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Assessing Improvement in the Public's Understanding of Hurricane Storm Tides Through Interactive Visualization Models

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ABSTRACT

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In order to better understand the efficacy of efforts to educate the public about the risks of hurricane storm surge, links on the local National Weather Service (NWS) website and various media outlets were used to recruit 575 Charleston-area residents to complete two anonymous internet-based surveys. Most participants knew that storm surge was the primary risk from a hurricane in low-lying areas, particularly younger, new residents with less prior experience with hurricanes. One in five participants indicated that the NWS always or usually overstates the dangers of hurricanes, although most participants actually overestimated the accuracy of NWS track forecasts. Many users of a hurricane storm-tide visualization model anticipated more storm surge than they would actually receive in various hurricane scenarios. After model usage, there was a noted increase in user understanding of the importance of landfall location on the amount of storm surge, particularly among women and older participants. Comparing surveys completed before and after model usage, there was no change in the number of users that claimed they would evacuate for a hurricane scenario that produced a small storm tide, but there was a substantial increase in the number that claimed they would evacuate for a hurricane scenario that produced a large storm tide, particularly among younger and new residents. A quarter of users stated they would have reconsidered living in their current home if they had investigated the model prior to their move. Thus, significant evidence exists to demonstrate the effectiveness of this type of model in improving risk awareness among users.

ADDITIONAL INDEX WORDS: *Coastal flooding, tropical cyclone, typhoon, storm surge, hurricane warning, survey, statistics, National Weather Service, public policy, development.*

INTRODUCTION

The operational meteorological community continues to realize the importance of the incorporation of social science efforts to complement the physical science components of the field (Demuth *et al.*, 2007; Hooke, 2009). Tropical meteorology and communicating its associated hazards are fertile ground for these complementary efforts, and some recent studies have analyzed these issues. As an example, the National Weather Service (NWS) has long sought to convey hurricane information through the use of visual displays. Up until recently, the efficacy of various visual displays had not really been studied (O'Hare and Stenhouse, 2009). However, recent work indicated that high-quality visualization is essential for effective risk communication (*e.g.*, Bryant *et al.*, 2014; Morrow *et al.*, 2015; Rickard *et al.*, 2017; Sherman-Morris, Antonelli, and Williams, 2015). Cox, House, and Lindell (2013) explored the usage of an alternate type of visual to the standard error cone in the forecasted hurricane track, while Lindner *et al.* (2018) examined the potential advantages of using an interactive hurricane storm-tide visualization model. Storm tide is defined as the combination of the astronomical tide, the storm-surge height, and the elevation of a specific location. Storm surge is defined as an abnormal rise in sea level accompanying a hurricane.

Hurricane forecasting has improved significantly over the past 30 years (Rappaport *et al.*, 2009), but much of the public still has difficulty interpreting the data disseminated by the NWS (Lindner and Cockcroft, 2013). As an example, Lindner and Cockcroft (2013) found that most Charleston, South Carolina, coastal residents did not know that storm surge was the main threat from a hurricane, despite living at low elevations, and despite (or perhaps because of) having experienced hurricanes in the past. Other studies have similarly noted a disconnect between the tropical cyclone information being sent out by the NWS and the ability of the public to understand the information and take proper protective actions (*e.g.*, Bryant *et al.*, 2014; Morrow *et al.*, 2015; Sherman-Morris, Antonelli, and Williams, 2015).

The Lindner *et al.* (2018) hurricane storm-tide visualization model adjusted simulated hurricane surge for astronomical tidal heights and the elevation of 2000 landmarks across the Charleston, South Carolina, metropolitan area. The net projected water depth was then overlain on photographs of those landmarks to give the public a visual street-view representation of the storm tide (*e.g.*, Figure 1). Users then interacted with the model to select the landmark, tide, and hurricane scenario, in turn educating themselves regarding the risks of hurricane surge. Note that the model does not accurately include freshwater flooding, which can potentially

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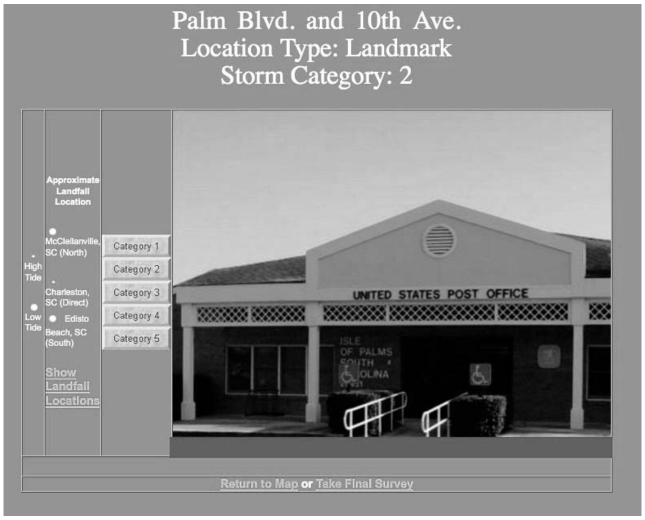

Figure 1. Screen shot of the default page of the hurricane storm-tide visualization website for the Isle of Palms Post Office (32.79°N latitude, 79.79°W longitude). Elevation above high tide at this location is approximately 1 m. The simulation is for a category 2 hurricane striking Charleston, South Carolina, at high tide. The overlay shows the expected depth of storm tide of approximately 0.3 m. The buttons on the left side of the image are used to select different tidal amounts, hurricane strengths, and landfall locations.

be important even in low-lying regions (Lam, 2017). This current study explored the efficacy for enhancing the transfer of information from the NWS to the public by using this interactive hurricane storm-tide visualization model. Additionally, public understanding of general hurricane concepts and public impressions of the forecast accuracy of the NWS were explored. While Charleston was the site of the prototype model as well as the survey, the same model and survey could be used at any location across the globe. However, the vulnerability and adaptive capability of other locations are also affected by parameters such as socioeconomic status, the development of infrastructure, and riverine/fluvial flooding (Lam, 2017; Lam *et al.*, 2014, 2016).

METHODS

While there are many potential methods that could be used to determine the ability of the public to process threat risk, the current study opted to use two anonymous surveys. The following sections describe the design of these surveys, the selection of the audience, and the statistical analysis of these surveys.

