Variation of Climate Change Impact on Hurricane Losses across US Coast

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ABSTRACT: Hurricanes are one of the most disastrous natural hazard impacting the US coastal regions causing a huge damage to property every year. Since hurricane develops in warmer regions of the ocean, hurricane risk varies across the different locations throughout the coast depending on their proximity to the ocean as well as the ocean temperature. This is reflected in terms of the regional variation of hurricane losses. Further, future climatic conditions are expected to be different compared to present with an overall increase in the sea surface temperature. This increase is found to be non-uniform spatially based on the projections provided by Intergovernmental Panel on Climate Change (IPCC 2013). This leads to varying level of increase in hurricane risks across the different locations. As such, some low-risk zones will be at a much higher risk whereas other regions observe only slight increase of risk in future. Thus, this study investigates the changes in the hurricane hazard and losses for residential buildings across the US south and east coast under the climate change scenarios.

Keyword: Climate change, Hurricane, Residential buildings, Risk, Sea Surface Temperature.

1. INTRODUCTION

Hurricanes are one of the most damaging and costliest natural hazards impacting the United States (III 2017). Hurricane losses are found to be specifically higher in the Southeast US coast, though the losses vary widely across the different regions even in the Southeast coast. The wide variation in spatial distribution of the regional hurricane losses in the US could be attributed to the variation of the factors impacting the losses. For instance, the major factors impacting the regional hurricane losses are the intensity of the hurricane hazard and the socio-economic state of the region. Intensity of hurricane hazard is a function of the region's proximity to the ocean, the sea surface temperature (SST) of the neighboring ocean, Coriolis effect etc. whereas the socio-economic conditions which influence the hurricane losses are building value, density of buildings in the region etc. All the above listed factors are location-specific, as such regional hurricane losses vary across the different locations.

Further, since hurricane is an atmospheric phenomenon, any change in the future climatic condition could impact the future hurricane losses. Various studies have stated that the future climate could be warmer compared to the present climate. Since high SST is one of the basic requirements for formation and development of hurricanes, anticipated future climatic conditions could impact the future hurricane hazard and the corresponding losses. Further, since different regions might experience different changes in future climate, hurricane losses across the different regions could be variably impacted.

Various studies have investigated the impact of climate change on hurricane intensity as well as the corresponding losses. In majority of these studies, hurricane intensity (Emanuel 2008, Knutson et al. 2010) as well as the hurricane losses (Liu 2014, Pant and Cha 2018) are found to increase in the future climate. Among the climate-dependent loss studies, there are only a few studies that have investigated the regional hurricane losses for different locations. These studies have found different degrees of changes in future hurricane losses for different locations. For example, Liu (2014) had investigated the impact of climate change on hurricane losses in Orleans, Miami, Charleston and New York. For RCP8.5 scenario in the year 2100, the respective change in 700-year return period hurricane losses was found to be 1.8, 0.8, 1.2 and 9.9. Similarly, Bjarnadottir et al. (2013) had also found hurricane damages to increase variedly across Miami-Dade, New Hanover and Galveston even for the same percentage increase in wind speed.

Based on the review of the existing studies, it is inferred that though many studies agree that hurricane intensity will be impacted in future, there is a lack of studies investigating the impact of climate change on future hurricane losses, specifically considering losses across different regions. Since hurricane losses vary spatially, assessment of future hurricane losses in different regions is vital for long-term risk management planning. As such, this study makes an effort to assess the climate-dependent regional hurricane losses across the US south and east coast. The following sections detail the methodology adopted in this study as well as discuss the findings of this study.

2. REGIONAL HURRICANE LOSS ASSESSMENT FRAMEWORK

This study evaluates the climate-dependent regional hurricane losses in selected locations across the US south and east coast by considering hurricane damage due to both wind and rain ingress in residential buildings. The following sections detail the framework adopted for loss assessment.

2.1. Study regions and building inventory

The hurricane losses are evaluated for eight US coastal counties which are listed below:

- Harris, TX
- Orleans, LA
- Mobile, AL
- Miami-Dade, FL
- Chatham, GA
- Charleston, SC
- Norfolk, VA
- New York, NY

In this study, the loss evaluation is limited only to 1 and 2 story residential buildings. These buildings are assumed to have the following variations in their structural components.

