Implications of Hurricane – Sea Surface Temperature Relationship

Lauren Mudd
Staff Engineer, IntraRisk Division, Applied Research Associates, Raleigh, NC, USA

Chris Letchford
Professor and Department Head, Dept. of Civil and Environmental Engineering, Rensselaer Polytechnic Institute, Troy, NY, USA

David Rosowsky
Provost, Senior Vice President, and Professor of Engineering, University of Vermont, Burlington, VT, USA

ABSTRACT: This paper presents a study to assess the impact of possible future climate change on the joint hurricane wind and rain hazard along the northeast US coastline. A postulated climate change model (IPCC scenario) was considered, which suggested changes in sea surface temperature (SST) (i.e., the driving parameter in most modern hurricane models). Relationships between SST and hurricane genesis frequency, genesis location, and track propagation were incorporated into state-of-the-art hurricane simulation procedures. Results from the SST conditioned hurricane simulations indicate the wind and rain hazards for the northeast US are likely to increase in a warmed climate, while the overall number of landfalling events is likely to decrease.

The IPCC Fifth Assessment Report (Pachauri, 2014) states warming of the climate system is unequivocal, and continued emission of greenhouse gases will cause further warming and long-lasting changes in all components of the climate system, increasing the likelihood of severe, pervasive and irreversible impacts for people and ecosystems. The consideration of extreme environmental event hazards in the presence of such warming would allow for a better understanding of the risk to our existing inventory of civil infrastructure. A more thorough understanding of future risks in turn will ensure that target safety and performance levels are met when designing structures and infrastructure systems in the future.

For US coastal regions, specifically along the Atlantic Ocean and Gulf of Mexico, a quantitative assessment of climate change impact on hurricane hazard performance levels is needed. The northeast US coast was selected as the sample study region herein for several reasons. First, the future climate scenario used in this study projects the largest increases over modern day values of sea surface temperature (SST) to occur just off the northeast US coast (see Section 2). The second motivation for choosing the northeast US as the study region comes from the current (already high) vulnerability of many areas in the region, such as New York City and Boston. In addition, increases in both population and development along coastal areas are only expected to increase the vulnerability of this region.

1. FUTURE CLIMATE PROJECTION

Representative concentration pathway (RCP) scenarios have been developed recently for climate change projections for the IPCC Fifth Assessment Report and future editions. The RCPs are projections of radiative forcing, based primarily on the forcing of greenhouse gases. This study utilizes RCP 8.5 as the future climate scenario. RCP 8.5 is a high forcing scenario, with 8.5 W/m^2 total radiative forcing in the year 2100, representing a case in which no technology or policies have been implemented to reduce greenhouse gas emissions. In comparison, the 2005 radiative forcing level, according to the IPCC fourth Assessment report, is 1.6 W/m^2. The difference between the current (2012) SST and the future (2100) projected SST in August, typically the most active hurricane month, is shown in Figure 1. The largest SST increases occur just off the coast of the study region (i.e., the northeast US/Canadian coast).

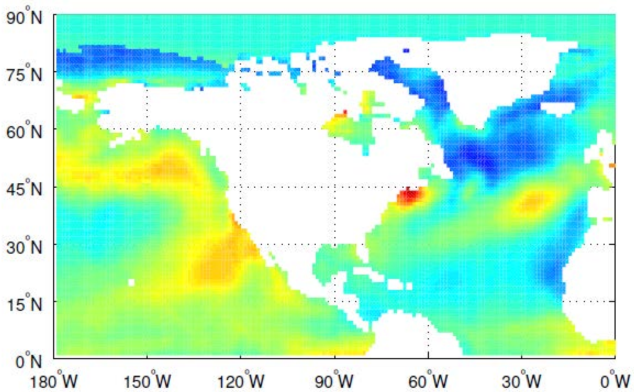

Figure 1: Projected SST change under climate scenario RCP 8.5 from August 2012 to August 2100.

2. PREVIOUS METHODOLOGY

This study builds upon state-of-the-art probabilistic hurricane simulation procedures. Key components include modeling of hurricane genesis frequency and location, gradient wind field, track propagation, central pressure, central pressure decay, and rainfall.

