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Increasing Risk Perception and Understanding of Hurricane Storm Tides Using an Interactive, Web-Based Visualization Approach

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ABSTRACT

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Previous studies have shown that much of the public misinterprets standard hurricane storm surge text advisories or standard color-coded storm surge maps. A supplemental approach is proposed that allows users to simulate storm tide for various locations, tidal amounts, and hurricane scenarios and then visualize the estimated water depth on photographs of neighborhood landmarks. Potentially, the visual nature of this approach could enhance risk perception and understanding. The interactive aspect of this approach may engage users more than standard approaches, in addition to providing users with more information. Showing the threats at the neighborhood scale could make the risk more apparent and discourage development of risk-prone areas. Vulnerable groups such as the elderly, transient, or non-English speakers could benefit from the visual representation of the risk. Graphics could be useful for broadcasters and emergency management. However, as is the case with current techniques, this approach has difficulty representing uncertainty. One major shortfall of all current approaches is the parameterization and inclusion of waves as the storm surge travels inland. Waves could be easily visualized with this approach, should the science provide an adequate parameterization.

ADDITIONAL INDEX WORDS: *Coastal flooding, tropical cyclone, typhoon, storm surge, shallow-water waves, hurricane warnings, simulation, modeling, public policy, communication.*

INTRODUCTION

Tropical cyclone (hurricane and tropical storm) events have historically been the costliest natural disasters in the United States (Pielke and Landsea, 1998). Interestingly, while the North Atlantic region features fewer, and less intense, hurricanes than some other regions of the world, the North Atlantic region leads the world in economic loss from them (Woodruff, Irish, and Camargo, 2013). Of the many dangers that hurricanes pose, storm surge (an abnormal rise in sea level accompanying a hurricane) and related high surf has caused more than half of all the deaths and most of the damage in the North Atlantic region from 1963 to 2012 (Rappaport, 2014).

Simply warning people of imminent danger from storm surge does not motivate action; risk must be perceived by those receiving the warnings (Dash and Gladwin, 2007). To that point, surveys of Charleston residents found that most did not fully perceive such risk when they read text-only hurricane advisories from the National Weather Service (NWS) that outlined the threats from an approaching hurricane (Rappaport *et al.*, 2009), particularly in vulnerable groups such as the poor, the less educated, and minority groups (Lindner and Cockcroft, 2013). The National Oceanic and Atmospheric Administration (NOAA) and the National Hurricane Center (NHC) have been experimenting with visualization to enhance their advisories. The NHC began producing storm surge inundation graphics in 2014 once hurricane watches or warnings are issued for locations vulnerable to storm surge (Morrow *et al.*, 2015). These graphics are based on tropical cyclone storm surge probabilities generated by the NOAA/NWS Meteorological Development Lab (NHC, 2018a). Most often the inundation maps are supplemented by color-coded flood zone maps issued from emergency managers or broadcast meteorologists that depict maximum possible storm tide (the sum of astronomical tide and storm surge). Additionally, many high-level decision makers reference predefined outcomes from the Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model (Jelesnianski, Chen, and Shaffer, 1992) based on the expected strength of a landfalling tropical cyclone (NHC, 2018b). Both of these more advanced efforts, however, provide information in plan view map form, which may be misinter-

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preted (Bryant *et al*., 2014; Morrow *et al*., 2015; Sherman-Morris, Antonelli, and Williams, 2015), especially by those new to an area who may be unfamiliar with their local geography.

The NOAA has created a web site to allow people to estimate the effects of sea-level rise through a visualization technique (NOAA, 2018). However, it does not tie the visualization into direct tropical cyclone impacts but, instead, potential climate impacts. It also only supplies very limited locations for a given local area, and does not give values high enough to represent the threat from a major hurricane's storm surge. Higher quality visualizations are essential for effective risk communication (Morrow *et al.*, 2015).

The current study presents an interactive hurricane storm tide visualization technique as a potential supplement to textual advisories and flood zone maps. Rather than presenting water depth from an overhead perspective, as is done with flood zone maps, this visualization approach presents water depth from the perspective of someone in the street looking at a landmark with which they are familiar. Basically, this visualization approach uses the same data currently in use, but changes the visual perspective of the person getting the data. Rickard *et al*. (2017) have shown that using photographic images (*e.g*., a home being inundated) more effectively conveys the risk of storm surge, and this study builds upon that by using a network of photographic images, and a variety of hurricane scenarios that users can select.

Although a visualization approach should be applicable for any location across the globe that is threatened by hurricane storm surge, Charleston, South Carolina, was the site selected to examine this alternative approach for communicating that risk. As is true for many other parts of the North Atlantic, the Charleston shoreline and offshore morphology enhances the risk of storm surge death and destruction (Woodruff, Irish, and Camargo, 2013). Indeed, Charleston has experienced many deadly and damaging tropical cyclones in its history (Alsheimer and Lindner, 2011; Calhoun, 1983; Fraser, 2006; Lindner and Neuhauser, 2018). Thus, it is clear that citizens of cities like Charleston need to be aware of the risk and danger of storm surge.

The main purpose of this study is to develop a novel alternative approach to increasing awareness in the general public of the risks associated with hurricane storm tide. The primary goals are to develop a fully functioning storm tide visualization model and then to explore the connections between this approach and other research that has examined this issue. The Methods section discusses the development and usage of the model. Output from the model is shown in the Results section. The manner in which the model ties in with the current state of the field is examined in the Discussion section, along with a particular focus on the perceived benefits and problems of this approach. Finally, the main points are summarized in the Conclusions.

METHODS

The overall approach was to create a variety of synthetic hurricanes and allow the public to visualize the resultant differences in storm tide between these hurricanes to get a better understanding of the overall hazard of storm tide. Synthetic hurricanes were created for many combinations of intensity, landfall location, and tide level. Estimates of the resultant storm tide are shown on photographs of landmarks. The details of the approach are given in the following paragraphs, describing first the input parameters to the model (elevation, tide, and storm surge), then discussing the landmarks used in the model, then presenting an overview of the computer coding, and finally explaining how the model would be utilized.

The storm tide inundation at any location is the combination of the astronomical tide at that location, the storm surge height at that location, and the elevation of that location. Note that astronomical tides and storm surge physically interact, which can influence the net total by approximately 0.3 m (Forbes *et al*., 2014). The simple addition of astronomical tides, storm surge height, and elevation used in the visualization model ignores this interaction between tides and storm surge but was adequate for the purposes of this initial study. High-resolution elevation data for all locations in the Charleston area were obtained from the National Elevation Dataset (NED) maintained by the U.S. Geological Survey (Gesch *et al*., 2002; USGS, 2005), which provides elevation data down to the scale of individual homes. Astronomical tides vary significantly on weekly and seasonal timescales and vary spatially within the Charleston region. The daily range between astronomical high and low tide in Charleston varies from less than 1.8 m to more than 2.4 m. To avoid additional complexity, this initial model only offers users a choice between a high tide of 2.1 m (7 ft) and low tide of 0 m.

