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Hurricane wind hazard assessment for a rapidly warming climate scenario

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ABSTRACT

Although there is still much debate as to the causes, it is generally accepted in the scientific community that the climate is changing. The IPCC (2007) Fourth Assessment Report states that warming of the climate system is unequivocal, and that this warming has likely influenced observed changes in many physical systems at the global scale. In order to meet target safety and performances levels when designing structures and infrastructure systems in the future, it is essential that current design codes and standards adapt to reflect global climate change. With the trend toward performance-based engineering, for US coastal regions, along the Atlantic Ocean and Gulf of Mexico, this means a quantitative assessment of climate change impact on hurricane hazard performance levels is needed.

This study couples a projected climate change scenario with state-of-the-art probabilistic event-based simulation procedures to assess the hurricane wind hazard under a worst-case climate change scenario. The hurricane wind hazard is defined herein using the hurricane intensity (maximum wind speed) and hurricane size (radius to maximum wind speed). Through Monte Carlo simulation, 10,000 years of hurricane events, under the current (2012) and future (2100) climate conditions, were generated. The hurricane intensity distribution and the joint distribution of hurricane intensity and size, under current and future climate scenarios, were then compared.

1. Introduction

Hurricanes cause extreme weather and severe damage along impact zones, such as the US east coast, putting major urban population centers at risk. In 2012, US landfalling hurricanes accounted for 143 of the 284 US fatalities caused by natural disasters, and over $52 billion in losses (Rosenthal et al., 2013). The severity of hurricane hazards has led to many studies seeking to improve forecasting, warning and evacuation. However, as meso-scale meteorological events hurricanes are affected by climate change (Emanuel, 1987, 2008; Bender et al., 2010), the impact of which has received little attention to date. In order to continue to ensure the safety of our built world in the future, current design codes and standards must be adapted to account for future climate change impacts on hurricane hazards (wind, surge, flood). The study performed herein makes use of similar probabilistic simulation procedures used in the development of wind speed maps contained in the US design standard ASCE 7 from the years 1993 (ASCE, 1993) through 2010 (ASCE, 2010), and can serve as a basis for updating coastal design wind speeds for future editions.

There have been some initial studies to examine the effect of climate change scenarios on wind, storm surge and flooding in recent years. Nishijima et al. (2012) conducted an impact assessment of climate change on the northwest Pacific typhoon wind risk, focusing on potential damages to residential buildings in Japan. In their work, typhoons were simulated using the Atmospheric General Circulation Model (AGCM) under the 2005 and future climate scenarios. Similar procedures were adopted herein; however, the atmospheric model, the projected scenarios and hurricane models are different, as explained in the following sections. Irish. (2008) examined the influence of climate change on hurricane flooding for Corpus Christi, TX and Lin et al. (2012) investigated the influence of climate change on hurricane induced storm surge for New York, NY. However, the hurricane models used in the two previous studies were deterministic.

The availability of the historical Hurricane Database (Hurdat, 2013) maintained by the National Hurricane Center (NHC) has enabled event-based simulation procedures (Vickery et al., 2000a,2000b) to be developed in the public sector. In Mudd et al. (2014), state-of-the-art hurricane prediction models were used to

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simulate hurricanes in the year 2100 under IPCC climate change scenario RCP 8.5. A framework developed by Lee and Rosowsky (2007) was then implemented to develop a hurricane wind speed database for the Northeast US coast, including the states of Maryland, Delaware, New Jersey, Pennsylvania, New York, Connecticut, Rhode Island, Massachusetts, Vermont, New Hampshire and Maine, under both the 2005 and future climate states. Note that although Vermont and Pennsylvania are not coastal states, they have been affected by hurricanes in the past (e.g., Irene in 2011) and were considered as part of the hurricane-prone US Northeast. Key components of the simulation framework used in Mudd et al. (2014) were the gradient wind-field model (Georgiou, 1985) and the tracking and central pressure models (Vickery et al., 2000a, 2000b). The post-landfall decay model proposed by Vickery and Twisdale (1995) was used with site specific decay constants determined through statistical analyses of historical data. Finally, trends in hurricane genesis frequency and hurricane track were also explored.

The assessment presented herein represents an update to the analysis performed in Mudd et al. (2014). Since the development of the hurricane simulation techniques (Vickery et al., 2000a, 2000b) used in Mudd et al. (2014), significant improvements have been made (Vickery et al. 2009). These improvements consist of an updated statistical model for the determination of the Holland pressure profile parameter and the radius to maximum winds (Vickery and Wadhera, 2008), and a new model for hurricane decay after landfall (Vickery, 2005). In addition, several major hurricane events have occurred since 2005, which was used as the current scenario in Mudd et al. (2014). The study presented herein makes use of all available historical hurricane data to extend the current scenario to the year 2012. In addition, the most current historical hurricane database (HURDAT, 2013) incorporates findings of several re-analysis projects (Landsea et al., 2004a, 2004b, 2008, 2012; Hagen et al., 2012) to correct errors and biases that have previously appeared in the historical data. While storm surge and flooding due to hurricanes also cause damage, only the direct hurricane wind hazard (maximum wind speed and storm size) is considered herein. The Northeast US coast was selected as the sample study region; however, the framework can be applied in other hurricane affected regions as well. Details of the projected future climate change scenarios and the probabilistic hurricane simulation models are described in the following sections.