Survey Design

To examine the efficacy of the Lindner *et al.* (2018) storm-tide visualization model, the participants were surveyed both before and after interacting with the model. Before being permitted to complete the initial survey, participants first accessed a page that provided an overview of the survey process and an acknowledgement that they were 18 years of age or older. They then moved to a second page that provided a standard consent form and noted the anonymity of the process. The first survey consisted of 21 questions, because a long survey might have cut down on the number of volunteers. Additionally, questions were worded to be neither too technical nor too boring, which may cause volunteers to lose interest while doing the survey. All questions were either multiple choice using drop-down menus or very short answer using a small text box (all questions and answers can be seen in the Appendix). The main ideas of the first survey were divided into three sections. The first section posed nine standard sociodemographic questions that allowed the answers to be partitioned into sociodemographic groups. Lazrus *et al.* (2012) noted the value of comparing the responses of newer and longer-term residents; thus, one question asked how many years they lived in the area. Following Lazrus *et al.* (2012) and Rickard *et al.* (2017), the second section examined the prior experience of participants with hurricane effects and their views on the likelihood of impacts. The third section explored their initial knowledge of tropical meteorology. Additionally, two questions unrelated to the usage of the storm-tide visualization model, but pertinent to the NWS mission, gauged user opinions on the accuracy of NWS warnings and forecasts. Once the initial survey was submitted, participants were connected to the Lindner *et al.* (2018) hurricane storm-tide visualization model. After exploring the model, users then completed the second survey. The first section of the second survey explored the ease of use of the storm-tide visualization model. The second section reexamined their knowledge of tropical meteorology. In both the initial and final surveys, several of these questions were purposely exactly repeated to seek improvement in understanding. The third section explored behavioral changes.

Population Selection and Survey Implementation

Preliminary versions of the survey were tested by members of the research team and by select meteorology students. Then, the prototype survey was reviewed by members of the local NWS office and by other peers for scientific accuracy, clarity, ease of use, misinterpretations, and errors of language. Those questions were rephrased to correct the problems.

The tricounty metropolitan Charleston area covers 6713 km^2 with a potential pool of 549,033 subjects (U.S. Census Bureau, 2000). The first survey sampled 575 subjects: 277 (48%) from the tricounty area, 178 (31%) from neighboring coastal counties (predominantly from the cities of Beaufort, Hilton Head, and Savannah, approximately 80 to 130 km southwest from Charleston), 93 (16%) from neighboring inland counties, 15 (3%) from further distances (although some of these may have lived in Charleston in the past and then moved away), and 12 (2%) that did not provide a valid zip code. Only 119 of the 575 total subjects (21%) completed the second survey. Groves and Couper (1998) also had a low response rate to a second survey. Couper (2000) noted a lack of motivation can cause participants to skip a second survey, which may explain the findings in the present study.

A purely random survey was not feasible given insufficient funding. Instead, convenience/snowball sampling was used. In other words, opportunities were used as they arose to solicit participants to do a self-selected internet survey, and those participants occasionally solicited friends and acquaintances to do the survey. An article on the College of Charleston website advocated the study website from October 2014 through April 2015 and produced less than 1% of survey participants. An interview that was broadcast on a Charleston television station on 24 February 2015 mentioned the study website address and resulted in approximately 15% of survey participants. Interviews that were broadcast on Georgia Public Radio on 14 April 2015 and published in Hilton Head and Beaufort newspapers on 6 April 2015 noted the study website address and generated approximately 16% of survey participants (most of whom were recruited *via* the newspaper articles). The majority (69%) of survey participants were recruited *via* the Charleston NWS website, which posted a link to the study website from 2 March 2015 to 25 April 2015. The area of responsibility for the Charleston NWS office covers the coastal region from Charleston County, South Carolina, to McIntosh County, Georgia. Thus, much of the messaging for the study was received in the Hilton Head, Beaufort, and Savannah area, either *via* the NWS website or the radio and newspaper interviews. This produced many of survey participants from coastal counties outside the tricounty Charleston area, despite the fact that most of them have less personal motivation in seeing simulated images of Charleston landmarks underwater. In all cases, the respondent rates peaked right after the links were posted and rapidly decreased after that.

While not as good as a purely random survey in examining every subsection of society, this study nonetheless did provide data on participants from many locations throughout the tricounty area from many sociodemographic groups. A phone survey of coastal residents nationwide found that half access local NWS websites (Lazo and Morrow, 2013), implying that oversampling those who accessed the Charleston NWS website will bias the responses, but that useful conclusions can still be drawn.

Statistical Analysis of the Surveys

A chi-squared analysis was conducted to examine the statistical significance of the differences in answers observed between comparison groups (clusters for each demographic factor can be seen in the Appendix). The level of significance was set at $p = 0.05$. The formula used to calculate chi-squared was $\chi^2 = \sum[(O_{ij} - E_{ij})^2/E_{ij}]$, where O_{ij} is the number of observed events for the cell at row i, column j, and E_{ij} is the expected number of events for the cell at row i, column j. The expected value, E_{ij}, was calculated using the formula $E_{ij} = [(\text{row total})_i(\text{column total})_j]/(\text{overall total})$. If the observed values differ enough from the expected values, chi-squared will be large, and the p-value will be small, and the differences will be statistically significant (Daniel, 1995).

RESULTS

Results are grouped into six categories to facilitate the different interests of the readers. Specifically, the following sections describe the partitioning of audience demographics, the understanding of the relevant threats, the impressions of the functionality of the storm-tide visualization model, the improvement resulting from model usage in the knowledge of the relevant threats, the changes in lifestyle after using the model, and the impressions of the NWS.

Demographics

Because study participants were not sampled randomly, demographic percentages of study participants differed in several significant ways from the metropolitan area. When compared to U.S. Census data, the study sample was more white, male, educated, married, and older (Table 1). Of those participants that lived in Charleston, a good mix existed between those study participants that were new residents and those who have lived in the area for a long time (Table 2). However, almost half of study participants have never lived in Charleston (although 17% of these nonresident participants stated they had lived in the metropolitan area in the past). The demographics of those participants from within the Charleston metropolitan area were very similar to the demographics of those participants from outside the metropolitan area. The demographics of those participants who accessed the model *via* the NWS website link were slightly different from those who accessed *via* the media links, but not enough to be statistically meaningful. The demographics were similar for the 119 participants who did both surveys compared to the 456 participants who did only the first survey. A significant exception was the strong correlation between the willingness to do the second survey and the number of years lived in the metropolitan area. Only 34 out of 247 (14%) of participants who lived in the area less than 2 years did both surveys, while 60 out of 127 (47%) of participants who had lived in the area at least a decade did both surveys ($p = 0.00$). There was also a weak correlation between not completing the second survey and the demographic groups of single, young, or those without college degrees.