Storm surge heights were computed using the SLOSH model (Jelesnianski, Chen, and Shaffer, 1992), a computerized numerical model developed by the NWS to estimate storm surge heights by taking into account the atmospheric pressure, size, forward speed, and track data, which are used to create a model of the wind field that drives the storm surge. Spatial resolution ranges from 10 m to more than 1 km. The SLOSH model incorporates bay and river configurations, water depths, bridges, roads, levees, and other physical features. SLOSH surge height data were obtained for hurricanes traveling due NW at a forward speed of 24 km/h (essentially the mean translational velocity for tropical cyclones near Charleston; Lindner and Neuhauser, 2018), with tidal effects removed, and for 10 different landfall locations up and down the coast of the southeastern United States (specifically, 480 km S of Charleston near New Smyrna Beach, Florida [29.0° N, –80.9° W]; 320 km SSW, near Jacksonville, Florida [30.3° N, –81.4° W]; 240 km SW, near Brunswick, Georgia [31.0° N, –81.0° W]; 160 km SW, near Ossabaw Island, Georgia [31.8° N, –81.1° W]; 80 km SW, near Fripp Island, South Carolina [32.3° N, –80.5° W]; 40 km SW, near Edisto Island, South Carolina [32.5° N, –80.2° W]; downtown Charleston [32.8° N, –79.9° W]; 40 km NE of Charleston, near McClellanville, South Carolina [33.0° N, –79.5° W]; 80 km NE, near Winyah Bay, South Carolina [33.2° N, –79.2° W]; and 160 km NE, near North Myrtle Beach, South Carolina [33.8° N, –78.7° W]). Having multiple landfall locations in the model allows users to visualize how their storm surge risk varies with landfall location. In the initial version of the simulator, only three of these 10 landfall scenarios were used, namely downtown Charleston, Edisto Island, and McClellanville. Later improvements will include all

10 landfall scenarios and could potentially include additional total water level guidance from other models that simulate storm surge. For each landfall scenario, SLOSH surge data were obtained for each category on the Saffir-Simpson hurricane wind scale. Having multiple intensities in the model allows users to visualize how their storm surge risk varies with intensity. While the Saffir-Simpson scale may not be directly related to the damage potential from storm surge (Kantha, 2006; Powell and Reinhold, 2007; Simpson and Saffir, 2007), this scale is still a good parameter to use in the model because, for most people, the Saffir-Simpson scale is a salient risk communication mechanism (Morss and Hayden, 2010; Morss and Zhang, 2008). Thus 50 scenarios for hypothetical hurricanes were created, with five different hurricane intensities for each of the 10 landfall locations. The visualization model uses the maximum surge expected during the event at each landmark, which will occur close to, but not necessarily coincident with, the time of landfall. This output data on storm surge depths were then compiled into SLOSH basin grids and archived for locations throughout the Charleston metropolitan area.

People are drawn to their own locations when viewing maps because attention is influenced by how they view relevance personally (Severtson and Vatovec, 2012). To address this, more than two dozen undergraduate students collected data on 2000 landmarks around the tri-county area (mostly within a 15-km radius of downtown). The intent was to obtain one landmark approximately every couple blocks, so that no matter where one lived or worked, a landmark could be found nearby. Note that the metropolitan area is extremely flat, and any elevation change is usually extremely gradual (Gesch *et al.*, 2002); thus a landmark would usually have the same elevation as, and therefore simulate the same effect on, neighboring buildings. Students were assigned districts within the region, traveled in teams, and selected landmarks where the effects of inundation were clearly seen (thus, they avoided landmarks that were heavily obscured by bushes, landmarks that consisted of large blank walls, or landmarks where a sense of scale was not easily discerned). Each district was visited at least twice to provide redundancy and a crosscheck on data. The most suitable landmarks typically consisted of homes, restaurants, and shops, because users could easily visualize themselves standing next to these. For each landmark a digital photograph was made, a street address was recorded (for labeling and verification purposes), and a Garmin GPS device was used to determine the field location (latitude and longitude). Each photo was assigned a digital number for depiction and included in an Excel file consisting of latitude, longitude, and the picture title. Other undergraduate students collated these datasets and determined a scale for each photograph. For many locations, a meter stick or other measure was placed next to the landmark, but in many cases this was not feasible (unsafe neighborhood, busy street, *etc.*). In those cases, door frames, window frames, and floor levels were used to provide scale, with a notation made of the uncertainty in that scale. Landmarks where good scales could not be determined were discarded.

GIS software hosted on the ArcGIS (ESRI, 2005) website was used to combine the SLOSH basin grids, NED maps, and landmark database. First, a basemap of the Charleston metropolitan area was chosen as the source map that included labeled features such as roads, rivers, lakes, barrier islands, and parks. Users could select either a standard road map or satellite imagery, scroll around the image, and zoom to focus in on specific regions, right down to clear images of each home. Task-irrelevant information on maps distracts all users regardless of their knowledge of meteorology (Canham and Hegarty, 2010); thus, the presentation of the maps was kept purposely simple. The landmark file was then incorporated into the basemap by overlaying the latitude and longitude coordinates. Finally, each SLOSH basin grid for all height intervals of storm surge (Category 1 through 5) was merged into one final output grid file. For these layer files to be linked to the actual data, shapefiles were created for each. Within these shapefiles existed an attribute table in which information on features were displayed. For example, the features of SLOSH within its attribute table included, but were not limited to, an object identifier, latitude, longitude, and storm surge heights. A feature class was created for the landmarks for the generation of an object identifier for each landmark. The object identifiers were then appended to the SLOSH attribute table on the basis of the relative locations of the features in the two layers. This new output layer was then spatially joined with the final output layer, including all height intervals of storm surge that corresponded to each landmark, creating a single shapefile containing all points. Configuring these features that are associated with each layer within the basemap brought it to life.

This visualization simulator was displayed within an Internet website encoded with HTML and Dynamic HTML (DHTML), which is a combination of PHP, JavaScript, and cascading style sheets (CSS). The website had a series of eight linked pages and links to external websites. The home page provided users with a brief introduction of the research and how this visualization approach differed from a standard flood zone map. Links were provided to an interview with a local broadcast meteorologist, wherein this visualization approach was discussed in more detail, as well as a link to a mirror site in Spanish that provided the basic information needed to use the simulator. Finally, a link was provided to the second page, which provided five links to external websites that provided additional background information. One survey found that 85% of the public does not know where to find educational material on storm surge (Lazo and Morrow, 2013); therefore, it was essential to provide links to such material. Specifically, a link was provided to background information on storm surge published on the NHC and Weather Underground websites; to a 24-page preparedness guide published by the NWS, the Federal Emergency Management Agency, and the American Red Cross; to an internal website that discussed the history and probability of hurricanes in Charleston; to an internal website that discussed the technical details of the model; and to an internal website that listed the goal of the research. Users could peruse these links, or clicked on the bottom link that took them to a third page that discussed the uncertainties inherent in modeling storm tide, because a majority of the public found it useful to have information on uncertainty (Morss, Demuth, and Lazo, 2008). This page also noted that critical life decisions