2. Projected future climate change scenarios

Representative Concentration Pathway (RCP) scenarios have been developed recently for climate change projections for the IPCC Fifth Assessment Report (to be published October 2014) and future editions. A discussion of the RCP scenarios can be found in Mudd et al. (2014). In this study, only the worst-case projected future climate change scenario, RCP 8.5, was considered. RCP 8.5 is a “high forcing” scenario with 8.5 W/m^2 total radiative forcing in the year 2100. Comparatively, the 2005 radiative forcing level, according to IPCC Fourth Assessment Report (IPCC, 2007), is 1.6 W/m^2. The radiative forcing estimates are primarily based on the forcing of greenhouse gases. All climate change scenarios from January 2005 to December 2100, based on the RCP 8.5 pathway projection, were simulated using the Community Earth System Model (CESM, 2012). CESM (2012) is a fully coupled, global climate model that provides state-of-the-art computer simulations of the Earth's past, present, and future climate states. As the driving parameter of most hurricane models, the monthly average sea surface temperature (SST) values were then extracted from the CESM (2012) simulation for use in the hurricane simulation procedures described in the following section. The SST values were originally stored on a displaced-pole grid and were transformed to lie on the regular rectangular $1^\circ \times 1^\circ$ grid. The difference between the current and future SST in August, the most active hurricane month, is shown in Fig. 1. As shown in Fig. 1, the largest SST increases are along the Northeast US/Canadian coast.

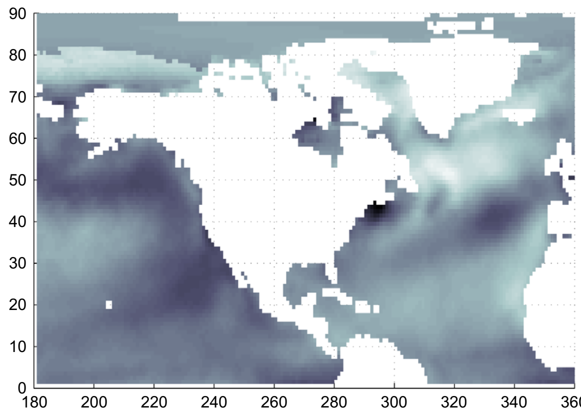

Fig. 1. Projected SST change (°C) under climate change scenario RCP 8.5 from August 2012 to August 2100.

3. Probabilistic hurricane modeling and simulation procedures

3.1. Hurricane genesis model

Simulated hurricanes are generated according to a Poisson arrival process. Considering all storms generated in the Atlantic basin and assuming a constant annual hurricane occurrence rate with time, the annual hurricane occurrence rate, λ, for the year 2012 was found to be 8.4 based upon work performed by Lee and Rosowsky (2007). Also considering all storms generated in the Atlantic basin, Mudd et al. (2014) used a least-squares regression to fit a linearly increasing trend to the annual hurricane occurrence rate and found λ for the year 2100 to be 13.9. However, when considering only historical hurricanes that made landfall in the US, no linearly increasing trend in annual hurricane occurrence rates is seen (Mudd et al., 2014), and λ is found to be approximately 2.9 hurricanes per year. The historical data and fitted trends are shown in Fig. 2 for all hurricanes occurring in the Atlantic basin and for only hurricanes making landfall in the US.

Several recent studies (Mann and Emanuel, 2006; Holland and Webster, 2007; Mann et al., 2007; Knutson et al., 2008; Landsea et al., 2010; Vecchi and Knutson, 2008) have examined the completeness of the HURDAT database and its validity in determining the frequency of occurrence of historical hurricane events. Due to the high variability of frequency of storms from year to year, as well as physical limitations of past observing and reporting capabilities, no consensus has been reached on the subject. However, in regards to the accuracy of the record of US landfalling hurricanes, there is little debate. Using population data from US census reports and other historical analyses, Landsea et al. (2004a) provided dates for when landfalling hurricane records in specified regions of the US could be deemed accurate. For every geographical region considered, they concluded that the records were accurate after 1900, and that the records along the US Northeast coast may be accurate as far back as 1660. In order to remove a source of uncertainty from the simulations performed herein, this study utilizes an annual hurricane genesis frequency based only upon historical events that made landfall in the US. In addition, limiting the number of historical hurricanes to only those that made landfall in the US results in a lower annual hurricane genesis frequency to be used during simulation (since the number of hurricanes generated that hit the US annually is much less than the total number of hurricanes generated