HURRICANE HAZARD ASSESSMENT:
CONSIDERATIONS FOR SEA-LEVEL RISE AND CLIMATE CHANGE

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Assessment of hurricane flooding risk is an essential component for effective coastal planning and engineering design. Existing methods for evaluating extreme-value flood statistics traditionally assume that flood conditions are stationary, such that historical information represents future conditions. However, dynamic changes in the environment, specifically changing sea levels and potential changes in hurricane intensity and rate of occurrence, mean that future flooding risk will not be adequately represented by historical conditions alone. In this paper, an approach is proposed for incorporating future sea level and hurricane climate projections into extreme-value flood probabilities and risk assessment.

Keywords: Storm surge; extreme-value statistics; hurricanes, risk

INTRODUCTION AND BACKGROUND

Here, the influence of long-term climate change on hurricane flooding statistics is considered. The impact of long-term future climate change is difficult to quantify with a high degree of certainty. However, a growing body of literature supports a future global warming trend. The Intergovernmental Panel on Climate Change (IPCC 2007) reported sea-surface temperature (*SST*) rise projections of 1.1 ^{o}C to 6.4 ^{o}C over the next century. With potential global warming, the IPCC (2007) concluded that sea-level rise (*SLR*) will most likely continue to accelerate, with *SLR* projections for the next century being 0.18 to 0.60 m; others reported *SLR* projections of more than 1 m over the next century when major ice-sheet melting is considered (e.g., Overpeck et al. 2006; Pfeffer et al. 2008; Rahmstorf 2007).

Climatology analyses support the hypothesis that tropical cyclones will intensify with global warming (e.g., Elsner et al. 2008; Emanuel et al. 2008; Knutson and Tuleya 2008; Vecchi and Soden 2007; Webster et al. 2005). Knutson et al. (2010) summarized the results of these studies by concluding that tropical cyclone wind intensity is expected to increase by 2 to 11% by 2100. While hurricanes are expected to intensify with global warming, recent studies concluded that the rate of occurrence of hurricanes might diminish with global warming. By review of a number of tropical cyclone frequency forecasting studies (e.g., Bengtsson et al. 2007; Gualdi et al. 2008; Oouchi et al. 2006; Zhao et al. 2009), Knutson et al. (2010) concluded that tropical cyclone frequency will either remain unchanged or decrease somewhat with future global warming, by 6 to 34% by 2100.

In the following, we present a method for assessing future hurricane flooding and damage statistics, with sample results shown for the Houston-Galveston region along the United States Gulf of Mexico coastline.

STUDY AREA

The study area is the Houston-Galveston coastline along the northern United States Gulf of Mexico (Figure 1). This area is highly populated and supports an array of industries, including oil and gas and tourism. This region is also prone to hurricane activity, and much of the coastal area is low-lying, making the region susceptible to coastal flooding. Surge generation in this region is dominated by wind surge, due to the rapidly widening continental shelf offshore of the study area. Over the last half decade, this region has been impacted by surges generated by Hurricanes Katrina, Rita, and Ike. The most recent significant flooding event was Hurricane Ike, which made landfall as a Category 2 hurricane in September 2008. This storm devastated the coastal region, and was associated with surges in excess of 4 m along much of the study area.

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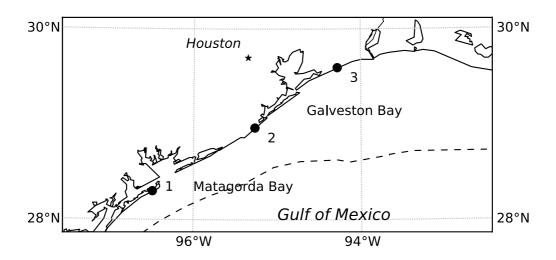[4] Civil Engineering, Texas A&M University, 3136 TAMU, College Station, TX, 77843, USA

Figure 1. Location map, where the Houston-Galveston study area lies between locations 1 and 3. The shoreline is given by the solid line while the 30-m depth contour is given by the dashed line.