- Type of wall: masonry or wood-framed
- Type of roof: hip or gable
- Roof cover: shingle or tile
- Roof nailing: 6d with 6/12” nailing pattern, 8d with 6/12” nailing pattern or 8d with 6/6” nailing pattern
- Number of stories: one-story or two-story

The variations are based on the wind-resisting characteristics of the buildings which have been identified in the existing studies (FEMA 2013, Cope 2004). The proportion of buildings with the above variations in each study region is taken to be the same as in HAZUS.

2.2. Individual building damage assessment

In this study, damages in all the vulnerable components of each prototype building are evaluated. These components can be broadly categorized into three major categories – structural, interior and content. The damage ratio in the individual components are evaluated based on damage due to wind or rain ingress. In this study, structural damage is attributed to wind whereas interior and content damages are attributed to rain ingress.

The structural damage is evaluated for each vulnerable structural component of a building. Based on the existing studies, the vulnerable structural components chosen for this study are roof-sheathing, roof-cover, windows and doors, roof to wall connections and walls. For each vulnerable component, damage is evaluated by comparing the hurricane wind load with the capacity. The capacities for these components are obtained as probability distribution from HAZUS manual (FEMA 2013) and Cope (2004). The load is then evaluated based on the equations provided in ASCE with some modifications. These modifications include consideration of uncertainty in the coefficients, explicit consideration of wind directionality etc. The complete details of these modifications are provided in Cope (2004), Pant and Cha (2018). Thus, for each hurricane scenario, an instance of load is compared with the capacity and if the capacity is lower than the load, damage is recorded. For the same component type, the damage in individual sub-components is recorded and the damage ratio is calculated as the proportion of damage.

Besides structure, interior and content are also the major components of a residential building. In this study, the interior and content damage are assumed to be explicitly due to rain ingress. The volume of rain ingress inside a building is evaluated using the equation below (Baheru 2014).

$$Vol_t = (RAF \cdot A_o \cdot HRR + SRC \cdot A_{SR} \cdot HRR) \cdot t \quad (1)$$

where HRR is the horizontal rain rate, A_o is the area of opening, A_{SR} is the area for surface runoff and Vol_t is the volume of water accumulated during time interval t. RAF is rain admittance factor which represents rain impinging through the openings in a building. SRC is the surface runoff coefficient. These coefficients are obtained from Baheru (2014). The depth of rain ingress is calculated by dividing the accumulated volume by the floor area.

A linear model is used to relate interior damage to rain ingress (Pita et al. 2012 and FEMA 2013) as given in Eq. (2).

$$IDR = \begin{cases} \frac{1}{t_d} \cdot d_w & d_w < t_d \\ 1 & d_w \geq t_d \end{cases} \quad (2)$$

where IDR is interior damage ratio, d_w is the depth of water and t_d is the threshold depth of water representing complete interior damage. The threshold depth is taken to be 1 inch (Gurley et al. 2005). Further, content damage is assumed to be accrued at a rate of 0.35 times the interior damage (Gurley et al. 2005).

2.3. Hurricane loss assessment

For each prototype building, the loss ratio is evaluated based on the damage in each vulnerable component and sub-component as given in Eq. (3).

$$LR = \sum_{l=1}^{n} (DR_l \cdot RCR_l) \quad (3)$$

where DR_l represents damage ratio in the l^{th} component, RCR_l represents replacement cost ratio for the l^{th} component, and n is the number of all the considered individual components. The replacement cost ratio is defined as the cost of replacing the component divided by the insured value of the building and its contents. The replacement costs from Gurley et al. (2005) are used for this study.