Due to the high variability of frequency of hurricanes from year to year, as well as physical limitations of past observing and reporting capabilities, there is no consensus regarding the completeness of the HURDAT database (Holland and Webster (2007); Mann and Emanuel (2006); Mann et al. (2007); Knutson et al. (2008); Vecchi and Knutson (2008); Landsea et al. (2010)). However, US landfalling hurricane records have been shown to be accurate from 1900 onwards (Landsea (2000)). Therefore, only historical events that made landfall in the United States are used in the development of the hurricane models herein.

The simulation of a hurricane from genesis until it is no longer hurricane strength follows a Monte Carlo simulation procedure. For each iteration (i.e., year) of the simulation, an annual hurricane genesis frequency is generated according to a Poisson process. Each simulated hurricane is first generated in the Atlantic basin with initial parameters (i.e., initial location, heading angle, translational velocity, and central pressure) based directly on a randomly selected historical hurricane contained in the HURDAT database.

The hurricane then moves along a track defined by an empirical tracking model. In developing the tracking model, the Atlantic basin was first divided into a 5º square grid. Using historical data contained in the HURDAT database, linear regression was employed to determine the heading and translational velocity in each grid cell as a function of latitude, longitude, and previous values of heading and translational velocity. Further detail on the tracking model can be found in Mudd et al. (2014), Vickery et al. (2000b).

At each subsequent 6-hour interval, the central pressure, gradient wind field and rainfall are obtained. The central pressure model is identical to that presented in Vickery et al. (2000a), which in turn is based upon the relative intensity concept presented in Darling (1991). The gradient wind field model is presented in Georgiou (1985). The rainfall model employed here is a Weibull construct, wherein the scale and shape parameters are dependent upon the gradient wind field, the sea surface temperature, and the location of the hurricane eye.

3. ANALYSIS: TIME AND SST

The gradient wind field, central pressure, central pressure decay, and rainfall models used herein include a T_s term. Therefore, possible changes in hurricane behavior due to climatological effects can be assessed, using SSTs from both the current climate and from future projected climate scenarios as input to those models. The genesis and track propagation models, however, do not include T_s and therefore cannot be investigated in this way. In this section, trends in genesis frequency, genesis location, and track propagation are explored. First by examining whether a temporal trend exists in the historical record, and second by examining any relationship that exists with SST.

3.1. Genesis Frequency

Genesis of hurricanes was simulated according to a Poisson arrival process. With the decision to only utilize landfalling hurricane records, linear regression was used to fit a trend to the 20-year moving average landfalling hurricane frequency. As can be seen in Figure 2, no trend is apparent (versus a clear increasing trend when utilizing the complete HURDAT database). The annual occurrence rate, for both the current (2012) and future (2100) climate scenarios, was found to be approximately 2.9 hurricanes per year.

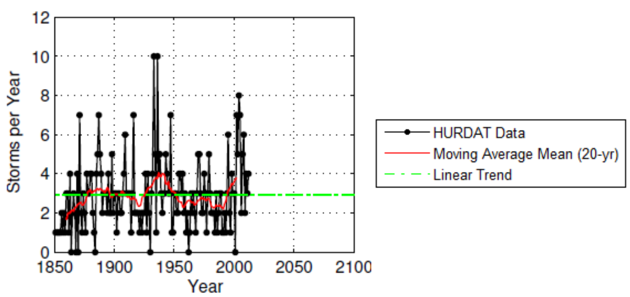

Figure 2: Projected SST change under climate scenario RCP 8.5 from August 2012 to August 2100.

An alternative method of investigating climate induced changes in hurricane frequencies would be to identify some trend in annual occurrence rates directly with SST, instead of indirectly with time. In order to do this, an average value of SST in the main development region (MDR) is obtained for each year by averaging the historical SST values from July to October over the North Atlantic MDR. The MDR in this study extends from 5ºN to 25ºN between the African and Central American coasts.

First the relationship between the number of US landfalling hurricanes and Atlantic basin hurricanes with MDR SST was examined using regression analysis. To minimize uncertainty arising from the completeness of the HURDAT database, only data from the start of routine aircraft reconnaissance measurements (1948) to the present is utilized. US landfalling hurricanes show a weak correlation at the 5% significance level (R^2 = 0.0715) when related directly to MDR SST. Relating all hurricanes generated in the Atlantic basin to MDR SST reveals a significant trend at the 5% significance level, with a higher R^2 value of 0.2217. Furthermore, a significant relationship was also noted between Atlantic basin hurricanes and US landfalling hurricanes at the 5% significance level, with an R^2 value of 0.2994.