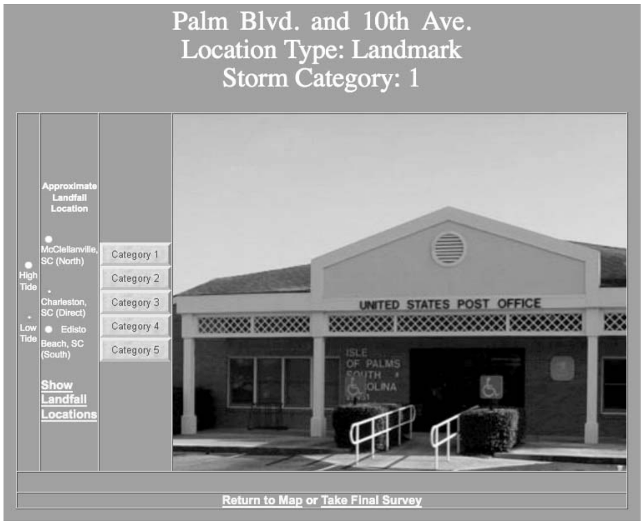

Figure 1. Screenshot of the default page of the hurricane storm tide visualization website for the Isle of Palms Post Office (32.79° N, 79.79° W). Elevation above high tide at this location is approximately 1 m. The simulation is for a Category 1 hurricane directly striking Charleston at low tide. No storm tide is expected. The buttons on the left side of the image are used to select different tidal amounts, hurricane strengths, and landfall locations.

should not be based on the use of the simulator because of the uncertainties contained within. A link to an internal website was provided that listed the specific uncertainties. At the bottom was the link to the fourth page, which provided directions for navigating the simulator, as well as an external link to the NHC website that discussed the Saffir-Simpson scale for those who may not be familiar with it. Hegarty, Canham, and Fabrikant (2010) showed that providing a bit of training before showing maps and visuals increased attention to task-relevant areas. At the bottom was a link to the GIS program itself. After exploring the GIS program, users were then linked to pages that acknowledged agency sponsors of the research, listed the names of the principal investigators and collaborators, and provided links to contact the principal investigators.

On opening the link to the GIS program, the basemap appeared with yellow thumbtacks denoting each landmark for which data exist. After a landmark was selected, a descriptive pop-up window appeared that displayed the street address, elevation, latitude, longitude, and a small picture of that landmark. If the user chose to investigate the projected storm tides for that landmark further, the user would have to click a link within the pop-up window to view the storm tide simulator template. A sample of the template is shown in Figure 1. On the template, under the label for that landmark (usually the street address), was a large photo of the landmark with a set of buttons to the left that were used to select either a high or low tide, approximate landfall location, and the category of the storm (a redundant external link is provided to the NHC website describing the Saffir-Simpson scale). Users could also select a link titled "show landfall locations" to bring up a small map showing the locations of Edisto and McClellanville relative to Charleston to aid users in selecting their landfall location. The default view is always the scenario of a Category 1 hurricane making a direct strike on Charleston at low tide. Once the scenario parameters were selected, the photo reappeared with a blue transparent overlay to simulate the water depth for the selected scenario. The choice of blue color follows the recommendations of the Interactive Information Processing Systems Subcommittee on color guidelines and other studies (Hoffman *et al*., 1993; Schiavone *et al*., 1993). The template was purposely kept simple, because graphics can confuse people and impede risk communication (Tufte, 2001). Users were encouraged to repeat the process using various combinations of astronomical tide, landfall location, and hurricane category or to return to the map and explore other landmarks.

Before the public was given access to the website, the website and simulator were tested by select groups of NWS personnel for scientific accuracy, ease of use, and grammatical errors. On the basis of those comments, the website and simulator were revised and then tested by a class of introductory meteorology students, which resulted in further refinements.

In short, this method combined GIS spatial analysis capabilities with the modeling capabilities of a programming language to produce an interactive simulation, allowing the public to visualize their vulnerability to storm tide. This visualization approach was definitely not perfect because of a few small errors and several approximations, but it might be good enough to test the approach and then refine it in later versions.

RESULTS

Several sample results are useful to conceptualize the output from the surge visualization model. Storm tide is primarily dependent on either landmark (through latitude, longitude, or elevation) or hurricane scenario (through tide level, landfall location, or hurricane intensity). To make the presentation of the results straightforward, one of these two variables is held constant while the other is allowed to vary. The results for varying hurricane scenarios are presented first, and then the results for varying the landmark.

Figure 1 shows the default page for the Isle of Palms Post Office, several blocks from the ocean near the center of a heavily populated barrier island in metropolitan Charleston. No normally dry location would be inundated by storm tide from a Category 1 hurricane making a direct strike on Charleston at low tide. Should users select a Category 2 hurricane making a direct strike on Charleston at high tide, the view would update to that shown in Figure 2. Note the blue overlay on the image that represents the 0.3-m storm tide likely expected in this scenario. Thus, users should realize by viewing the image that even a Category 2 hurricane could cause moderate inundation for low-lying areas. Figure 3 repeats the scenario of Figure 2 except for a stronger Category 3 hurricane striking at low tide. Note the likely lack of inundation despite the increase in the Saffir-Simpson scale. Such simulations may help the public better understand the importance of the astronomical tide when considering the effect of hurricane surge.

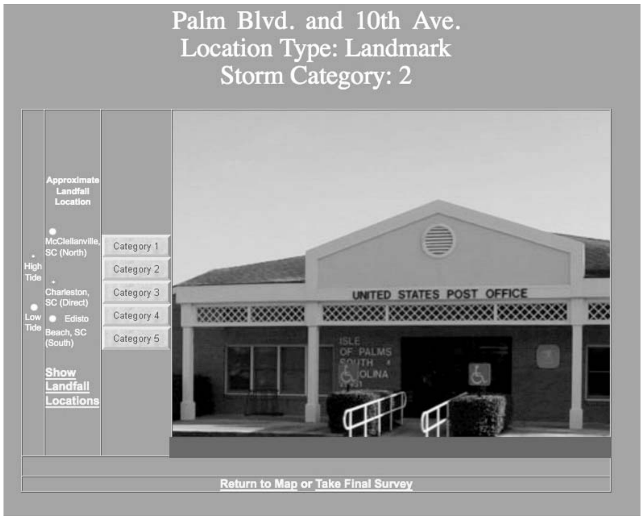

Figure 2. The same scenario as presented in Figure 1, except when simulating a Category 2 hurricane directly striking Charleston at high tide. The overlay shows the expected depth of storm tide of about 0.3 m.

Users could select different landfall locations and easily visualize the change in storm tide that resulted. For example, Figure 4 repeats the scenario of Figure 3, except for a landfall near Edisto Island, about 40 km SW of Charleston. In other words, the location of the landmark has remained the same, and the tidal level and hurricane intensity have remained the same, but the location where the center of the hurricane makes landfall has shifted by 40 km to the SW. Whereas no inundation is likely experienced for a direct strike on Charleston, moderate inundation could be experienced for a strike near Edisto Island.