Almost all (98%) of survey participants reported access to the internet in their home, whereas only 84% of the general public reported the same. The remaining 2% of survey participants reported access to the internet at work, in the library, or at a friend's home, and none of the survey participants reported difficulty obtaining internet access. This probably was a result of conducting an internet-based survey, and it may also explain some oversampling in the study demographics. Even though the recruitment methods for this study included television and print media, very few participants used library or other public methods of connecting to the internet.

Charleston has experienced tropical storm– or hurricane-strength winds from a tropical cyclone on average once every year and a half over the past 165 years (Lindner and Neuhauser, 2018), and there were many significant systems that have passed close to Charleston in the past couple decades (Lindner and Neuhauser, 2018). Therefore, it was not surprisingly that most (86%) survey participants stated that they had experienced hurricane- or tropical-storm–force winds; 54% answered that they personally experienced property damage due to a hurricane, and 15% reported injuries to themselves or someone they knew due to a hurricane (percentages were slightly lower for participants outside the metropolitan area than within it). These percentages were substantially below those reported in another survey done in Charleston almost a decade earlier (Lindner and Cockcroft, 2013), perhaps due to a recent decrease in the number of strong tropical systems from that of prior decades (Lindner and Neuhauser, 2018), and the increased number of participants from outside the metropoli-

Table 1. *Notable deviations in study demographics*.

Group	This Study	Metropolitan Area
Minorities	3%	32%
Males	72%	50%
Graduate Degrees	38%	6%
Married	74%	50%
Over Age 46	62%	34%

Table 2. *Number of years participants lived in Charleston*.

Never	43%
0.01–2 years	6%
2–6 years	10%
6–11 years	9%
11–20 years	12%
20+ years	20%

tan area in the present study. However, Lazo and Morrow (2013) also noted that fewer of their survey group knew someone that was injured (1%) or affected (60%) by a hurricane, although their group had a similar percentage experience property damage (48%). Demuth *et al*. (2013) noted that most of the participants in their survey on weather risk had lived in their area for a long time, somewhat consistent with this current study. This may indicate a preference for self-selected storm-surge surveys by those who had previously experienced hurricanes.

As expected, there was a very strong correlation ($p = 0.00$) between a participant's experience with tropical cyclone winds and a participant's number of years of residency, and a weaker but still meaningful correlation between a participant's experience with tropical cyclone winds and a participant's age ($p = 0.01$). The correlation with age was notably weaker than the correlation with years of residency, perhaps due to the recent influx of retirees into the area. Hurricane Hugo hit Charleston in 1989, and many of those participants that resided in Charleston for more than 20 years recalled those winds. Some six to 20 year residents experienced winds from numerous storms that grazed Charleston and hit Wilmington in that time frame. However, few newer residents have experienced significant winds due to the few systems impacting the area in those years prior to the survey (Lindner and Neuhauser, 2018). Note that the survey was completed before Hurricane Matthew made landfall in northern Charleston County in 2016. There was a strong correlation ($p = 0.00$) between participants reporting property damage from hurricanes and their number of years of residency (Figure 2), particularly when residency exceeded 20 years (likely due to damage from Hurricane Hugo), but this was less correlated when residency ranged from six to 20 years (numerous grazing cyclones in that time period produced higher wind speeds but did not produce significant property damage). Most (62%) of those participants without college degrees reported that they personally experienced property damage due to a hurricane, while only half of those participants with college degrees reported the same ($p = 0.03$).

Prior Understanding of Threats

To explore how well participants comprehend the basic principles behind storm surge, the survey questioned their awareness of the tidal range in Charleston, the height above mean sea level of their home, the possibility that a home 1.6 km (1 mi) inland could be impacted by storm surge, and the greatest danger from a hurricane. Slightly more than half of the participants knew that a 1.8 m (6 ft) tidal range occurs in Charleston, with men answering correctly more often than women (51% *vs*. 40%; $p = 0.03$). There was also a strong correlation between the knowledge of tidal range and the number of years of residency ($p = 0.01$). Participants who accessed the model *via* a link on the NWS website also had a better knowledge of tidal range (53% NWS; 44% media; $p = 0.04$). Nonetheless, this indicated that all residents should be informed of the tidal range along with the expected storm surge in order for them to form a more accurate risk assessment, and that women and new residents should be particularly targeted.

Two thirds of respondents stated that they knew their home's elevation, regardless of their zip code. The survey did not verify if their knowledge of elevation was correct; participants were merely asked if they "knew" their elevation (the purpose of the question was to examine if they had approximate knowledge of their elevation). Strong correlations were noted between the perceived knowledge of their home's elevation and a participants' gender (men 73%, women 57%; $p = 0.00$) and age ($p = 0.00$; Figure 3), and a weak correlation was found to higher education ($p = 0.07$). This may indicate women, younger adults, and the less-educated population need to be particularly targeted when explaining the risk of storm surge. Those participants that accessed the model through the NWS website had a higher percentage claim of knowing their home's elevation (75% NWS; 65% media, $p = 0.01$). Since the NWS sample was overrepresented and not statistically representative of the general populace, a general survey of the populace may find that a lower fraction know the elevation of their home. However, Lazo and Morrow (2013) found that 29% of their survey group did not know the elevation of their home, consistent with the findings of this current study. The results of this current study indicate that many residents may not be capable of properly assessing their risk if the NWS provides them with solely an expected storm surge amount.

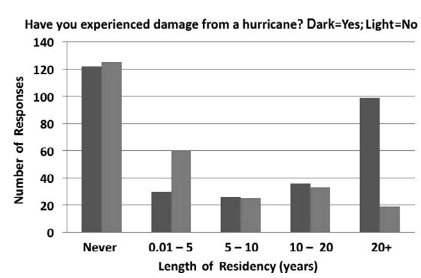

Figure 2. Participant responses when asked if they had ever experienced damage from a hurricane, partitioned by length of residency in years. These data correlate well with the history of hurricanes in Charleston. Hurricane Hugo devastated Charleston 28 years prior to the survey, several near misses produced significant damage in the two decades thereafter, but there had been minimal impact from the few tropical cyclones in the 5 years prior to the survey.