Acknowledging that a significant relationship exists at the 5% significance level between the number of Atlantic basin hurricanes with MDR SST and with the number of US landfalling hurricanes, a prediction scheme is developed using MDR SST to first predict the annual number of hurricanes generated in the Atlantic basin and then to predict the number of Atlantic basin hurricanes that will actually make landfall in the US. This analysis builds upon the previous work of Jewson et al. (2008). Using the two statistically significant relationships does not change the relationship between the number of US landfalling hurricanes and MDR SST, but results in a narrowing of the 95% confidence bounds. The final relationship between US landfalling hurricanes and MDR SST is shown in Figure 3. The genesis prediction scheme uses linear relationships between MDR SST, Atlantic basin hurricanes, and US landfalling hurricanes to determine the Poisson arrival rate (λ) used to generate pseudo-random annual hurricane

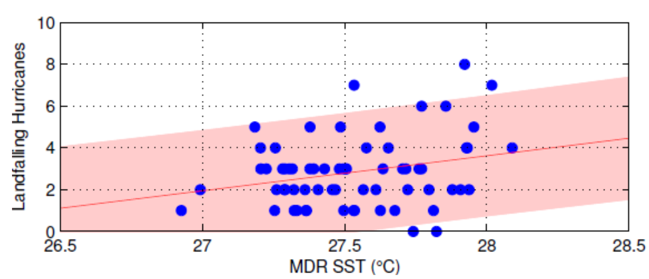

Figure 3: Relationship between US landfalling hurricanes vs. MDR SST. Historical data (blue), best-fit and 95% confidence bounds (red).

occurrence rates within the simulation procedures.

3.2. Genesis Location

Historical hurricane genesis locations were analyzed to identify possible temporal trends. Unlike the genesis frequency analysis, only US landfalling events were considered in the assessment of genesis location. The genesis locations, obtained from the HURDAT dataset for the period 1851-present, were first divided into eight approximately 20-year periods, as well as three approximately 50-year periods. The 20-year period was chosen as it has been shown to cover both the active and inactive phases of the decadal oscillation cycle. The 50-year period was chosen, somewhat subjectively, in light of the limited amount of historical data occurring in some 20-year periods.

Histograms were then created using a 1º square spatial grid of the Atlantic basin, and recording the number of occurrences in each grid cell for the period of interest. In order to make a meaningful comparison of genesis locations over time, the resulting histograms were normalized for each time period of interest. The distribution of genesis location in the Gulf of Mexico becomes more concentrated further north with time, while genesis location in the MDR remains relatively unchanged. The average MDR SST during the periods 1851-1911, 1912-1961, and 1962-2012 was 27.22, 27.38, and 27.54ºC respectively. No spatial or temporal trends were found using the 20-year segmented data, likely due to the relatively small number of US landfalling hurricanes captured in each time period.

Similar to the normalized histograms from the temporal analysis, probability density functions (PDFs) were created to assess the relationship between genesis location of US landfalling events and MDR SST. This assessment builds upon analysis of Hall and Jewson (2007) and Hall and Yonekura (2013), where genesis location was modeled using steady-state Gaussian kernel density estimation. Hall and Jewson (2007) utilized all hurricane events occurring in the Atlantic basin from 1950 to 2003 (i.e., high quality data after the advent of routine aircraft reconnaissance) as the basis for their analyses. Hall and Yonekura (2013) then used the Hall and Jewson (2007) genesis model to assess what effect genesis location in a warmed climate would have on the number of hurricane events that made landfall in the US.

The genesis location PDFs were obtained by the summation of two-dimensional Gaussian kernel density estimates (Hall and Jewson (2007)) as in Eq. 1, which were conditioned on yearly averaged MDR SST.

$$f(\psi,\chi)=\frac{1}{2\pi NL^2}\sum_{i=1}^{N}\exp\left[\frac{-D_i^2}{2L^2}\right] \tag{1}$$

where $f(\psi,\chi)$ = the PDF at location at latitude ψ and longitude χ, D = the distance between location (ψ,χ) and the ith genesis site, and L = bandwidth of the genesis location PDF. In order to condition the PDF on MDR SST, the historical genesis locations were first binned according to the yearly averaged value of MDR SST. MDR SST bins with a range of 0.5ºC, centered every 0.1ºC were employed. Once the PDFs corresponding to each value of MDR SST were obtained, regression analysis was used to determine the probability density of genesis location as a linear function of SST.