Figure 3. The same scenario as presented in Figure 1, except when simulating a Category 3 hurricane directly striking Charleston at low tide. No storm tide is expected.

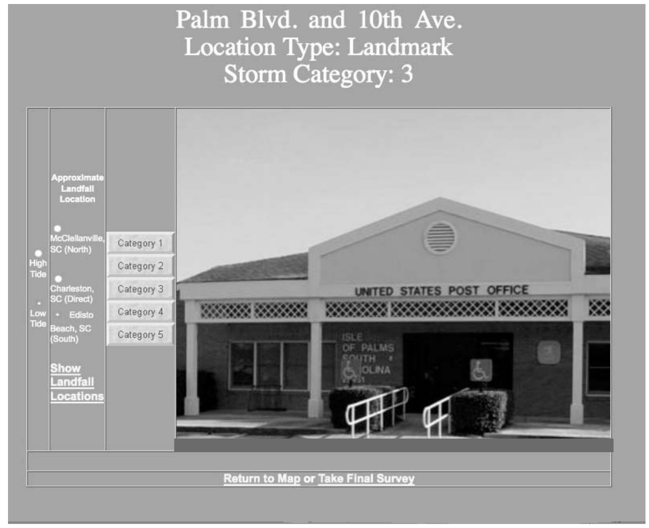

Figure 4. The same scenario as presented in Figure 1, except when simulating a Category 3 hurricane striking Edisto Beach at low tide. The overlay shows the projected storm tide of about 0.3 m.

For much of the public, this is a counterintuitive concept (Lindner and Cockcroft, 2013).

Users would likely be drawn to worst-case scenarios, namely a Category 5 hurricane making landfall near Edisto Island at high tide (Figure 5). Not surprisingly, the Post Office is likely completely underwater in this scenario. Users could easily visualize themselves standing in the street in front of this landmark and struggling to remain above water. Repeating the scenario but changing the landfall location to near McClellanville, about 40 km NE of Charleston, showed that only moderate inundation might

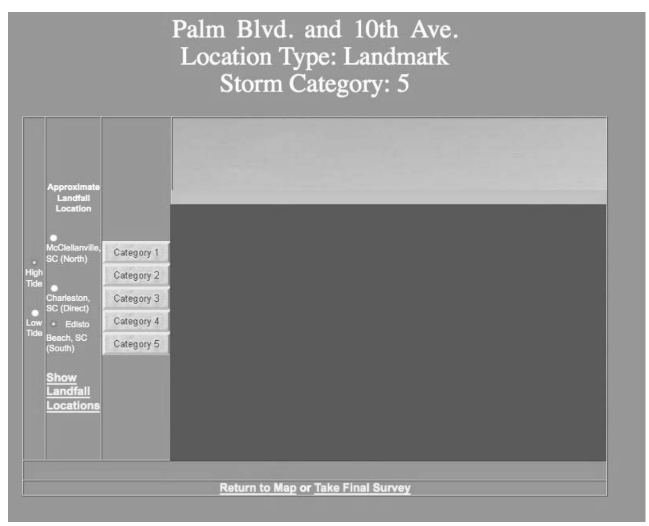

Figure 5. The same scenario as presented in Figure 1, except when simulating a Category 5 hurricane striking Edisto Beach at high tide. The building would be completely inundated.

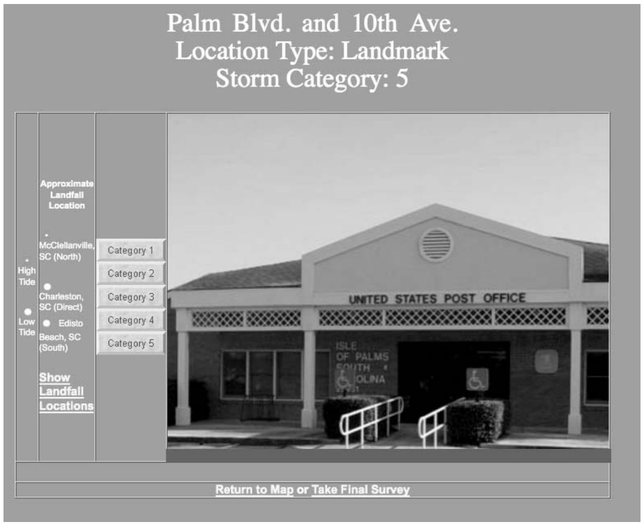

Figure 6. The same scenario as presented in Figure 1, except when simulating a Category 5 hurricane striking McClellanville at high tide. The overlay shows the projected storm tide of about 0.3 m.

be expected (Figure 6). In other words, the landmark location, tidal level, and hurricane intensity are the same, but the location where the center of the hurricane made landfall has shifted by 80 km to the NE. The inundation for this hypothetical scenario could be about the same as that shown in Figure 2 (Category 2 hurricane making landfall at Charleston at high tide) and Figure 4 (Category 3 hurricane making landfall at Edisto at low tide). Three very different hurricane scenarios yield the same result for storm tide on the Isle of Palms. Thus, this visualization approach could convey the importance that a small change in landfall location can have on the amount of storm tide. Moreover, Figure 6 has personal significance for the Charleston area. In 1989, Hurricane Hugo made landfall between Charleston and McClellanville as a Category 4 storm, with a storm tide of 6 m in McClellanville but just 3 m in Charleston (Coch and Wolff, 1991). Survivors in Charleston have often stated that their home was not inundated with Hugo, and thus they reasoned that they have nothing to fear from hurricane surge. They remembered the wind and rain damage as being more significant. Simulations as shown in these figures may help convince many that they in fact managed to avoid most of the hurricane surge from Hugo.

By selecting other landmarks, users could visualize storm tide at a thousand other locations (Figure 7). The variance in storm tide at other locations was similar to that shown in the prior figures, the primary difference being the elevation of the landmark (a linear adjustment), with a slight difference from the SLOSH spatial map (incorporated via the latitude and longitude). Because the model did not account for the attenuation of storm tide as the storm tide moves inland, inland landmarks are affected to the same degree as those on barrier islands that have similar elevations (Figure 7).

Figure 7. Projected storm tides at inland landmarks on Riverland Drive (A, B), and Fort Johnson Road (E, F), and at barrier island landmarks on 12th Street, Folly Beach (C, D), and Middle Street, Sullivan's Island (G, H). Panes A, C, E, and G simulate a Category 1 hurricane making landfall at low tide at Edisto Beach, whereas panes B, D, F, and H simulate a Category 4 hurricane making landfall at high tide at Edisto Beach.

DISCUSSION

This new approach to communicating the risk of hurricane storm tide through the use of an interactive visualization model would appear to have several advantages to traditional methods for doing so. In the first subsection of the Discussion, the current state of research related to the communication to the public of the risk of hurricane storm tide is summarized, and specific notation is made as to how this visualization approach complements research in this field. Indeed, some aspects of this new approach have the potential to reduce some of the problems that have been identified in the literature. However, potential problem areas may arise with the use of this new approach, which are discussed in the second subsection. The particularly difficult but important issue of waves is discussed in the third subsection. Finally, recommendations for future research are made in the last subsection.