The regional hurricane loss is then evaluated for each location in terms of annual aggregated loss (AAL) as given below.

$$AAL = \sum_{j=1}^{m} \sum_{i=1}^{nb} \left(\sum_{k=1}^{nh} (LR_{ijk}) \cdot n_{ij} \right) \cdot IV_j \quad (4)$$

where IV_j is the median insured value of residential buildings in the j^{th} area, n_{ij} is the number of the i^{th} building type in the j^{th} tract , nb is the number of building prototypes, nh is the total number of hurricane per year, and LR represents the proportion of hurricane loss in a building to its insured value. The insured value of exterior structure and interior of the building is taken to be 50% of the median value of the building (Davis and Palumbo 2008). The content insured value is taken to be 50% of the insured value of exterior structure and interior (Bhinderwala 1995).

3. TROPICAL CYCLONE SIMULATION MODEL

Tropical cyclones (TCs) comprise of hurricanes and tropical storms, the only difference between the two being that hurricane has a higher intensity compared to tropical storm. Currently, TCs are modeled using physics-based or statistical model. Generally, the statistical models are faster than physics-based models. For this study, a statistical model by Vickery et al. (2000) is adopted to model tropical cyclones. This model also includes a temperature term making it useful for climate-dependent analysis.

In this study, 40,000 years of TCs are simulated for each climate scenario. For this, the TCs are initiated based on a Poisson process. This study does not consider the climate change impact on frequency, since there is not a consensus among the existing studies on how the climate change could impact on hurricane frequency (Mann and Emanuel 2006, Landsea et al. 2010, Bengtsson et al. 2007). As such, the mean frequency for the Poisson process is assumed to be a constant evaluated based on the frequency of past hurricane data since 1944.

Once the TCs are initiated, central pressure, translation velocity and approach angle are recorded at a time-step of 6-hour. The equations adapted from Vickery (2005) and used in this paper to evaluate the hurricane parameters are given below.

$$ln(I_{i+1}) = c_0 + c_1 \cdot ln(I_i) + c_2 \cdot ln(I_{i-1}) + c_3 \cdot ln(I_{i-2}) + c_4 \cdot T_s + c_5 \cdot \left(T_{s_{i+1}} - T_{s_i}\right) + \varepsilon \quad (5)$$

$$ln\left(V_{t_{i+1}}\right) = a_1 + a_2 \cdot \psi + a_3 \cdot \lambda + a_4 \cdot ln\left(V_{t_i}\right) + a_5 \cdot \theta_i + a_5 \cdot T_{s_i} + \varepsilon \quad (6)$$

$$\Delta\theta = b_1 + b_2 \cdot \psi + b_3 \cdot \lambda + b_4 \cdot ln(V_{t_i}) + b_5 \cdot \theta_i + b_6 \cdot \theta_{i-1} + \varepsilon \quad (7)$$

where I is the relative intensity, T_s is the sea surface temperature, ε is a random error term, the subscript i represents the time step, ψ and λ are the latitude and longitude of the storm center at the time step, V_t is the translation velocity and θ is the approach angle. Relative intensity provides the measure of the central pressure and is also a function of SST (Darling 1991). Relative intensity helps bound central pressure within the limit dictated by the heat potential of the ocean. The coefficients $a_i's$, $b_i's$ and $c_i's$ are obtained from regression analysis of past HURDAT data. The analysis is performed for each 5°x5° grid. Further, the increase in each of the above parameters between two time-steps are bounded based on the past hurricane data to ensure realistic limits. For example, $\Delta\theta_{bound}$ is taken to be a function of V_t as suggested in existing studies (FEMA 2013). Thus, if $\Delta\theta$ exceeds $\Delta\theta_{bound}$, $\Delta\theta$ is replaced by $\Delta\theta_{bound}$. In this study, $\Delta\theta_{bound}$ is obtained based on the analysis of past hurricane data. The simulated values of central pressure, translation velocity, approach angle and frequency for hurricanes landfalling the US were compared with the actual data from HURDAT and were found to have a good match to the actual data.

If a hurricane makes a landfall, translation velocity and approach angle are evaluated using the same equations as above but without the temperature term. However, the relative intensity is converted back to central pressure and is decayed using the equation given in Vickery 2005.

The velocity at the selected locations are then evaluated based on the equation given in Georgiou et al. (1983).