The bandwidth of the PDF was optimized by maximization of the coefficient of determination R^2. When the value of L is too small, the genesis PDF is concentrated around many local maxima; when the value of L is too large, trends in the genesis location are smoothed out. The optimal value of L was found to be 125 km, with an R^2 value of 0.86. Figure 4 shows the normalized histogram of historical genesis locations and the normalized Gaussian kernel genesis location PDF, which compare quite favorably.

With confidence in the MDR conditional genesis location PDF to replicate the historical data, a future genesis location PDF was conditioned on the value MDR SST under RCP

8.5 for the year 2050 and 2100. The normalized PDF for the year 2100 is shown in Figure 4. The increase in MDR SST for the year 2100 is 1.90ºC. In general, as MDR SST increases, the distribution of genesis location in the Gulf of Mexico appears to be concentrated further north, just off of the Gulf Coast of the US. Along the east coast of the US, genesis concentration decreases with increasing MDR SST. Interestingly, the distribution of genesis location in the MDR displays only slight shifts.

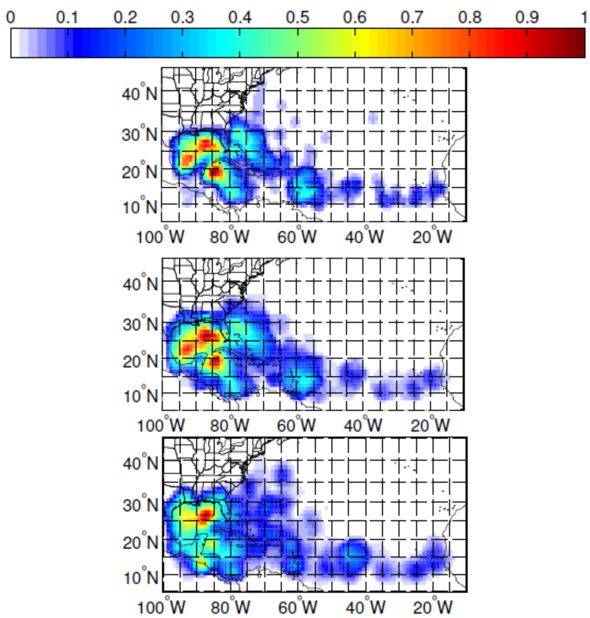

Figure 4: (top) Normalized histogram of historical genesis locations of US landfalling hurricanes (1851-2012), and normalized Gaussian kernel genesis location PDF with a bandwidth of 125 km for (middle) 2012 and (bottom) 2100.

3.3. Track Propagation

Two approaches were used to identify a trend in hurricane track with time. The first approach involved visual inspection of the historical hurricane tracks themselves, to identify any overall trends between the time periods chosen. From the historical tracks of hurricanes that made landfall in the US, segmented into approximately 50-year periods, no trend was evident in the behavior of the hurricane tracks with time. Next, the eastern US coast and Gulf of Mexico were segmented into five different regions, and landfalling rates in each region were analyzed over time in order to determine if there existed any obvious change in the spatial or temporal distribution of landfall locations with time. No trend in hurricane track over time was seen for any area. Additionally, the spatial distribution of landfalls remains relatively constant over all time segments. Therefore, no clear trend in hurricane track could be identified qualitatively (e.g., changes in tracks over time) or quantitatively (e.g., changes in landfall rates over time).