Potential Benefits to This Visualization Approach

Risk perception is key in preparing for and reducing danger from storm surge (Slovic, Fischhoff, and Lichtenstein, 2000).

However, as noted by Melton *et al*. (2010) and Lazo (2012), better approaches need to be designed to communicate the risk of hurricane surge. Indeed, for much of the public, risk is best shown via images, as opposed to textual or numerical alternatives (Lindner and Cockcroft, 2013; Lipkus, 2007; Rickard *et al*., 2017). Survey results found that two-thirds of the public expressed a preference for an advisory describing storm surge height in relation to landmarks such as Charleston's city hall (Lindner and Cockcroft, 2013). In line with all of these findings, the hurricane storm tide visualization approach was designed so that the public can use interactive images to educate themselves about the risks associated with hurricane surge. By exploring various hypothetical scenarios, the public could learn about the importance that landfall location and astronomical tide have on water levels. The inland risk of storm surge becomes more visually apparent. A better presentation of the risks associated with hurricane surge could possibly result in a decrease in death and injury and perhaps improved evacuation. The use of the model as an educational tool could also expand the outreach of the NWS.

One objective of this visualization approach is to bring the concepts down to a level that can be appreciated by anyone, particularly the vulnerable segments of society. Older residents often say they would not evacuate (Lazrus *et al*., 2012). An approach that uses pictures of familiar landmarks and is more focused on neighborhoods may be more effective for conveying risk to older residents. University students form another vulnerable group (Simms, Kusenbach, and Tobin, 2013). This visualization approach may reach this visually oriented and interactive subgroup. Also, many people with poor math skills understand risk better if the presentation of the risk has fewer numbers (Lipkus, 2007). Although standard approaches contain the same data presented in this visualization approach, some of the people who are unable to process numerical information effectively may benefit from this image-centered approach.

Tourists and new residents form yet another vulnerable group (Lazrus *et al*., 2012; Phillips and Morrow, 2007). It is possible that they may be traveling or moving from areas where tropical cyclones are not a concern and thus may be completely unfamiliar with the risk of storm tide. Some may also speak foreign languages and not be able to fully comprehend standard hurricane warnings. The visual nature of this approach quickly conveys the risk, regardless of prior knowledge of hurricanes or the ability to speak English. While brief, the Spanish mirror site in the model provides enough information for Spanish speakers to be able to utilize the model. This also addresses another group that is vulnerable to standard hurricane warnings, and that is the native Hispanic population (Phillips and Morrow, 2007). Additional mirror sites could be easily created to address the native languages of other tourists and American citizens.

About 8% of the U.S. population is color-blind (Schiavone *et al*., 1993). This population is poorly served by approaches that use standard color-coded flood zone maps. However, this visualization approach could address this population because the landmark picture would appear the same as the landmark appears to them in real life, and the simulated water level would still be clearly visible (although the blue tint would not be discernable). However, even those that are not color-blind often find color scales used in flood zone maps to be confusing or misleading (Bryant *et al.,* 2014; Morrow *et al*., 2015; Sherman-Morris, Antonelli, and Williams, 2015). This visualization approach uses no color scales or false colors.

Improved storm surge forecasts have resulted in fewer deaths; however, property damage continues to increase (Willoughby, Rappaport, and Marks, 2007). As is the case for much of the coast of the United States (Pielke, 1997), development has been rampant in low-lying areas in the Charleston metropolitan area. Current warnings do little to discourage development of marginal land (Sorensen, 2000). The public may need better awareness of the risk they are assuming before building or purchasing a home. Sixty percent of the public admitted in surveys that no one had told them of the storm surge vulnerability of their area (Morrow *et al*., 2015). Through the use of the model, the public can simulate the effect of storm tide from various hurricane scenarios on potential homes they are considering buying or building. Flood zone maps do convey this information, but many people have difficulty interpreting their risk when using these maps (Rickard *et al*., 2017). Not only could the public benefit, but realtors, builders, and local zoning committees may also find this visualization approach more useful than standard flood zone maps. Any additional outreach that may convince people not to build or buy homes that are in serious danger of loss from storm surge could potentially save money and lives.

Intense hurricanes (those rated Category 3, 4, or 5 on the Saffir-Simpson wind scale) have accounted for over 83% of the damage suffered in the continental United States from tropical cyclones (Pielke and Landsea, 1998). However, much of the public has difficulty understanding the reasons behind this statistic. Upon using this model, they will discover that very few properties experience storm tide from Category 1 or 2 hurricanes. Furthermore, they will see images of storm tide from Category 4 or 5 hurricanes completely inundating many structures, which could help make the connection between the damage from storm surge and the Saffir-Simpson wind scale. Similar approaches can be used to help the public visualize wind damage, inland flooding, and tornadic damage.

The potential effect of climate change on future storm surge is difficult to get across to the public (Lindner, Alsheimer, and Johnson, 2018). The number of tropical cyclones observed in Charleston has not been increasing or decreasing in the past century and a half (Alsheimer and Lindner, 2011; Lindner and Neuhauser, 2018; Zhang, Douglas, and Leatherman, 2000), which seems to agree with the trend for the North Atlantic as a whole (Landsea, 2007). However, climate change may be lengthening the hurricane season near Charleston (Kossin, 2008; Lindner and Neuhauser, 2018; Truchelut, 2016) and could result in even more intense hurricanes in the future (Ellis, Trepanier, and Hodges, 2016; Knutson *et al*., 2010), in agreement with evidence for an increase in the number of intense hurricanes in the North Atlantic from the past (Elsner, Kossin, and Jagger, 2008; Emanuel, 2005). The increase could be larger in Charleston, because the southeastern United States may be particularly susceptible to increased major hurricane activity as a result of increasing temperatures of the nearby ocean waters (Dailey *et al*., 2009;

Wang *et al.*, 2011). More intense hurricanes should increase property damage in the United States as a result (Emanuel, 2011), assuming that management remains the same with no new mitigation or resilient management actions. In addition to the possibility of an increasing number of intense cyclones, sea-level rise would also increase property damage from hurricane surge (Hoffman *et al.*, 2010). Much of the public may have difficulty understanding what an increase in sea level or in the number of intense hurricanes means to them personally. Perhaps providing users an option to select from various scenarios for future sea levels together with linking the storm tide visualization technique to an informational page would allow them to simulate both the potential increase in sea level and in the number of intense storms. Visualization is very important for conveying risk data (Eppler and Aeschimann, 2009).

Most people get warning information from television (Burger *et al.*, 2013; Wei, Lindell, and Prater, 2014). Broadcast meteorologists desire high-resolution visuals to provide information clearly, and they find those made by the NWS and NHC too difficult for the public to understand (Demuth *et al.*, 2012). This visualization approach produces visuals that would be well suited for use by broadcast meteorologists because it uses multiple local landmarks with which residents are familiar. Also, these visuals are uncluttered and easy to explain, an important consideration given the tight time constraints broadcast meteorologists face.

