Perceptions of Hurricane-Track Forecasts in the United States

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ABSTRACT

Hurricanes Isaac (2012), Harvey (2017), and Irma (2017) were storms with different geophysical characteristics and track forecast consistencies. Despite the differences, common themes emerged from the perception of track forecasts from evacuees for each storm. Surveys with a mixture of closed and open-ended responses were conducted during the evacuations of each storm while the storm characteristics and decision-making were fresh in the minds of evacuees. Track perception accuracy for each evacuee was quantified by taking the difference between three metrics: perceived track and official track (PT − OT), perceived track and forecast track (PT − FT), and home location and perceived track (HL − PT). Evacuees from Hurricanes Isaac and Harvey displayed a tendency to perceive hurricane tracks as being closer to their home locations than what was forecast to occur and what actually occurred. The large sample collected for Hurricane Irma provided a chance to statistically verify some of the hypotheses generated from Isaac and Harvey. Results from Hurricane Irma confirmed that evacuees expected a storm to be closer to their home locations after controlling for regional influences. Furthermore, participants with greater previous hurricane experience perceived a track as being closer to their home locations, and participants residing in zip codes corresponding with nonmandatory evacuation zones also perceived tracks as being closer to their home locations. These findings suggest that most evacuees from hurricanes in the United States appear to perceive storms as being closer to their home locations than they are and overestimate wind speeds at their homes, thus overestimating the true danger from landfalling hurricanes in many storms.

1. Introduction

Researchers from a variety of disciplines have studied the reasons why people do or do not evacuate from hurricanes. Often it is difficult to ascribe just one or two reasons for an evacuation decision due to the complexity of the social and physical interactions involved. Furthermore, the complexity of evacuation decision-making has become even more layered and nuanced with widespread social media usage after 2010 (Ripberger et al. 2014; Stokes and Senkbeil 2017; Demuth et al. 2018). In a review of hurricane evacuation research spanning the preinternet period (before ~1995) and dawn of the multiple-source information era, Dash and Gladwin (2007) called for future research to emphasize three objectives. They argued for more accurate and geographically focused prediction of evacuation rates, better estimation of potential hurricane consequences that depend on evacuation rates, and a focus on understanding spontaneous and shadow evacuations. Some of the most recent research on hurricane evacuations has advanced our understanding of these three objectives. In a statistical meta-analysis of 49 studies, Huang et al. (2016) found that official warnings, mobile home residence, risk area residence, storm conditions, social cues, and expected impacts all consistently influence evacuation. Similarly, Stewart (2015) found that personal self-efficacy, fear of extreme weather consequences, and threat appraisal of behavior that could result in injury or death predicted the self-reported likelihood of evacuating. In addition to these factors, individual and household characteristics, cultural worldviews, and past hurricane experiences also influence evacuation intention (Lazo et al. 2015). In particular for Florida residents, respondents with more individualistic worldviews rated forecast information as being overhyped or overblown, resulting in significantly lower evacuation intention (Morss et al. 2016). Regardless of the impacts of

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personal characteristics or viewpoints that influence decision-making, understanding the graphical representation of a forecast storm track may be the most tangible and universal variable that initiates the decision-making process (Broad et al. 2007; Radford et al. 2013; Meyer et al. 2013; Saunders and Senkbeil 2017; Sherman-Morris and Del Valle-Martinez 2017; Sherman-Morris and Antonelli 2018).

Evacuation decision-making is complicated for forecasters, emergency managers, and individuals. For all three the decision hinges on the relationship between minimizing evacuation costs and saving lives, although each group cognitively emphasizes this ratio differently. For individuals, personal safety is the most important factor, but this is constrained by the social and economic costs of evacuation. Similarly, forecasters and emergency managers also want to preserve life and protect property, but they are constrained by the high costs of evacuations (Whitehead 2003). Improving the accuracy of hurricane forecasts is often perceived by forecasters to be a primary enhancement to increasing forecast value; however, that is sometimes incorrect, since unexpected property damage and fatalities may still occur with accurate forecasts (Bostrom et al. 2018). Although the relationship between improved forecasts and increased forecast value seems logical, the forecast value only increases if people are correctly comprehending the message of the forecast. A particular emphasis of this research is to analyze how well people perceive the spatial elements of hurricane-track forecasts in relation to their home locations.

A number of published articles have analyzed one or more aspects of perception in hurricane-track forecasts. In the United States, the official graphic used to communicate the likely path of a hurricane is the track forecast cone, commonly referred to as the cone of uncertainty (COU) from the National Hurricane Center (NHC). The COU is communicated via television, the Internet, and social media platforms, subjected to privatized modification, and used by the public and emergency officials (Cox et al. 2013). Some of the ways it can be misinterpreted were first summarized by Broad et al. (2007). In that research, Broad et al. (2007) used three hypothetical hurricane scenarios with two experimental graphics in addition to the COU. Due to it possibly being the source of widespread confusion, the primary argument following the active 2004 hurricane season was whether or not to remove the track line from the COU. Participants preferred to retain the track line within the COU, partly out of familiarity, but also because many people estimate it to be located at the center of the COU anyway if it was removed. Radford et al. (2013) expanded upon these findings by asking preferences for several different types of hurricane warning graphics, but also by assessing what aspects of graphics were comprehended and why. Results showed a preference for a color-coded cone structure. A graphic modeled after the Australian Bureau of Meteorology design showing hurricane size and a postlandfall hazards graphic were also used. Neither were popular or better at communicating risk. Therefore, efforts to substantially change the COU may not result in a considerable increase in accurate hazard comprehension. Furthermore, removing the track line from the COU also may not increase the accuracy in perception of the location of the storm's worst impacts. Research has found that the track line is a vital component of forecasts. Distance from the track line was a major factor of concern in hypothetical scenarios (Matyas et al. 2011; Saunders and Senkbeil 2017), while the presence of a track line was also associated with higher levels of concern and preparation (Meyer et al. 2013). Perceived helpfulness of forecast graphics increased with the track line included. Track information significantly altered risk perception from damaging winds, while the error cone did not (Sherman-Morris and Antonelli 2018). Other research has somewhat contrasted with these findings, suggesting that there were no differences in strike probability judgements between those who viewed cone, track, and cone–track scenarios (Wu et al. 2014, 2015).