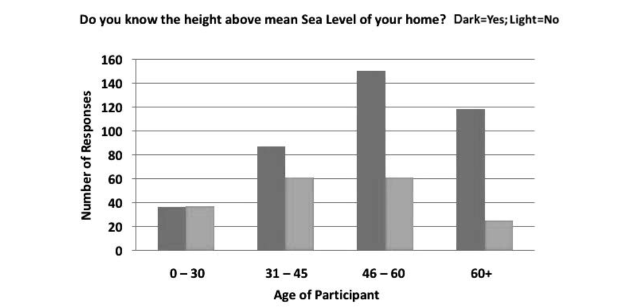

Figure 3. Participant responses when asked if they knew the elevation of their home, partitioned by age group.

When asked if a home 1.6 km (1 mi) inland cannot flood from storm surge, 91% correctly answered false (participants recruited *via* the NWS website and the media both had the same high percentage). Thus, most respondents seemed well informed, understanding that there is little impediment to storm surge flowing well inland in this flat region. In hindsight, however, the double-negative wording of this question may have confused some people. Again, the oversampling of older, well-educated participants may also have biased the result.

When asked for the greatest danger in the Charleston metropolitan area from a typical hurricane, participants selected either wind (4%), storm surge (79%), rain-related flooding (16%), or tornadoes (2%). Those that replied storm surge did so regardless of zip code. Those participants that accessed the model *via* the NWS website were more likely to respond that storm surge is the primary threat, as did newer residents (Table 3). Those participants that completed both surveys had half as many incorrect responses as those that only completed the first survey (Table 3), perhaps indicating a more risk-aware audience among those that finished both surveys. Considering that most participants were mindful to the study's focus on hurricane surge, this may have biased them for selecting storm surge as their answer. Lindner and Cockcroft (2013) found that fewer than half of survey participants in Charleston correctly replied to the exact same question on a survey that was neither internet based nor had frequent mention of storm surge. Similarly, Morrow and Nadeau (2013) found only 27% knew that storm surge was the biggest cause of death. Lindner and Cockcroft (2013) found a statistically significant correlation with education level, which was not noted in the current study.

User Impressions of the Model Functionality

Upon completion of the first survey, participants were connected to the storm-tide visualization model. Participants were allowed to investigate the model without time limits. The mean time that participants examined the model was 19.5 minutes, and the median time was 13 minutes. Morss, Demuth, and Lazo (2008) also noted a substantially larger mean than median time, consistent with these results. There was a range of 2 to 420 minutes in the amount of time participants investigated the model, with 10% of users taking less than 5 minutes, and 10% of users taking more than 30 minutes. These results indicated that most users did not spend much time exploring the versatility of the model (2000 landmarks with 30 potential hurricane scenarios for each), but instead likely focused on a few scenarios.

Table 3. *Percentage of participants that selected storm surge as the greatest danger in the Charleston metropolitan area from a hurricane, partitioned by notable demographic groups. The p-values between access methods (NWS site vs. media link), length of residency (<10 years vs. >10 years), and survey completions (both surveys vs. only the first survey) are shown on the right.*

All groups	79%	
Accessed *via* NWS site	87%	$p = 0.01$
Accessed *via* media link	74%	
Resident <10 years	95%	$p = 0.00$
Resident >10 years	68%	
Completed both surveys	87%	$p = 0.01$
Completed only first survey	76%	

Most (91%) participants responded that they found a landmark near their home easily, and most (86%) reported they could easily change hurricane landfall and intensity. However, 8% of participants indicated they could never find a landmark, and 9% of participants reported they could never change the hurricane scenario. New residents had more difficulty finding landmarks, or changing hurricane scenarios, than longer-term residents ($p = 0.01$). Women had more difficulty in finding landmarks than men ($p = 0.03$), and older residents had more difficulty than younger residents (statistically insignificant $p = 0.47$). Most participants (86%) examined 10 or fewer landmarks, with almost half (42%) looking solely at landmarks near their home or work. This result was true across all demographic groups. This would also explain the short mean time for model usage. While having a thousand landmarks did serve an educational purpose by showing how the amount of storm surge varies across the area, the users tended to focus on those specific locations of interest to them. This finding agreed with the study of Severtson and Vatovec (2012), which found that users viewing maps are drawn to their own locations because attention was influenced by how they view relevance personally. This may also indicate the preference people have for personalized, neighborhood-level forecasts (Phillips and Morrow, 2007; Willoughby, Rappaport, and Marks, 2007).

In contrast, most participants (71%) explored a variety of landfall scenarios. This result was true across all demographic groups. While most participants (71%) found the model clarifying, 29% reported that the model confused them. Thus, more participants reported confusion than the 8% or 9% that reported difficulty getting the model to function properly, indicating a need for additional instruction on model usage and the interpretation of model output. There were no statistically meaningful correlations among demographics groups, although there was evidence that women were more confused than men (41% to 25%, $p = 0.10$), and older residents were more confused than younger residents (38% to 19%, $p = 0.24$). If poorly designed, graphics could confuse people and impede risk communication (Tufte, 2001). Thus, a measure of the confusion is related to the effectiveness of the model.

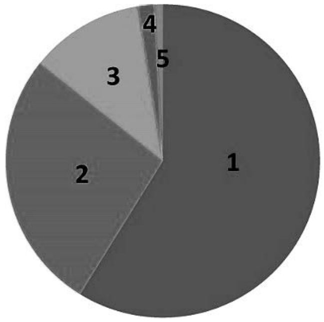

Figure 4. Participant responses when asked to rate their anxiety from none (1) to high (5) after using the hurricane storm-tide visualization model, expressed as a percentage of all 119 that answered the second survey.

As shown in Figure 4, most (59%) reported that model usage caused them no anxiety at all, and only 3% reported high anxiety. Thus, initial concerns by the authors that images of their home underwater might cause undue panic in users were unfounded. Women reported more anxiety ($p = 0.01$); nonresidents reported more anxiety (statistically marginal $p = 0.11$); however, none of the other demographical data showed any correlations. Nevertheless, the NWS and media may need to consider the anxiety of women and nonresidents when using such imagery.

Improvement in Tropical Meteorology Knowledge After Model Use

Three survey questions were repeated on both the initial survey, conducted before model usage, and the final survey, conducted after model usage. Participants were asked to estimate the water height at their home if a category 4 hurricane made landfall 32 km (20 mi) south of Charleston. Comparing the before and after surveys, many participants initially incorrectly assumed flooding would occur at their home, and many participants initially overestimated the chance of high water depths. In other words, participants as a whole may have initially felt more in danger from storm surge than they actually are. The biggest improvement in understanding the risk of flooding occurred for younger participants, female participants, and new residents. The results from this question indicate the need to further educate the public (perhaps through the storm-tide visualization model), so as not to underestimate their risk in the future if experiencing less storm surge from a tropical cyclone than anticipated. This also supported the recent NWS move to go from messaging total storm surge to messaging inundation (Rappaport, 2014).