Similarly, the rainfall rate is evaluated based on the equation given in R-Cliper model (Marks and DeMaria 2003, Tuleya, DeMaria and Kuligowski 2007).

$$VRR(r) = \begin{cases} T_0 + (T_m - T_0) \cdot \left(\frac{r}{r_m}\right) & r < r_m \\ T_m \cdot exp\left(-\frac{r - r_m}{r_e}\right) & r \geq r_m \end{cases} \quad (9)$$

where $VRR(r)$ is the vertical rainfall rate, r_m is the radial extent of the inner-core rain rate T_m, r_e is the measure of radial extent of the tropical system rainfall and T_0 is the rainfall rate at r=0. The above parameters, T_0, T_m, r_e, r_m, are evaluated based on Tuleya et al. (2007) based on equations which relate them to maximum wind speed of the storm at each time-step.

The R-Cliper gives the vertical rain intensity; however, horizontal rainfall rate is required for evaluation of damage. Thus, the vertical rainfall rate is converted to horizontal rainfall rate using the equation provided in Straube and Burnett (2000).

It is noted that though both hurricanes and tropical storms are simulated in this phase since one can change to other and vice-versa; however, only hurricane level winds are considered for damage and loss assessment.

4. CLIMATE CHANGE MODEL

Various studies have confirmed that the future climate will be very different than the present. Among them, IPCC is the most dominant and leading studies in the field. IPCC has projected four different climate change scenarios based on the anticipated level of anthropogenic and natural processes – RCP2.6, RCP4.5, RCP6.0 and RCP8.5, among which RCP2.6 corresponds to the lowest climate change and RCP8.5 corresponds to the highest climate change.

In this study, hurricane losses are evaluated for both present and future climate. The present climate corresponds to the year 2005 and the future climate corresponds to the year 2100. RCP2.6 and RCP8.5 are considered for future climate scenarios. The climate parameter used in this study is SST. The SST corresponding to present climate is taken from COBE database (NOAA 2017a). The future SST parameters are obtained from NOAA's GFDL(NOAA 2017b). As expected, the SST parameters vary across the ocean. The difference between the SST of future climate corresponding to RCP8.5 scenario to present climate is shown in Figure 1. It is noted that some grids have missing SST data. For these grids, the SST is assumed to be the same as the SST of grid before the current time-step of the TC.

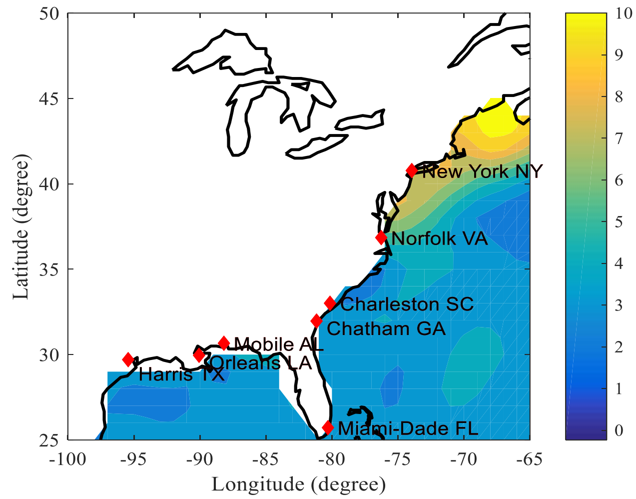

Figure 1: SST increase in future RCP8.5 scenario compared to present climate.

5. IMPACT OF CLIMATE CHANGE ON HURRICANE HAZARD AND LOSSES

The above methodologies are used to evaluate climate-dependent hurricane wind speeds and rainfall rates for the selected locations based on which damage and losses in individual building prototypes are evaluated. The individual building losses are then combined to obtain regional hurricane losses. The following sections detail the findings of this study

5.1. Impact of climate change on hurricane wind speed

Wind speed is the primary indicator of damages and losses during a hurricane scenario. As such, the maximum spatially averaged wind speeds corresponding to various annual exceedance probabilities are evaluated for the climate-dependent hurricane scenarios as shown in Figure 2 and Figure 3. It is noted that wind speeds corresponding to low exceedance probabilities are considered in this analysis since these are more damaging and hence of higher concern. Besides, hurricane itself is an extreme event, as such it is associated with low probability but high intensity wind speeds.