However, the Internet is becoming a key source for hurricane information (Dow and Cutter, 2000; Morss and Hayden, 2010). Surveys found that 83% of Charleston residents ranked the availability of hurricane information on the Internet as important (Lindner and Cockcroft, 2013). Thus, the model has been imbedded within web pages to provide this information. Furthermore, many people comfortable with technology may view the model as essentially an interactive toy or app and may find it more pleasurable to use this visualization approach as opposed to other existing approaches. If people spend additional time educating themselves as a result, then that would aid in the mission of the NWS.

The storm tide from Katrina traveled as far as 10–20 km inland in Mississippi (Rappaport, 2014), the storm tide from Ike reportedly traveled nearly 50 km inland in Texas and Louisiana (Sebastian *et al.*, 2014), and the storm tide from Rita traveled up to 80 km inland in Louisiana (Berenbrock, Mason, and Blanchard, 2009). A similarly deep penetration of storm tide from a strong hurricane would be expected in Charleston given the low, flat topography (Gesch *et al.*, 2002). Using the model while planning evacuation routes could help some people avoid those routes that have the potential to become flooded by storm tide should they experience traffic jams or vehicle malfunctions before they have left the danger zone. The model may also convince more people to evacuate in the first place. Risk perception is key to evacuation decisions (Villegas *et al.*, 2013). In deciding whether to evacuate, people first get the data and determine their risk (Stein *et al.*, 2013; Whitehead *et al.*, 2000). Effective communication requires that information be both received and understood, either audibly or visually (Renn, 2008). Residents are more likely to evacuate if they believe that their homes are likely to be damaged by storm surge (Baker, 1991; Rickard *et al.*, 2017; Wei, Lindell, and Prater, 2014), but that message does not often seem to be getting across to them via current methods. The visualization model may be particularly effective at making this case. Seeking to encourage evacuation, the NWS tried including the phrase "certain death" in warnings about Hurricane Ike, but this approach could be counterproductive for future warnings (Morss and Hayden, 2010; Wei, Lindell, and Prater, 2014). Perhaps an approach that is more visual and is capable of presenting a variety of scenarios may be more effective.

When a hurricane strike is forecast, the visualization model could easily be modified to incorporate SLOSH projections to provide real-time storm tide estimates. The local NWS could issue a hurricane warning with a link to the model, potentially making the warning more effective at communicating the danger. Willoughby, Rappaport, and Marks (2007) note the need to have "neighborhood-level" forecasts. Phillips and Morrow (2007) have shown the need to personalize messages. The interactive nature of this model allows users to customize the storm surge forecast to their specific location, which may make the warning more effective. This visualization approach could also complement the official warning products from the NWS, which began to include a separate storm surge warning product for the 2017 hurricane season. However, this visualization approach could also stand alone, as Morrow *et al.* (2015) have shown that most of the public and most experts support a separate storm surge warning.

This visualization approach allows alternative input parameters. Output from the Advanced Circulation model (Luettich, Westerink, and Scheffner, 1992), the Semi-implicit Eulerian Lagrangian Finite Element model (Zhang and Baptista, 2008), the Finite-Volume Coastal Ocean Model (Chen, Beardsley, and Cowles, 2006), or any hurricane surge model can be used. These models offer some advantages over SLOSH and could be used to build an ensemble storm surge database, with appropriate care for how that information is presented to the general public. Other alternative input parameters to the visualization approach include additional landmarks and a more sophisticated treatment of the spatial variability of astronomical tides. This visualization approach could be adapted to other cities around the globe; there is nothing unique to Charleston.

Verification is straightforward with this visualization approach. When the next hurricane makes landfall along the Georgia–South Carolina coast, rapid comparisons could easily be made between the model projections for storm tide levels at each of the landmarks with the actual recorded amount of storm tide (for those sites where either photographs or eyewitness accounts are available or a clear signature of water height is discernable). Such an event would be useful in fine-tuning the simulation, particularly for examining why certain landmarks were more inaccurately predicted than other landmarks. Were the errors caused by poor elevations for those landmarks a result of inaccurate storm tide projections or because of incomplete modeling of the hurricane structure?

Pitfalls to this Visualization Approach

Many people have difficulty interpreting uncertainty (Demuth, Morrow, and Lazo, 2009), and communicating uncertainty to the public is still a big problem, regardless of the approach taken (Morss, Demuth, and Lazo, 2008). Unfortunately, as is the case with standard flood zone models, each component in this visualization approach used to compute water levels (storm surge, elevation, and tide) has an element of uncertainty.

Storm surge projections from the SLOSH model are accurate to about ±20%, based on a comparison of SLOSH predictions with measured high-water marks and tide gauge data after storms (Forbes *et al.*, 2014). The choice of grid size, bottom friction, and changes in topography with time contribute to this uncertainty (Kerr *et al.*, 2013; Lin *et al.*, 2010a), as do uncertainties in hurricane structure, air-sea momentum transfer, and rainfall runoff (Resio and Westerink, 2008). All storm tide models, including SLOSH, have difficulty reproducing inland storm surge (Kerr *et al.*, 2013; Wamsley *et al.*, 2010). Few observational studies have been conducted to determine the attenuation of storm tide as it travels inland. The Corps of Engineers (1963) determined that storm surge decreased by 1 m for every 14.5 km of wetlands, but this rate varied between storms from 1 m per 5 km to 1 m per 60 km (Wamsley *et al.*, 2010). During Hurricane Andrew, attenuation rates for storm surge of 1 m per 20 km and 1 m per 23 km were observed (Lovelace, 1994). During Hurricane Rita, attenuation rates for storm surge of 1 m per 4 km to 1 m per 25 km were observed (McGee *et al.*, 2006; Wamsley *et al.*, 2010), consistent with average rates observed for four hurricanes of about 1 m per 10 km (Barbier *et al.*, 2013). During Hurricanes Gustav and Ike, the attenuation of storm surge within marshes was less and seemed dependent on wind direction (Dietrich *et al.*, 2011a; Hope *et al.*, 2013; Kennedy *et al.*, 2010). Other types of vegetation have different rates of bottom friction (Dietrich *et al.*, 2011a), which will cause different attenuation rates, and urbanized development will undoubtedly have completely different rates of attenuation altogether. Numerical simulations demonstrate that attenuation rates also depend very strongly on storm intensity, track, forward speed, size, and coastal landscape (Wamsley *et al.*, 2010). Moreover, the further inland the storm surge travels, the more significant all these uncertainties become.