Several studies (Elsner (2003); Elsner & Jagger (2006); Hall & Yonekura (2013)) have shown hurricane tracks to behave differently in varying climate states. Having found no trend in hurricane track propagation with time, this study then analyzed the variation in hurricane track behavior directly with SST. In order to do so, three variations of the empirical tracking model were considered. The first candidate model included the effects of the relationship between SST and translational velocity; the second candidate model included the effects of the relationship between SST and heading angle; and the third candidate model included the effects of the relationship between SST and both components of the empirical tracking model. The relationships of the translational velocity and heading angle with SST were considered through the inclusion of a T_s term in the equations of the empirical tracking model as in Eq. 2 and Eq. 3 respectively. .

$$\Delta \ln(V_T) = a_1 + a_2\psi + a_3\chi + a_4 \ln(V_T) + a_5\theta_i + a_6 T_s + \varepsilon \quad (2)$$

$$\Delta \theta = b_1 + b_2\psi + b_3\chi + b_4 V_T + b_5\theta_i + b_6\theta_{i-1} + b_7 T_s + \varepsilon \quad (3)$$

where V_T = translational velocity, ψ = latitude at eye, χ = longitude at eye, θ = heading, and T_s = SST at eye. The Atlantic basin was divided into a 5º square grid, and regression analysis of the HURDAT data was used to obtain values of the coefficients a_i and b_i for each grid location. For grid locations with little or no hurricane data, the coefficients were assigned the values from the nearest grid location. A unique set of coefficients was obtained for easterly and westerly moving hurricanes. The candidate tracking models conditioned on SST were used to simulate 10,000 years of hurricanes with initial conditions (e.g., latitude, longitude, translational velocity, heading angle, central pressure) in the current climate.

A comparison of 100 storms simulated in the current climate using each of the candidate models versus a subset of historical tracks is shown in Figure 5. It is clear that the inclusion of a SST term directly in the computation of the hurricane heading introduces unrealistic variation in the track behavior. Landfalling rates corresponding to Figure 5 are presented in Table 1, for the five segmented regions of the eastern US coast. Again, it is clear that the candidate models considering a direct relationship between SST and the hurricane heading angle are not able to reproduce historical tracking behavior. From both Figure 5 and Table 1 however, the candidate model which only considers the direct relationship between SST and hurricane translational velocity ($T_S - V_T$) produces results which agree quite well with the historical data in overall track behavior as well as in the rate of landfall on the US coast.

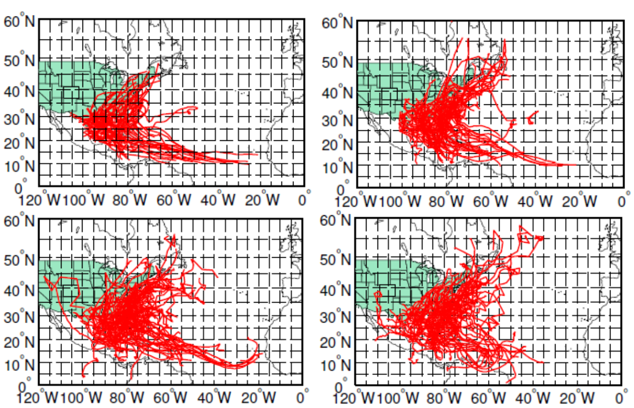

Figure 5: (top-L) Historical tracks of US landfalling hurricanes (1962-2012); Simulated tracks of 100 storms in the current climate produced from tracking paramters with SST considerations in relation to (top-R) translational velocity only, (bottom-L) heading only, and (bottom-R) translational velocity and heading.

It should be noted that in this tracking model, the hurricane heading angle and translational velocity are coupled. Therefore, although a direct relationship between SST and hurricane heading angle was not apparent, effects of changing SSTs on the hurricane heading angle are implicitly considered through the effects of changing SST on the translational velocity.

Table 1: Observed historical rate of landfall and simulated current climate rate of landfall of empirical tracking models conditioned on SST for regions of eastern US coast.

	NE	VA-GA	E. FL	GoM	TX
Historical	0.11	0.37	0.35	1.02	0.40
$T_S - V_T$	0.12	0.36	0.37	1.08	0.43
$T_S - \theta$	0.08	0.18	0.14	0.56	0.18
$T_S - V_T, \theta$	0.10	0.29	0.24	0.76	0.29

4. SIMULATION

The historical rate of landfalling hurricanes for the northeast US coast was found to be approximately 0.11 per year. The simulated landfalling rate in the current climate, for all model variations, was approximately 0.12 to 0.13 hurricanes per year, for all scenarios. Considering the effects of SST only on the hurricane genesis frequency, the annual landfalling rate in the future climate scenario approximately doubled to 0.25 hurricanes per year. The landfalling rate reduced when considering the effects of SST on hurricane genesis location and track propagation, to 0.07 and 0.09 hurricanes per year respectively. When considering the effects of SST on all components of the hurricane, the simulated landfalling rate in 2100 was approximately 0.08 hurricanes per year. These results indicate that in a warmed climate, more events may be produced, but fewer would actually make landfall in the northeast US.