METHODS

Future-Climate Surge Prediction with Surge Response Functions (SRF)

Peak hurricane flood elevation at some location x, $z_{max}(x)$, is a function of hurricane meteorological conditions, future SST and mean sea level (MSL) conditions, and regional and local topographic conditions. Thus, flood elevation can be written as (Irish and Resio in press):

$$z_{\max}\left(x, SST\right) = \phi\left(x, p_o\left(SST\right), R, v_f, \theta, x_o, MSL\left(SST\right)\right) + \varepsilon_z \qquad (1)$$

where ϕ is a continuous flood response function, x is location of interest, x_o is landfall location, R is hurricane radius, θ is hurricane track angle with respect to the shoreline, v_f is hurricane forward speed near landfall, and ε_z is epistemic uncertainty in the flood response (Resio et al. 2009; Resio et al. in press). Here, analysis is limited to open-coast water levels; thus we will assume that the total flood elevation in the future may be represented by the product of the storm surge (ζ_{max}) and change in MSL (ΔMSL), such that $\phi = \zeta_{max} + \Delta MSL$. We will further assume that the effects of track angle and forward speed on surge generation are small, with respect to other factors. For this case, ζ_{max} may be estimated from the dimensionless, algebraic surge response functions of Song et al. (in press):

$$\zeta' = \frac{\gamma \zeta_{\max}}{\left(p_{far} - p_o\right)} + m\left(x, x'\right)\left(\frac{p_{far} - p_o}{p_{far} - p_{o-\min}}\right)^{\alpha\left(x, x'\right)}\left(\frac{R/L\left(x_o\right)}{\left[R/L\right]_{ref}}\right)^{\alpha\left(x, x'\right)} \qquad (2a)$$

$$x' = \frac{\left(x - x_o\right)}{R} - \lambda\left(x_o\right) + cH\left(\frac{\left(x - x_o\right)}{R} - \lambda\left(x_o\right) - 1\right)H\left(\frac{L\left(x_o\right)}{L_{ref}} - 1\right)\left(\frac{R}{L\left(x_o\right)}\right) - F\left(1 - \frac{R}{R_{thres}}\right) \text{(2b)}$$

where p_{far} is far-field barometric pressure, L is cross-shore distance from the shoreline to the 30-m depth contour, H is the Heaviside step function, F is a kernel function, and the remaining parameters are location-specific constants. See Song et al. (in press) and Irish et al. (2009) for full details on SRF development. The above model may be used to specify continuous probability density functions on flood elevation for extreme-value analysis using a joint-probability approach (Resio et al. 2009). For the case of a changing future climate, Irish and Resio (in press) proposed:

$$f\left(SST, p_o, R, x_o\right) = \Lambda_{SST}\Lambda_{p_o}\Lambda_R\Lambda_{x_o} \qquad (3)$$

where the Λ functions are the joint probabilities. Here, we will assume that (1) Λ_R is normally distributed with a dependence on p_o; (2) Λ_{xo} equals the storm rate of occurrence, uniformly distributed

along the coast; (3) Λ_{po} follows a Gumbel distribution, where the fit coefficients a_o and a_1 are allowed to slowly vary in time:

$$\Lambda_{p_o} = f\left(p_o \mid x_o, \Delta SST\right)$$

$$= \frac{1}{a_1\left(x_o, \Delta SST\right)} \exp\left[-\frac{\Delta p - a_o\left(x_o, \Delta SST\right)}{a_1\left(x_o, \Delta SST\right)} \right] \exp\left\{ -\exp\left[-\frac{\Delta p - a_o\left(x_o, \Delta SST\right)}{a_1\left(x_o, \Delta SST\right)} \right] \right\} \quad (4)$$

where $\Delta p = p_{far} - p_o$ and ΔSST is *SST* change; and (4) Λ_{SST} is uniformly distributed across all sensitivities for a given future climate storyline, where *SST* values slowly vary in time. Finally, the MSL is assumed to correlate directly with *SST*. See Irish and Resio (in press) and Resio et al. (2009) for full details on the joint probability method with optimal sampling using SRFs.