When asked whether the Charleston peninsula could never be entirely flooded by a very strong hurricane, 94% correctly responded false in the first survey, and 95% correctly responded false in the second survey. Thus, while the use of the model helped a few participants whose initial assumption was incorrect, most participants already knew the correct answer. The bias in the survey demographics may have inflated both of these numbers.

Participants were surveyed as to the potential landfall location that produced the most storm surge. Despite the bias of the sample towards older, well-educated adults that frequent the NWS website, there was a significant decrease in those who answered incorrectly after using the model (Figure 5). The improvement was most pronounced for women, those above age 60, and those who had previously experienced hurricane damage (Table 4). Participants who live inland had higher incorrect answer rates both before and after model interaction ($p = 0.00$). Newer residents (residents for less than a decade) were more than twice as likely to get the answer incorrect as longer-term residents, both before ($p = 0.03$) and after model usage ($p = 0.14$). Lazrus *et al*. (2012) noted that hazard and risk education is important for new residents, which is consistent with the findings in this current study.

Lifestyle Changes

The survey examined whether participants were more likely to evacuate after using the model. Specifically, participants were given two scenarios, a category 2 hurricane making landfall directly at Charleston, and a category 4 hurricane making landfall at Edisto (32 km south of Charleston). For the first scenario, a moderate amount of flooding would have occurred, affecting mostly very low-lying areas. In this scenario, participants were as likely to evacuate after using the model as they would have prior to using the model (Figure 6a). For the second scenario, substantial storm-tide flooding would be expected in Charleston (Lindner and Neuhauser, 2018). More than a third (38%) of participants were more likely to evacuate in this scenario after having used the model (Figure 6b). This was consistent with the study of Rickard *et al*. (2017), which found that using a photograph may make people more likely to evacuate. As shown in Table 5, the largest changes in evacuation likelihood were among new residents, residents over age 60 (these two demographics may both be related to the recent influx of retirees to coastal islands), women, nonresidents, participants who reported damage from a previous tropical cyclone, those who accessed the model *via* the link on the NWS website, those age 30 and younger (Figure 7), and those who had lived in Charleston less than 10 years (these last two demographic groups overlapped significantly but not completely). Trumbo *et al*. (2011) found that those residents who lived further from the main impacts of Hurricanes Katrina and Rita perceived lower risk, consistent with some of these findings.

More than a quarter of the participants would have reconsidered their choice of residence if they had used the model beforehand (Figure 8). Reconsideration rates were highest among women, newer residents, and participants with no college degree (Table 6).

Impressions of the NWS

One out of every five participants described the NWS as always or usually overstating the danger associated with hurricanes (Figure 9). There was a marginally significant correlation between lower education level and the impression that the NWS always overstated the danger ($p = 0.06$). Younger participants were also more inclined to have this impression, but this was statistically insignificant ($p = 0.16$), and no trends could be found among other demographic groups. Participants that were recruited *via* the NWS website were slightly more

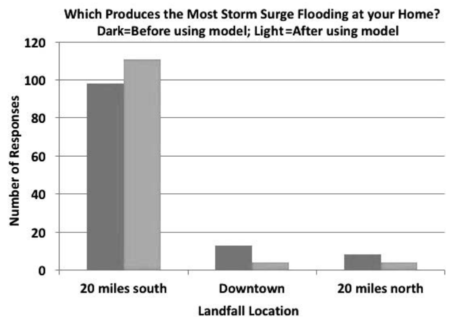

Figure 5. Participant responses when asked before using the model and after using the model, which landfall location caused the most flooding in Charleston: a direct hit, a hit 32 km (20 mi) south, or a hit 32 km north. Only those 119 participants that answered both surveys are listed.

inclined to have this impression than those participants that were recruited *via* the media ($p = 0.01$).

More than three quarters of the participants felt that the probability was 50% or greater that the hurricane would pass directly over them if the NWS 3 day forecast predicts that outcome (Figure 10). This implied that most had overconfidence in the accuracy of the forecast and did not understand the errors involved. Overconfidence in forecast accuracy was widespread, with at least 70% of respondents selecting 50% or 90% NWS forecast accuracy in every demographic group. Overconfidence was particularly prevalent among vulnerable groups such as women ($p = 0.03$), people over age 60 ($p = 0.03$), and those with less education ($p = 0.02$). Even more troubling, 30% of all participants had the impression that the 3 day forecast of the track was 90% accurate, particularly women (38%, $p = 0.01$) and participants over age 60 (39%, $p = 0.00$).

DISCUSSION

As was typical of internet-based surveys (*e.g.*, Demuth *et al.*, 2013), the use of opportunity sampling (convenience/snowball sampling), as opposed to purely random sampling, prevented direct inference about the general population (Daniel, 1995). Despite these limitations, the results of this research could be quite useful for indicating directions for further study. In addition, the result that a generic participant in the study was an older, white, well-educated, married man could indicate that those demographics are more inclined to explore hurricane surge effects. After all, it is likely that homeowners would be more inclined to worry about hurricane surge, and older, well-educated, married men would be more likely to be homeowners. Thus, future studies may have to target renters more aggressively. The demographics in this current study could also indicate that the NWS website particularly attracts those demographics, considering that most of the study participants were recruited from that source. Demuth *et al.* (2013) also used a NWS-linked survey and found a similar demographic representation to this current study. It would perhaps be worthwhile for the NWS to examine what demographics are underserved by their websites.

Demuth *et al.* (2013) also noted an overrepresentation of older (median age of 54), white (94%), rich, college-educated men (72% male) in their survey, which are all very consistent to the demographics of this current study. Lazo and Morrow (2013) noted that their telephone survey group also skewed older, white, and more educated, although their group had a higher female percentage than this current study. Morss, Demuth, and Lazo (2008) also reported an underrepresentation of poorly educated, young, and low-income subgroups, consistent with the demographics of this current study, although they had better representation on the basis of gender and race, which could be indicative of a broader audience in that study. Flemming and Sonner (1999) found that internet-based surveys overrepresented young, college-educated men, consistent with the demographics of this current study, except for the age of the participants, which could perhaps be explained by the fourfold increase in internet usage by older Americans since the Flemming and Sonner (1999) study.