However, because SLOSH is strongly dependent on meteorological input, the largest component to the uncertainty in SLOSH output is the uncertainty in this input data. This visualization approach predefines most of the meteorological parameters by allowing the public limited choices for hurricane scenarios. As a result, this reduces most of the uncertainty in SLOSH output. However, restricting meteorological input also introduces problems, because users may not appreciate the variability inherent in tropical cyclones that share the same categorization on the Saffir-Simpson wind scale. Storm surge height can vary with storm velocity (Irish, Resio, and Ratcliff, 2008; Rego and Li, 2009; Weisberg and Zheng, 2006), angle of storm approach (Irish, Resio, and Ratcliff, 2008), storm size (Irish, Resio, and Ratcliff, 2008; Rappaport *et al.*, 2009; Resio and Westerink, 2008), and the range in wind velocity within each category (Sebastian *et al.*, 2014), among other variables. In future versions of the model, these variables could be additional parameters that the public could select to reduce this uncertainty. Additionally, a probabilistic distribution of the surge depth derived from the database may better facilitate the stakeholder for land use planning. However too many choices could also overwhelm the public, so caution would need to be exercised. Other issues stem from the general public understanding probabilistic information and interpreting such graphics properly. If not done properly, graphics with probabilistic information can actually cause inaction and indecision by the public.

As is the case with the SLOSH model, this visualization approach does not include rainfall, river flow, meteotsunamis, or wind-driven waves. Rainfall not only adds directly to the storm tide, but rainfall in coastal watersheds flows down rivers to meet the incoming storm surge (Lin *et al.*, 2010b). Additionally, the high saline composition of rainfall in hurricanes (Lindner and Frysinger, 2007) acts in conjunction with the saline storm tide to destroy plant life. River channels allow storm surge to flow inland more easily because of reduced friction and may even magnify storm surge as the channel narrows (Berenbrock, Mason, and Blanchard, 2009; Kerr *et al.*, 2013). River channels can even cause tidal bores, as seen in the 1933 Chesapeake-Potomac Hurricane. Meteotsunamis sometimes accompany hurricanes and can cause a sudden raise in water height, much like earthquake-generated tsunamis (Monserrat, Vilibic, and Rabinovitch, 2006; Weems, 1958). Should SLOSH or other storm surge models incorporate these effects in future versions, the new data could easily be input into this visualization approach.

The USGS estimates an uncertainty in the elevation data of approximately 1.2 m for the low slopes characteristic of Charleston, but it could be higher for certain landmarks (Gesch, Oimoen, and Evans, 2014). The lack of inclusion of fine-scale features such as ditches and levees in the NED causes part of this uncertainty (Gesch, 2013) and could be an issue for events of low storm surge when zoomed to the neighborhood level. This uncertainty is not unique to this visualization approach and is a problem in standard flood zone maps (Gesch, 2013). Astronomical tides are very well known but have substantial spatial and temporal variability of about 1 m in magnitude. The spatial variability can be mapped and incorporated into the model, but the temporal variability is more complex to incorporate. Not only does the tide level change during the day, but the amount of high and low tide changes from day to day and week to week. This causes uncertainty as to what level to include in the model to represent high and low tide.

Although most of the uncertainty in the water levels displayed using this visualization approach mirrors that of standard flood zone models, some is unique to this visualization approach. A scale was determined for each photograph, sometimes using yardsticks, but sometimes inferred through door or window sizes. This method introduces additional uncertainty. Each landmark was geolocated by the students, but these coordinates are uncertain, which may cause the landmark to be mislocated on the map and thus given an incorrect elevation. Finally, the storm tide was assumed to be a simple sum of storm surge and astronomical tide, which ignores the interaction between storm surge and tides (Horsburgh and Wilson, 2007; Rego and Li, 2010), which introduces an additional uncertainty of about 0.3 m (Forbes *et* *al*., 2014). This could be remedied by using as input a storm tide model that includes these effects (Forbes *et al*., 2014).

The challenge is presenting all of these uncertainties to the public. Even though most of the uncertainties present in this visualization approach also exist with standard flood zone maps, because this visualization approach brings storm tide down to the neighborhood scale, they could be more easily misinterpreted as to the uncertainties present. However, although each image in this visualization approach is deterministic, users can vary inputs to develop an appreciation for uncertainty that they could not get from standard flood zone maps. Additionally, in numerous locations within the site there are prominent statements as to the various uncertainties involved and that life decisions should not be made based on the simulations. The public needs to realize that they are not getting more accuracy in their storm tide forecasts than the state-of-the-science will support.

As is likely the case with flood zone maps, this visualization approach may be incompatible with certain platforms (tablet, cell phone, *etc*.), browsers, or both. This visualization approach was field tested on a variety of platforms and browsers, and no problems were noted; however, platforms or browsers that were not tested might experience problems, and compatibility could change with browser and platform updates. Obviously this visualization approach will not reach those members of the public who do not have Internet access (this is also an issue for standard flood zone maps). The fact that this visualization approach is very media friendly may expose those without Internet access to the capability of the model and may encourage them to use Internet service at libraries or other spaces with public or private access.

Waves

One potentially very significant advantage that this visualization approach has over standard flood zone maps is the ability to clearly convey the destructive power of waves on top of the storm surge. The horizontal movement of waves can demolish even the strongest structures (Kennedy *et al*., 2011); thus, wave action needs to be presented in addition to storm surge depth. By not including waves, the public may underestimate the damage from storm tide, particularly near the coast. Current models ignore the effect of waves completely and simply show color-coded mean levels of inundation. However, as was well documented in aftermath studies of Katrina in Mississippi, waves can be as high as 20 m offshore and 3 m onshore (Dietrich *et al*., 2011b; Wang and Oey, 2008). Breaking waves inside bays can reach 2.1, 2.7, 4.2, 7.3, and 9.2 m for hurricanes with categories on the Saffir Simpson scale ranging from 1 to 5, respectively (Guard and Lander, 1999). Wave heights vary with distance from the eye, with higher waves closer to the eye (Kennedy *et al*., 2011), and increase as storm surge depth increases (Tancreto, 1958). Waves also transfer momentum to the storm surge, increasing its destructiveness (Kerr *et al*., 2013; Resio and Westerink, 2008). Additionally, the momentum of breaking waves can carry water to levels twice the wave height before breaking (Granthem, 1953), inundating additional areas that would otherwise remain dry.