The focus of this study is to probabilistically characterize the hurricane hazards at the time of landfall. To concomitantly characterize the hurricane hazards, a histogram can be constructed in four-dimensional space, using maximum surface wind speed (V_{max}), radius of maximum winds (R_{max}), and rate of rainfall (*RR*) recorded at the time of landfall. Bin sizes of 2 m/s, 10 mm/day, and 10 km were used for wind speed, rainfall intensity, and storm size, respectively. The annual exceedance probability is obtained from the histogram by dividing the number of data points within a specified bin by the total number of data points, and multiplying by the annual hurricane occurrence rate. Hazard levels, with different annual exceedance probabilities, can then be defined by three-dimensional equi-probability surfaces. The hazard level can also be described as an MRI or as an exceedance probability in N years (e.g., 2%/50 years). The hazard surfaces for the current climate scenario and future RCP 8.5 climate scenario are shown in Figure 6, considering the relationships between SST and all hurricane components.

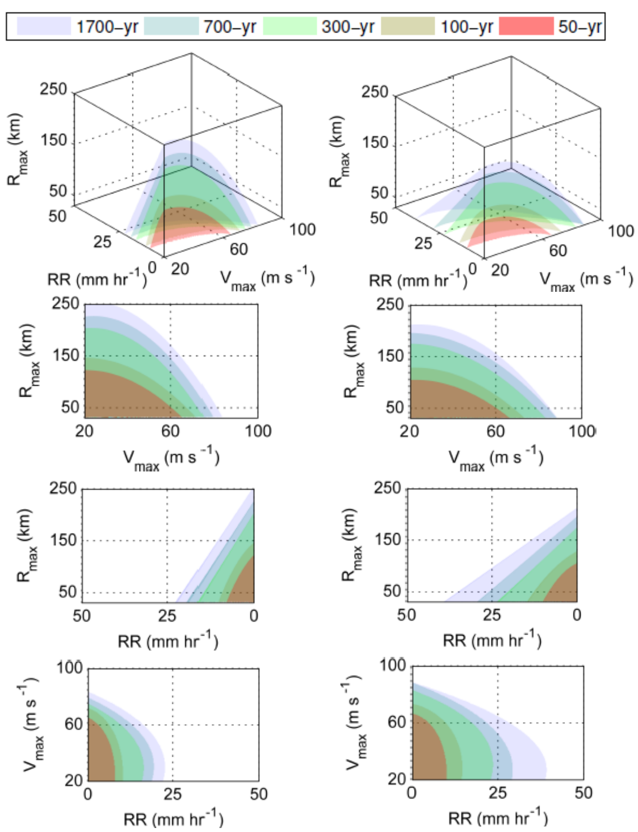

Figure 6: Trivariate hazard level (MRI) surfaces for the northeast US coast under the current (2012) climate scenario (left) and the future (2100) RCP 8.5 climate scenario (right).

Concomitantly characterizing the hurricane hazards, and considering the effects of possible future changes in SST on the hurricane genesis frequency, V_{max} and *RR* are projected to increase 13% and 48% respectively, for the 700-year MRI. This is due to the large number of events making landfall in the northeast US in this scenario. Considering the effects of possible future climate changes in SST only on the hurricane genesis location (track propagation) results in less drastic increases in V_{max} and *RR* of 7% and 15% (6% and 22%) respectively, for the 700-year MRI. Including the effects of changes in SST on all components of the hurricane simulation, the projected changes in the values of V_{max} and *RR* for the 700-year MRI under RCP 8.5 are approximately 10% and 50%.

5. CONCLUSIONS

Using state-of-the-art empirical, event-based hurricane models, an analysis was presented to investigate possible future climate change impact on the hurricane wind and rain hazards. Sea surface temperature served as the index of climate change herein. Future SSTs were obtained from projected climate change scenario RCP 8.5, developed for the IPCC Fifth Assessment Report. The influence of changes in SST on the hurricane intensity, size, genesis frequency, genesis location, and track propagation were considered separately and together. A total of 10,000 years of hurricane events under the current (2012) and future (2050 and 2100) climate scenarios, was simulated to produce a synthetic hurricane database for every zip-code in the study region.