The increase in evacuation rates across all demographic groups was compelling evidence of the effectiveness of the model. The sample was biased towards older, educated, hurricane-knowledgeable participants. In other words, it was

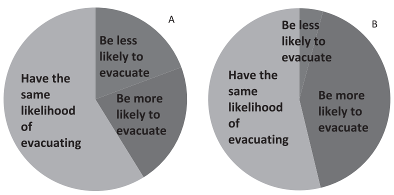

Figure 6. Participant responses when asked if usage of the model caused them to be more likely to evacuate, less likely to evacuate, or have the same likelihood of evacuating in the case of a category 2 hurricane making a direct hit on Charleston (a), and in the case of a category 4 hurricane making landfall 32 km (20 mi) south of Charleston (b), expressed as a percentage of all 119 participants that answered the second survey.

Table 4. *Percentage of participants that did not realize the most storm surge occurred from a hurricane making landfall south of Charleston, partitioned by notable demographic groups.*

Demographic Group	Before Model Use	After Model Use
All participants	18%	7%
Women	31%	9%
Over age 60	19%	5%
Previously experienced damage	15%	3%
Live inland	29%	16%
Newer residents (<10 years)	25%	10%
Longer-term residents (>10 years)	10%	3%

Table 5. *Change in the likelihood of participant evacuation after using the model, for a category 4 hurricane making landfall south of Charleston, partitioned by notable demographic groups.*

Newer residents (<10 years)	53%	$p = 0.07$
Non-residents	60%	$p = 0.02$
Over age 60	46%	$p = 0.41$
Age 30 or younger	62%	$p = 0.25$
Women	47%	$p = 0.52$
Previously experienced damage	46%	$p = 0.32$
Accessed *via* NWS website	46%	$p = 0.32$

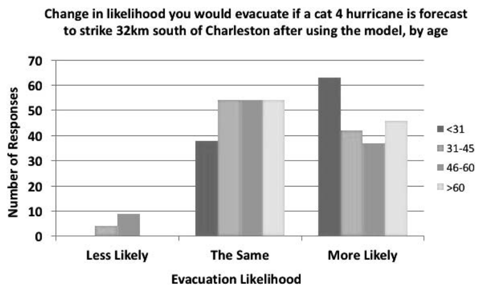

Figure 7. Division by age group of the participant responses when asked if usage of the model caused them to be more likely to evacuate, less likely to evacuate, or have the same likelihood of evacuating in the case of a category 4 hurricane making landfall 32 km (20 mi) south of Charleston, expressed as a percentage of all 119 participants that answered the second survey.

biased towards members of the public more familiar with the danger posed by storm surge. As mentioned earlier, before even using the model, 76% of all participants knew that storm surge is the greatest danger of a hurricane, and 82% recognized that a hurricane striking south of Charleston posed the greatest threat of storm surge. Despite this bias, more than a third of this group realized that they still underestimated the danger of the storm surge posed by a strong hurricane striking south of Charleston. Risk perception is a key factor in evacuation decisions (Villegas *et al*., 2013), and visualization is very important in conveying risk data (Eppler and Aeschimann, 2009). For much of the public, risk is best shown in images (Lipkus, 2007; Rickard *et al*., 2017), and the findings of this current study agreed with that assessment. It is also notable that particularly vulnerable groups (people over age 60, nonresidents, women) saw some of the biggest increases in evacuation likelihood, which again noted the effectiveness of the hurricane surge visualization model. Young and new residents were also vulnerable demographic groups (Lazrus *et al*., 2012; Phillips and Morrow, 2007; Simms, Kusenbach, and Tobin, 2013), and it was encouraging to see the substantial increase in evacuation rates in these groups as a result of using the model.

Table 6. *Percentage of participants that would have reconsidered living where they do, if they had prior access to the model, partitioned by notable demographic groups.*

Women	41%	$p = 0.04$
Newer residents	32%	$p = 0.15$
No college degree	34%	$p = 0.46$

More than a quarter of the sample would have reconsidered their choice of residence with prior interaction with the model. Most of the metropolitan area remained above water, even for worst case scenarios (except for highly unusual rain-induced flooding; *e.g*., Lam, 2017), which meant that most residents would have realized after using the model that storm surge is not a danger to their home, and thus would not have needed to reconsider their choice of residence. Hence, most of those at risk of storm-tide flooding would reconsider their choice of housing with prior interaction with the model. Combining this fact with the bias of the sample, this was again compelling evidence of the effectiveness of the model. As has been common around the country (Pielke, 1997), an epidemic of construction has been occurring in low-lying regions near the coast in Charleston, and the model could be an effective tool to counteract such development in the future. Note that vulnerability depends upon many other parameters, such as socioeconomic status and infrastructure (Lam *et al*., 2014, 2016).

The result that one quarter of the participants would have reconsidered their choice of residence after using the model was consistent with both the study of Morrow *et al*. (2015), who found that 60% of the public admitted that no one had told them of the storm surge vulnerability of their area, and the study of Morrow and Lazo (2013), who found that only one third of those vulnerable to storm surge understood their vulnerability. The correlation between reconsideration of their residence and their educational level may be due to a better understanding of the risk of storm surge among those with higher education levels.

One fifth of participants described the NWS as always or usually overstating the danger. It is again worth noting that the sample was recruited primarily off the NWS website. A telephone survey found that half of respondents used their local

Figure 8. Participant responses when asked if they would have reconsidered moving to their current residence if prior to moving there they had access to the model, expressed as a percentage of all 119 participants that answered the second survey.

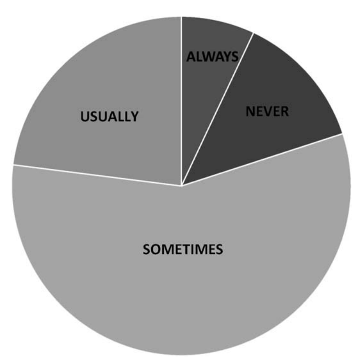

Figure 9. Participant responses when asked if they felt the NWS never, sometimes, usually, or always overstates the dangers associated with hurricanes, expressed as a percentage of all 575 survey participants.