The impact of *SST* rise on *MSL* and hurricane central pressure are assessed, while future changes in hurricane intensity are not considered. We considered the IPCC (2007) A1B storyline, which assumes a future balanced allocation of energy sources with moderated future carbon emissions. The climate model MAGICC/SCENGEN (Wigley 2004; personal communications Joel Smith of Stratus Consulting) was used to develop estimates of future *SST* rise and eustatic *SLR* for two time periods, the 2040s and 2080s (Table 1), while current-day results are assumed to represent the 2000s. The following simplified relationship was employed to estimate hurricane central pressure decrease with *SST* rise (Knutson and Tuleya 2008):

$$p_{o-\Delta SST} = p_{o-2000s} - 0.08\Delta SST\left(p_{far} - p_{o-2000s}\right) \quad (5)$$

where $p_{o-\Delta SST}$ is the adjusted central pressure corresponding to ΔSST, and $p_{o-2000s}$ is the current day p_o.

Table 1. Selected eustatic sea-level rise and sea-surface temperature rise climate projections, with reference to conditions in the 2000s (modified from Mousavi et al. 2011).		
	SST rise (^{o}C)	SLR (m)
2040s, low estimate	0.58	0.11
2040s, high estimate	1.80	0.22
2080s, low estimate	1.28	0.25
2080s, high estimate	3.80	0.51

Damage Estimation

Potential economic damages were assessed from within a geographic information system, following the methods presented in Frey et al. (2010). Several simplifying assumptions were employed:
1. Economic damages were based on available relationships between flood depth and damage within the Federal Emergency Management Agency's (FEMA) HAZUS database (FEMA 2009).
2. Damage to residential, commercial, industrial, public, and agricultural structures were based on information contained in the HAZUS General Building Stock Database (FEMA 2009).
3. Inundated area was determined by intersecting the predicted surge with U.S. Geological Survey 10-m digital elevation model.
4. To simplify the analysis, damage calculation was limited to the open coastal zone extending 1.6 km inland from the open coast, such that damages in more inland coastal regions along estuaries and bays were ignored.

The Houston-Galveston coastline was segmented into 10-km segments, and then damages were tabulated by segment based on surge elevations above mean sea level of 1.5, 3.0, 4.6, 6.1, and 7.6 m. Statistical estimation of damages were made by evaluating damages associated with each surge probability. Estimated annual damages were computed by integrating the damage-frequency curve.

RESULTS AND CONCLUSIONS

Flood elevation versus return period estimates were developed for three open-coast locations in the Houston-Galveston area (see Figure 1; Song et al. in press); estimates were developed for the decades of the 2000s (current day), 2040s, and 2080s (Figure 2). In this area, flood elevations are estimated to increase by 10 to 14% by the 2040s and by 21 to 30% by the 2080s. Most extreme flood elevations

during all time periods are expected in the northeastern portion of the study area. Along the open coast estimated annual damages are estimated to increase by about 20% by the 2040s and by about 40% by the 2080s.
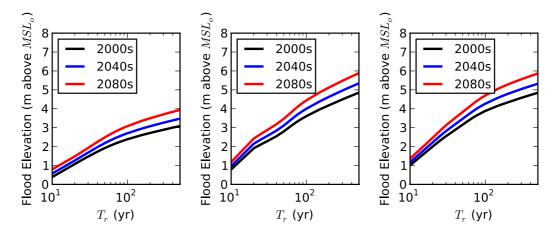

Figure 2. Estimated flood elevation versus return period for locations 1 (left) through 3 (right) for the A1B climate storyline for the following decades: 2000s (current day), 2040s, and 2080s. Flood elevation values are presented with respect to current day mean sea level (MSL_o).

The results presented here are intended to be illustrative only. It is important to note that, based on historical trends, relative *SLR* in the Houston-Galveston area is anticipated to exceed the eustatic rate. As such, the implications of *SLR* on future flooding statistics will be more severe than what is indicated in this analysis. Furthermore, the estimated annual damages do not consider possible damages in highly populated inland areas, most notably the Houston metro area. Actual damages will depend on the distribution of construction, with respect to proximity to vulnerable areas and with respect to topographic elevation.

Nonetheless, these illustrative results demonstrate the importance of planning for future sea level and climate trends. Even when a moderated carbon emissions scenario is assumed, the potential for increased economic damages is dramatic. Whenever possible, it is recommended that adaptive management strategies be considered as a means to minimize under- or over-design as a result of uncertainty in mean climate trends (Irish and Resio in press). In closing, the methods presented here present a practical method for assessing future changes in the hurricane flood hazard.

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