The US northeast coastline was used as the study region. The results of this analysis indicate that the number of landfalling hurricane events in the northeast US is likely to decrease in a warmed climate. However, the hurricane hazards in the study region were projected to increase at each design level (e.g., 300, 700, and 1700-year MRIs) under the RCP 8.5 climate scenario. In addition, increases in both population and development along coastal areas are only expected to increase the vulnerability of this region. As seen in recent hurricanes (e.g., Irene, 2011; Sandy, 2012) even moderate hurricanes are able to have devastating impacts in the region.

6. REFERENCES

Darling, R. (1991). Estimating probabilities of hurricane wind speeds using a large scale empirical model. *Journal of Climate*, *4* (10), 1035-1046.

Elsner, J. B. (2003). Tracking hurricanes. *Bulletin of the American Meteorological Society*, *84* (3), 353-356.

Elsner, J. B., & Jagger, T. H. (2006). Prediction models for annual US hurricane counts. *Journal of Climate*, *19* (12), 2935-2952.

Georgiou, P. N. (1985). *Design wind speeds in tropical cyclone-prone regions* (Doctoral Dissertation). Retrieved from University of Western Ontario Digitized Theses. (1523).

Hall, T., & Yonekura, E. (2013). North American tropical cyclone landfall and SST: a statistical model study. *Journal of Climate*, *26* (21), 8422-8439.

Hall, T. M., & Jewson, S. (2007). Statistical modelling of north Atlantic tropical cyclone tracks. *Tellus A*, *59* (4), 486-498.

Holland, G. J., & Webster, P. J. (2007). Heightened tropical cyclone activity in the North Atlantic: natural variability or climate trend? *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *365* (1860), 2695-2716.

Jewson, S., Binter, R., Khare, S., Nzerem, K., & O'Shay, A. (2008). *Predicting basin and landfalling hurricane numbers from sea surface temperature*. Retrieved June 21, 2013, from arXiv.org/abs/physics/0701170.

Knutson, T. R., Sirutis, J. J., Garner, S. T., Vecchi, G. A., & Held, I. M. (2008). Simulated reduction in Atlantic hurricane frequency under twenty-first-century warming conditions. *Nature Geoscience*, *1* (6), 359-364.

Landsea, C. W. (2000). Climate variability of tropical cyclones: past, present and future. In *Storms* (Vol. 1, pp. 220-241). London, UK: Routledge Press.

Landsea, C. W., Vecchi, G. A., Bengtsson, L., & Knutson, T. R. (2010). Impact of duration thresholds on Atlantic tropical cyclone counts. *Journal of Climate*, *23* (10), 2508-2519.

Mann, M. E., & Emanuel, K. A. (2006). Atlantic hurricane trends linked to climate change. *EOS, Transactions American Geophysical Union*, *87* (24), 233-241.

Mann, M. E., Sabbatelli, T. A., & Neu, U. (2007). Evidence for a modest undercount bias in early historical Atlantic tropical cyclone counts. *Geophysical Research Letters*, *34* (22), 1-6.

Mudd, L., Wang, Y., Letchford, C., & Rosowsky, D. (2014). Assessing Climate Change Impact on the US East Coast Hurricane Hazard: Temperature, Frequency, and Track. *Natural Hazards Review*, *15* (3), 1-13.

Pachauri, R. K. (2014). *Climate change 2014. synthesis report. contribution of working groups I, II and III to the fifth assessment report.* Geneva, CH: Intergovernmental Panel on Climate Change.

Vecchi, G. A., & Knutson, T. R. (2008). On estimates of historical north Atlantic tropical cyclone activity. *Journal of Climate*, *21* (14), 3580-3600.

Vickery, P. J., Skerlj, P., Steckley A. & Twisdale, L. (2000a). Hurricane wind field model for use in hurricane simulations. *Journal of Structural Engineering*, *126* (10), 1203-1221.

Vickery, P. J., Skerlj, P., & Twisdale, L. (2000b). Simulation of hurricane risk in the US using empirical track model. *Journal of Structural Engineering*, *126* (10), 1222-1237.