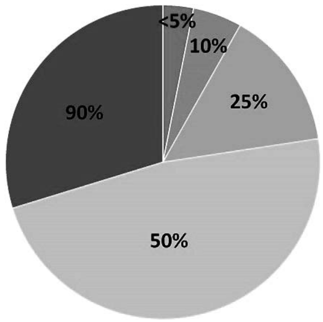

Figure 10. Participant responses when asked if the NWS predicts that a hurricane will pass directly over them in 3 days time, will it actually do so 10%, 25%, 50%, or 90% of the time, expressed as a percentage of all 575 survey participants.

NWS website at some point (Lazo and Morrow, 2013), and it was quite possible that the underrepresentation of those who were not using the website was positively skewing the results. A more representative survey of the general public by Lindner and Cockcroft (2013) found that participants felt that the NWS overstated the danger associated with hurricanes always (15%), sometimes (42%), seldom (31%), and never (9%). While not exactly the same question (the word "sometimes" is replaced by "usually"), this result still showed that the general public was more inclined to feel that the NWS overstated the danger. One potential reason for why people felt that the NWS overstated the danger could be the purposeful inclusion by the NWS of climatological forecast track error in creating warning areas and potential hurricane track graphics, resulting in parts of the warned area not experiencing hurricane effects (*i.e.* a false warning for residents of those areas).

The actual mean error in the forecasted hurricane location 3 days in advance is approximately 200 km (Rappaport *et al.*, 2009). Obviously, there is very little chance that a forecast 3 days in advance would be exactly on target (*i.e.* "pass directly over" the forecast location). Using more generous National Hurricane Center (NHC) definitions, a "direct hit" occurs when the location experiences the eye of the hurricane. Typically, the eye of a hurricane is approximately 30 km in radius (Elsner and Kara, 1999); thus, if the center of the eye passes within 15 to 30 km from a location, it is considered a direct hit. Under this definition, the 3 day forecast has correctly predicted a direct hit in approximately 20% of cases. Thus, the perception of most participants that they would experience a direct hit 50% or 90% of the time likely meant they were overconfident in the forecast, which could indicate either an improper understanding of the definition of accuracy, or the manner in which forecasts are generated. Lindner and Cockcroft (2013) found that 20% of the public even incorrectly felt that NWS projected-track forecasts are more accurate 3 days in advance of landfall than 1 day in advance of landfall (in truth, forecasts of the track actually get significantly more accurate as the hurricane gets closer to landfall). This supports the idea that many people may not understand forecast accuracy. Perhaps participants viewed "pass directly over you" in more general terms, *i.e.* merely anywhere that hurricane-force winds existed. By that definition, the NWS correctly forecasted 3 days in advance whether a location would have experienced hurricane force winds in approximately half of cases. However, under no definition could the forecast track be assumed to be 90% accurate 3 days out. Yet, almost a third had this impression, particularly women and participants over age 60.

CONCLUSIONS

The differences noted in the demographics between this study and the metropolitan area limited statistical inferences that can be extrapolated from this sample to the general population. However, results from a survey of 575 residents in the Charleston metropolitan area and beyond found evidence for enhanced understanding of hurricane storm tide after using a hurricane storm-tide visualization model among an audience that was already biased towards prior knowledge of those risks, implying that the general public may experience even greater improvement. There was an improvement in understanding the importance of landfall location on the amount of storm surge, particularly among women, people over age 60, and those who had previously experienced hurricane damage. The most encouraging result was a substantial improvement in the recognition of those types of hurricanes that required evacuation, particularly among the vulnerable groups of younger residents and new residents. Another very reassuring result was a significant improvement in the identification of areas that were not wise choices for owning or renting a home, particularly among women, new residents, and the less educated.

Participants were recruited from the NWS website and various media interviews. Demographically, these groups were similar, although participants recruited *via* the NWS website tended to be male, with fewer college graduates, and more longer-term residents. Despite less formal education, these NWS website participants understood hurricane risks better, as they had better knowledge of tidal range and elevation, which are key factors in understanding storm tide. NWS website participants also had a better appreciation of storm surge as the main threat of a hurricane, and they had a better understanding that a system striking slightly south of their location resulted in more storm surge than a direct hit. Despite their better appreciation of hurricane risks, NWS website participants were more likely to evacuate after using the model, indicating that even this group had an improvement of their understanding of the risks involved.

Suggestions for future surveys include advising users of the value of spending additional time using the model to explore more potential scenarios, accessing users outside of an online environment, including additional sociodemographic groups (such as income level, transportation needs, political affiliation, and social media usage), including additional redundant questions on the two surveys (thus obtaining a larger baseline), and increasing the sampling of vulnerable rural and island residents. Few participants reported that model usage resulted in high anxiety, but more than a quarter of participants reported confusion, which suggests that while most information was presented effectively, some additional instruction in the use of the model and interpretation of the data are required. Future surveys should more deeply probe the understanding in the public of uncertainties in the projected water level and in the danger posed by rain-induced flooding. Also, to increase the response rate to a second survey, an inducement needs to be offered, such as an entry into a drawing for a prize. Finally, this type of approach should be applicable to any coastal community susceptible to hurricanes, and future work could develop similar models for those locations.

While most survey subjects had experienced hurricane effects and were familiar with the NWS website, one in five believed the NWS usually or always overstates the danger of hurricane surge, particularly the young or less educated. Three quarters of the participants had substantial overconfidence in long-range track forecasts, particularly women and people over age 60. Both these results suggest that follow-up research should be conducted to examine alternate methods of displaying the uncertainty in forecasting. Innovative approaches may need to be studied to target specific subsets of the population that are not effectively understanding the message. However, this research overall shows that the NWS has been successful in their general approach to educating and warning the public. Their objective is to inform the public of the threat and all mitigation measures. It is the responsibility of the recipient to act on this information.

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APPENDIX

Survey Instruments

Note that all multiple choice options were given in drop-down menus, while answers to questions were typed into text boxes. Note that participants must feel comfortable that their responses are confidential (Couper, 2000). However, specific before and after surveys needed to be matched in order for the repeated questions to be more effective. Thus, at the top of each survey, participants created an identifier that included their birth month and day, and the first two letters of the first names of each of their parents. This effectively kept the surveys anonymous but allowed for the culling of repeat submissions and allowed the before and after surveys to be collated for each participant. Note 1 mile = 1.6 km; 1 foot = 0.3 m.

