Emanuel, K., Ho, C., Kossin, J., Mohapatra, M., Satoh, M., Sugi, M., Walsh, K., and L.Wu. 2020: Tropical Cyclones and Climate Change Assessment: Part II. Projected Response to Anthropogenic Warming. *Bulletin of the American Meteorological Society*, 101(3), DOI:10.1175/BAMS-D-18-0194.1.

C.-Y. Lee, S.J. Camargo, A.H. Sobel, and M.K. Tippett, 2020. Statistical-dynamical downscaling projections of tropical cyclone activity in a warming climate: Two diverging genesis scenarios. Journal of Climate, 33, 4815-4834, DOI: 10.1175/JCLI-D-19-0452.1.

NOAA National Centers for Environmental Information (NCEI), 2020. U.S. Billion-Dollar Weather and Climate Disasters. https://www.ncdc.noaa.gov/billions/, DOI: 10.25921/stkw-7w73

Li, L., Chakraborty, P, 2020. Slower decay of landfalling hurricanes in a warming world. *Nature* 587, 230–234. https://doi.org/10.1038/s41586-020-2867-7

McInnes KL, Macadam I, Hubbert G, O'Grady J. , 2013. An assessment of current and future vulnerability to coastal inundation due to sea-level extremes in Victoria, southeast Australia. *International Journal of Climatology*. 33(1):33–47.

Olsen, A.H. and K.A. Porter, 2010. "What we Know About Demand Surge". Report SESM 10-1, Department of Civil Environmental and Architectural Engineering, University of Colorado. Available at http://www.sparisk.com/pubs/Olsen-2010-CU-WWKADS.pdf

McKinsey and Company, 2017. "Insuring hurricanes: Perspectives, gaps, and opportunities after 2017". Available at https://www.mckinsey.com/industries/financial-services/our-insights/insuring-hurricanes-perspectives-gaps-and-opportunities-after-2017#

Slater, T., Hogg, A.E. & Mottram, R. 2020. Ice-sheet losses track high-end sea-level rise projections. Nat. Clim. Chang. https://doi.org/10.1038/s41558-020-0893-y

Sousounis, P.J. and C.M. Little, 2017. *Climate Change Impacts on Extreme Weather* , AIR Worldwide. https://www.air-worldwide.com/siteassets/Publications/White-Papers/documents/Climate-Change-Impacts-on-Extreme-Weather

Notes:

Figure 2 adapted from NOAA GFDL reference (Figure 7) at https://www.gfdl.noaa.gov/global-warming-and-hurricanes/#synthesis-and-summary-for-atlantic-hurricanes-and-global-warming

About AIR Worldwide

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