Initially, the transparent blue overlay that represents the water level in this visualization approach was to be topped by waves to give the public more realistic scenarios of the risk of hurricane surge. However, it became clear while doing this research that there was insufficient knowledge of the wavelength, wave height, or wave type (*e.g*., breaking waves) to allow parameterization of waves in this visualization approach. Moreover, the attenuation of waves as they travel inland is difficult to parameterize accurately at present, primarily because of the sparsity of quality observational data (Dietrich *et al*., 2011b; Hope *et al*., 2013; Kennedy *et al*., 2011; Suzuki *et al*., 2011; Wamsley *et al*., 2010). Significant progress has been made with numerical modeling of waves, such as the Simulating Waves Nearshore model coupled with the Advanced Circulation model, which has reasonably reproduced the limited observational data on waves and wave dissipation that occurred during Hurricanes Katrina and Rita (Dietrich *et al*., 2011b), Gustav (Dietrich *et al*., 2011a), and Ike (Hope *et al*., 2013). Waves with Hurricane Ike were observed to reduce in height by a factor of six as they passed over the completely inundated Bolivar Peninsula, a distance of 2 km (Kennedy *et al*., 2011). A reduction in wave heights of approximately a factor of four was observed during Hurricane Gustav as the storm surge traveled over marsh from the coast to 30 km inland (Kennedy *et al*., 2010). During Hurricane Ike, approximately 30 km of marsh induced a wave height attenuation of approximately a factor of three (Hope *et al*., 2013). The wave height attenuation rate varies significantly depending on the depth of the storm tide, the initial wave height, the wave angle, the degree of wave breaking, the seaward bathymetry, the characteristics of the hurricane, and the amount of friction (Gedan *et al*., 2011; Koch *et al*., 2009; Quartel *et al*., 2007; Shepard, Crain, and Beck, 2011). Wave height attenuation rates are higher in forested areas (Barbier *et al*., 2008; Quartel *et al*., 2007). To further complicate wave height simulations, friction can change quickly with time. As an example, the wave action from the great 1900 Galveston hurricane initially was absorbed by the homes nearest the ocean, leaving mostly flat water in the center of the city (Weems, 1958). As the homes nearest the ocean became demolished, waves were able to penetrate further inland (Weems, 1958). This was similarly observed with Hurricane Ike (Kennedy *et al*., 2011). Wetland friction may also change with time during the storm (Dietrich *et al*., 2011a).

Once further studies are done of the characteristics of waves and their attenuation as they travel inland, they would be easy to add to this visualization approach (replace the flat line for water level by a line with the same mean value but with waves embedded). Such images could be much more convincing than images of simply mean inundation.

Additional Recommendations for Future Research

Aside from adopting improved parameterization of the inland attenuation of storm surge and wave height, there are more straightforward recommendations for improvements to this visualization approach. While surveys of the public have demonstrated the efficacy of this approach (Lindner, Alsheimer, and Johnson, 2018), further options for hurricane scenarios could be useful for educating the public. Surveys of 200 Charleston residents found that most people misunderstood the consequences of a slower moving storm (Lindner and

Cockcroft, 2013). Additionally, it is likely that people would be confused about the consequences of different approach angles of the hurricane track or about the consequences of different hurricane sizes. By adding additional SLOSH scenarios to the database and allowing users to select different speeds, tracks, and sizes, the public could explore these consequences and enhance their understanding.

Although this approach has many benefits over traditional methods for presenting storm tide information to the public, it also raises some challenges in doing so. Uncertainty may need to be more clearly conveyed to the public to avoid a false sense of confidence in the accuracy of the simulated images. Perhaps instead of allowing users to try a variety of hurricane scenarios, a range of blue lines could be shown on the images to convey uncertainty (Morss, Demuth, and Lazo, 2008). Also, this approach is only as accurate as the input data. Thus, closer collaboration with the USGS to get better quality elevation data and with hurricane surge modelers to get better quality storm surge data would allow for more accurate simulations. Better treatment of temporal and spatial variability in tides would result in more realistic understanding of the importance of astronomical tides. The NHC improved SLOSH to include better treatment of tides for this reason (Taylor *et al*., 2013). This visualization approach could also be used to provide supplemental information and graphics to the NWS experimental program to create Tropical Cyclone Impact Graphics (Rappaport, 2014).

Charleston is a popular tourist destination with non-English speakers who are not familiar with tropical cyclones, which make them a very vulnerable group (Phillips and Morrow, 2007). Currently, the NWS and local media underserve this group. This visualization approach could easily have multiple links on the home page to overview pages in their native languages that guide them through the procedure to utilize the model. The home page already has a link to a Spanish language page that has been field tested by select Charleston Hispanic residents. To further serve tourists, the local NWS office and local media could simply provide a link to this visualization approach to spare them from having to prepare their own multiple language presentation.

One encouraging possibility would be to link this visualization approach to an existing photographic database, such as Google Street View. Google has obtained extensive visual images, which if identified by precise geolocation data or if already attached to a GIS grid could be overlain with SLOSH model output and the NED. Once summed, a transparent blue line would be placed over the Google image for the hurricane scenario selected. Linking with Google would eliminate the substantial effort required to obtain the landmark database, although the database would need to be culled to eliminate images that do not lend themselves readily to an overlay (*e.g*., images that have objects in the foreground). This visualization approach should be applicable for all coastal areas around the globe threatened by tropical weather systems, with obvious modification for local landmarks, and linking to existing photographic databases such as Google would greatly simplify that process.

This visualization approach could also be modified so that the current NHC forecast for landfall location and hurricane strength at landfall is directly input into the program. Then, when a hurricane is approaching, the user would simply click on their location and the program would automatically produce the current estimate for storm tide depth based on the NHC forecast. In final product form, this is what the user would typically desire. However, the significant uncertainties in NHC forecasts of track and intensity will need to be emphasized so that users do not incorrectly assume any unrealistic accuracy in the simulated images. Even a small change in track will result in a huge change in storm surge for locations near the eye (Rappaport *et al*., 2009).

CONCLUSIONS

Communicating the risk of hurricane storm tide to the public is challenging. Many of the difficulties that have been encountered in doing so could potentially be alleviated through the use of a hurricane storm tide visualization model that allows users to see images of local landmarks overlain with estimated water depth for various hurricane scenarios. A prototype of such a model has been developed for Charleston, South Carolina, a city particularly vulnerable to storm surge. However, the principles of such a model could easily be adapted to any city in the world, and doing so would be both low cost and technically straightforward. The model features photographs linked to a grid of 2000 landmarks across the metropolitan area, on which water depth based on storm surge, landmark elevation, and tidal amount can be simulated for various hurricane strengths and landfall locations. The model is web based and interactive, allowing users to explore many options easily. This approach combines the advantages of using photographic images to convey the risk with the ability of iconic visual representations to convey a rich dataset.

Results from the prototype model are easily used to demonstrate visually the importance of landfall location and tide on the resultant water levels. Indeed, simulations show approximately the same amount of water inundation in Charleston for three very different scenarios of tide level and landfall location: a Category 5 hurricane making landfall just NE of Charleston at high tide, a Category 3 hurricane making landfall just SW of Charleston at low tide, or a Category 2 hurricane making landfall directly in Charleston at high tide. This information is particularly relevant in the case of Charleston, because residents have predominantly seen hurricanes in the past half century overwhelmingly make landfall to the NE.

The visual nature of this approach may make it more effective in communicating risk, particularly with vulnerable demographic groups. This approach is adaptable to different hurricane scenarios, input data, and locations. The approach has far-ranging applications, including presentation of policy decisions to the public regarding development strategy and evacuation planning. The approach could even be connected to real-time data should a tropical cyclone be forecast to make landfall. Comparison with high-water marks would make model verification straightforward.

This approach could be very effective at displaying the devastating effect of wave action. However, the currently poor scientific understanding of the attenuation of storm surge depth and wave height with distance inland from the shore is a major problem that needs to be addressed. The display of uncertainty is another major problem that needs to be addressed. Nonetheless, this approach already shows promise and could be improved with additional hurricane scenarios, additional language options, fusion with ongoing outreach efforts by the NWS and NHC, and association with existing photographic databases like Google Street View.

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