Figure 2 shows the maximum wind speeds corresponding to the annual exceedance probabilities of 0.0001 to 0.02 for year 2100 under the present climate scenarios. The highest wind speed is found to be in Miami-Dade County and the lowest is found to be in New York.

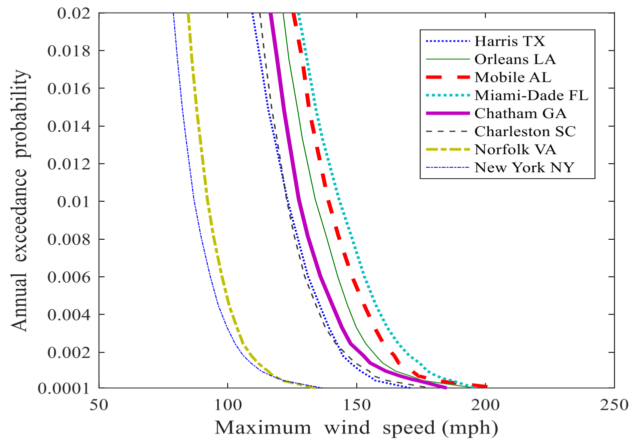

Figure 2: Hurricane wind speeds for present climate scenario.

Figure 3 shows the maximum wind speeds for future climate under RCP8.5 scenario. The wind speeds are found to increase for all the locations in future climate (30-50 mph for the exceedance probabilities shown in the Figure). However, the degree of increase is found to be different for the different locations. For example, the wind speeds within the exceedance probability of 0.0001-0.02 is found to be higher in Miami-Dade than Mobile for present climate, however they are almost equal in future climate scenario. Similar cases are also found between Harris and Charleston, Norfolk and New York etc. This shows that climate change would have a variable degree of impact in wind speeds across the different locations.

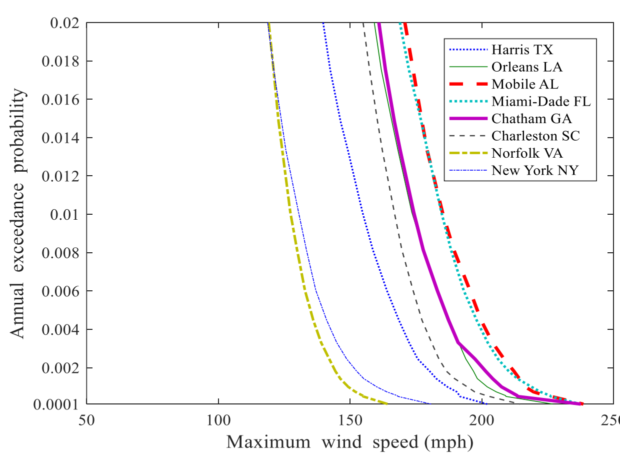

Figure 3: Hurricane wind speeds for future RCP8.5 climate scenario.

5.2. Impact of climate change on regional hurricane losses

After obtaining the wind speed and rainfall rate at the selected locations, regional hurricane losses are evaluated for present and future climate scenarios. It is noted that other factors like building number, value, inventory, exposure etc. is taken to be the same as of year 2005 since the major intention of this study is to investigate the impact of climate change on hurricane losses.

The average annual aggregated loss for present and future RCP2.6 and RCP8.5 climate scenario is shown in Figure 4. For all the climate scenarios, the highest hurricane loss is found to be in Miami-Dade and the lowest loss is found to be in Norfolk. It is to be noted that this is different than the locations of highest and lowest wind speeds for future climate under RCP8.5 scenario. This discrepancy occurs since hurricane losses are not just a function of wind speed but also of other factors like the number and value of buildings in the region, hurricane radius, rate of decay of hurricanes etc. For example, even though Mobile has comparable wind speeds to Miami-Dade, however the building value as well as the number of houses are found to be much lower in Mobile. This results in lower losses in Mobile compared to Miami-Dade. Similar kind of discrepancy between wind speed and hurricane loss is also observed in Chatham and Orleans, Harris and Orleans etc.