Survey 1:

Please fill in the following information to allow us to pair pre- and postsurveys. (DO NOT PUT YOUR NAME on this survey):
The first two letters of your mother's first name (*i.e*. Jessica would be JE): [ ]
The first two letters of your father's first name (*i.e*. Robert would be RO): [ ]
The month of your birth: [drop-down menu with numbers 1 to 12]
The day of your birth (*i.e*. 23): [ ]

SECTION 1. Socioeconomic Factors

(1) Your gender is:
a. Male
b. Female

(2) Your age is:
a. Under 18
b. 18 to 23
c. 23 to 30
d. 30 to 45
e. 45 to 60
f. 60 and above

(3) Your race:
a. Caucasian (White)
b. African-American (Black)
c. Hispanic
d. Other

(4) Your highest level of education:
a. Grade School (8th grade)
b. High School (12th grade)
c. A few years of college or a technical college
d. Associates degree
e. Undergraduate degree
f. Graduate degree

(5) Are you married?
a. Yes
b. No

(6) What is your zip code? [ ]

(7) How many years have you lived in the Charleston area (Berkeley, Charleston, or Dorchester County)?
a. Never; I'm from out of town
b. Less than 2
c. 2 to 5
d. 5 to 10
e. 10 to 20
f. Over 20

(8) How easy is it for you to access the Internet?
a. I have access at home
b. I can easily get access at work, the library or a friend's home
c. It is difficult to get access

SECTION 2: Hurricane Preparation

(9) Have you ever experienced tropical storm force or hurricane force winds?
a. Yes
b. No

(10) Have you experienced any property damage due to a hurricane?
a. Yes
b. No

(11) Were you or someone you know injured due to a hurricane?
a. Yes
b. No

(12) Do you know the height above mean sea level of your home?
a. Yes
b. No

(13) The National Weather Service overstates the dangers associated with hurricanes.

a. Always
b. Usually
c. Seldom
d. Never

(14) If the National Weather Service predicts that a hurricane will pass directly over you in three days time, would you guess that the likelihood that it actually will do so is:
a. Less than 5%
b. 10%
c. 25%
d. 50%
e. 90%

(15) The greatest danger in the Charleston metropolitan area from a hurricane is:
a. Wind
b. Storm surge
c. Rain-related flooding
d. Tornadoes

(16) Which produces the most storm surge at your home; a hurricane striking 20 miles south of Charleston, directly at Charleston, or 20 miles north of Charleston?
a. South
b. Direct hit
c. North

(17) How much water would you estimate would exist at your home if a category 4 hurricane struck Edisto (south of Charleston)?
a. none
b. 2 feet
c. 6 feet
d. 10 feet
e. 20 feet

(18) A home a mile inland cannot be hit by storm surge.
a. True
b. False

(19) The Charleston peninsula could be entirely flooded by a very strong hurricane.
a. True
b. False

(20) The typical difference between low tide and high tide along the shore is about:
a. 2 feet
b. 4 feet
c. 6 feet
d. 8 feet
e. 10 feet

Second Survey:

Website Usability

Please fill in the following information to allow us to pair pre- and postsurveys. (DO NOT PUT YOUR NAME on this survey):
The first two letters of your mother's first name (*i.e*. Jessica would be JE): [ ]
The first two letters of your father's first name (*i.e*. Robert would be RO): [ ]
The month of your birth: [drop-down menu with numbers 1 to 12]
The day of your birth (*i.e*. 23): [ ]

Begin Survey Questions:

(1) Rate how easily you could find a landmark near your home.
a. Very easy (just took a few seconds)
b. Straightforward (took a minute)
c. Challenging (took a while)
d. I was never able to do it

(2) Did you just look at landmarks near your home and/or near your work, or did you examine many different locations on the map?
a. Just those near home and/or work
b. Many locations

(3) About how many landmarks do you estimate you examined?
a. 5 or less
b. 5 to 10
c. 10 to 20
d. 20 to 50
e. over 50

(4) Rate how easily you could change the hurricane intensity and landfall location in the simulator
a. Very easy (just took a few seconds)
b. Straightforward (took a minute)
c. Challenging (took a while)
d. I was never able to do it

(5) Did you study most of the hurricane landfall scenarios, or just the ones that made landfall very near Charleston?
a. Many scenarios
b. Just those near Charleston

(6) Did this hurricane surge simulator confuse you?
a. Yes
b. No

(7) Did you find any errors in our simulator (in landmark positioning, web links, text, photographs, etc.)?
a. Yes
b. No

(8) Which produces the most storm surge at your home: a hurricane striking 20 miles south of Charleston, directly at Charleston, or 20 miles north of Charleston?
a. South
b. Direct hit
c. North

(9) How much water would you estimate would exist at your home if a category 4 hurricane (on the Saffir-Simpson Hurricane Wind Scale) struck Edisto (south of Charleston)?
a. none
b. 2 feet
c. 6 feet
d. 10 feet
e. 20 feet

(10) The greatest danger in the Charleston metropolitan area from a hurricane is:
a. Wind
b. Storm surge
c. Rain-related flooding
d. Tornadoes

(11) A home a mile inland cannot be hit by storm surge.
a. True
b. False

(12) Downtown Charleston could be entirely flooded by a very strong hurricane.
a. True
b. False

(13) The typical difference between low tide and high tide along the shore is about:
a. 2 feet
b. 6 feet
c. 8 feet
d. 10 feet

e. 20 feet

(14) Now that you have explored our hurricane surge simulator, if a category 4 hurricane were projected to strike Edisto (south of Charleston), would you now:
a. Be more likely to evacuate, based on your experience of using the simulator
b. Be less likely to evacuate, based on your experience of using the simulator
c. Have the same likelihood of evacuating

(15) Now that you have explored our hurricane surge simulator, if a category 2 hurricane were projected to directly strike Charleston, would you now:
a. Be more likely to evacuate, based on your experience of using the simulator
b. Be less likely to evacuate, based on your experience of using the simulator
c. Have the same likelihood of evacuating

(16) If you had access to this hurricane surge simulator prior to moving to your current home, would it have caused you to reconsider moving to your current home?
a. Not at all
b. I might have considered other homes more seriously
c. I definitely would not have moved here if I had used this simulator beforehand

(17) Would you prefer that the National Weather Service continue issuing hurricane warnings the way it is doing so currently, or would you prefer them to additionally have a hurricane surge simulator on their website similar to the one you used today?
a. Prefer the current method
b. Prefer the addition of a hurricane surge simulator

(18) Please rate your anxiety level after using this model, with 5 being most anxious [drop-down menu with 1 to 5]

Thank you very much for your help! If you found a landmark to be in the wrong position on our map, please send us an email. Also, if you went through Hugo, and either were in town or could see high-water marks, please let us know how close our simulations are to that.