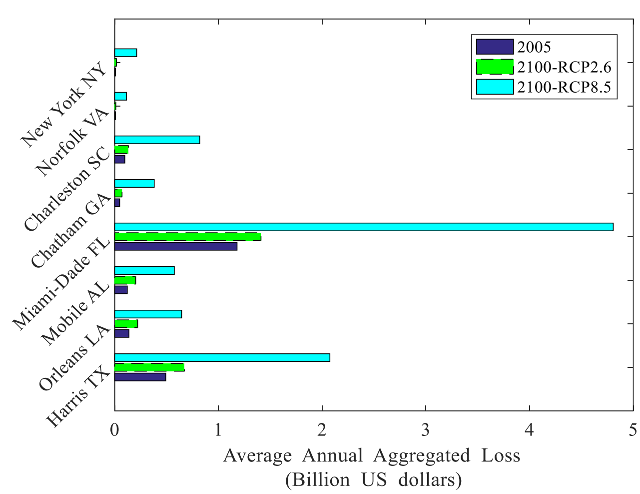

Figure 4: Average annual aggregated loss for the selected locations.

In order to better compare the impact of climate change across the different regions, the ratio of average regional losses in future (RCP8.5 and RCP2.6 scenarios) to present climate is evaluated at each location as shown in Figure 5. The ratio helps normalize for factors like building density, size of the selected location, value of buildings etc., hence helps compare the increase in future hurricane losses among the different regions based solely on the impact of climate change.

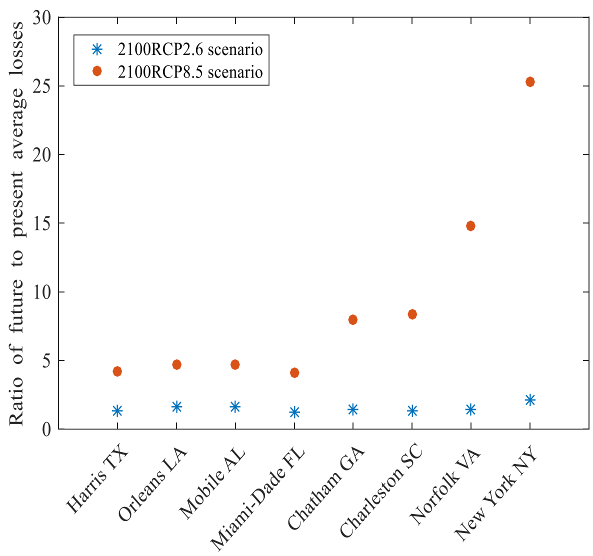

Figure 5: Increase in future hurricane losses compared to present losses.

From Figure 5, it is observed that Miami-Dade has the lowest ratio (1.2 for RCP 2.6scenario and 4.1 for RCP8.5 scenario) and New York has the highest ratio (2.1 for RCP 2.6 scenario and 25.3 for RCP8.5 scenario). It is to be noted that the ratio of increase is highest towards the Northeast side and it decreases along the South. This trend is very similar to the difference between future and present SST, i.e. the SST increase in future is highest towards the Northeast side and it decreases along the south as can be observed in Figure 1. This implies that SST of ocean adjacent to a region is a good indicator of the hurricane hazard and the corresponding regional losses. It is also to be noted that in some areas like New York, the present losses are quite low, thus even a slight increase in future losses would increase the ratio substantially.

6. CONCLUSION

This study analyzed the impact of climate change on hurricane intensity and losses across the US east coast. It is found that both hurricane wind speeds and losses increase in future climate, though the degree of increase is found to be highly variable spatially. For example, the highest increase in future to present losses is found towards the locations in the northeast side and it decreases along the south. This trend is found to be very similar to the difference between future and present SST. Since structures are expected to serve for considerable number of years, assessment of hurricane wind speed and losses spatially and temporally is vital for risk management planning for built-environment especially at the design code level.

It is to be noted that losses due to storm surge and flooding has not been considered in this study. Further, the impact of climate change on frequency have not been incorporated at present. Incorporating these factors as well could further increase the discrepancy between present and future losses.

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