It does not appear that the COU will be significantly modified or altered in the near future. Currently, a click of the button can either display the COU with or without the forecast track. Since it is likely that the track line within the COU will remain a prominent feature of hurricane risk communication, it is essential to continue studying the ways people interpret track forecast information and how the track forecast impacts their decision-making. All of the research mentioned above has employed hypothetical scenarios with large sample sizes to answer questions about hurricane-track forecast and COU perception. An important distinction of this research was the collection of hurricane-track risk perception data during the evacuation while the meteorological conditions of the storm were being forecast (Senkbeil et al. 2010; Collins et al. 2017, 2018; Senkbeil et al. 2019). This real-time data collection allows for participants to more accurately recount the intricacies of their decision-making process. Baker (1979, 1991) and Lindell et al. (2005) mention the alteration of evacuee ideas and perceptions with time, and Stallings (2002) notes that the potential for memory decay is a limitation when data are collected after the event. Furthermore, research collected during the evacuation can inform existing research on perceived attributes, behavioral expectations, and implementation timing of emergency response actions using hypothetical scenarios (Huang et al. 2017).

The focus of this research is on isolating and understanding the accuracy of the perception of hurricane-track forecasts. Track forecasting accuracy by the NHC has seen consistent improvement in the last 20 years with distance errors decreasing for every forecast time interval. Evacuees monitor hurricane-track and COU forecasts before they make their evacuation decision and continue to monitor the evolving forecasts during the evacuation process. Developing a deeper understanding of how evacuees interpret the location of hurricane impacts and comprehend risk from hurricane-track forecasts is important for the enhancement of accurate risk communication. Residents without adequate scientific knowledge may struggle to correctly interpret hurricane intensity, forecast track, and size (Drake 2012). For example, most people do not understand the exponential relationship between damage potential and the Saffir–Simpson scale category (Stewart 2011). Furthermore, many hurricane evacuees do not understand that the right front quadrant of a landfalling storm will be associated with the most threatening hurricane hazards, and those located outside of this region will see weaker impacts (Senkbeil and Sheridan 2006). Poor familiarity and understanding of forecast tracks from landfalling hurricanes is a possible latent factor contributing to shadow evacuation (Baker 1991; Dueñas-Osorio et al. 2012) and poor comprehension of meteorological forecasts. These shadow evacuations, when residents outside of mandatory evacuation zones often leave unnecessarily or leave to avoid non-life-threatening inconveniences (Cuite et al. 2017), contribute to economic loss, considerable traffic congestion, and fuel shortages depending on the specific storm circumstances.

Specific questions in this research were the following: 1) Are evacuees perceiving storm tracks that closely resemble the forecast storm tracks from the NHC? 2) Are there any external variables that influence perceived storm tracks? In the following sections, the methods explain the procedures for quantifying hurricane-track perception and also summarize the data collection procedures for each storm. The results for the small samples from Hurricanes Isaac and Harvey are combined to facilitate discussion. The Hurricane Irma results are divided into three sections.

2. Methods

a. *Quantifying hurricane-track perception*

Previous research on evacuation in Louisiana before Hurricane Gustav (Senkbeil et al. 2010) discussed and experimented with procedures to quantify hurricane-track perception. Evacuees were asked to place a dot on a map to mark where they thought landfall would occur (perceived landfall). The distance between this point, their home zip code, and where the forecast track and official track intersected the coastline was evaluated via three metrics called perceived landfall distance error (PLDE). The initial method of PLDE used a point measurement from the centroid of each evacuee's zip code to a point measurement at the landfall location which was standardized by latitude. Additional methods were calculated using the estimated distance from evacuee zip code to forecast landfall location, and evacuee zip code to the actual track of the storm. Although three methods were used, none proved to be a superior way of assessing perception error since two of the three estimates were based on point measurements.

The first objective of this manuscript was to develop a more efficient and accurate way of assessing the distance discrepancies between home zip code, perceived storm track, forecast storm track, and official storm track so that these methods can be used in future hurricanes to assess track forecast comprehension accuracy. Data were gathered during the evacuations of Hurricanes Isaac (2012), Harvey (2017), and Irma (2017). Each storm was different in its physical characteristics, intensification rate, track forecast consistency, and population at risk. These details are discussed in the next section.

A 20-question survey consisting of open-ended written responses and Likert scale answers was administered. The survey took between 5 and 10 min to complete, and rejection rates varied for each researcher. The survey consisted of four demographic questions (written response), two questions about previous hurricane experiences (written response), three questions about hurricane information and hurricane graphics (written response), and eight questions about hurricane hazards (two written response and six Likert scale responses). These are the same questions found in Table 1 of Senkbeil et al. (2019). The final question, which is the focus of this research, asked each evacuee to draw his or her perceived hurricane track. Responses to this question provided some of the clearest visual evidence about how people perceive the locations of forecast hurricane tracks.

Participants were instructed to draw their perceived tracks for each hurricane on a map starting from offshore in the ocean and extending inland. They were instructed to label the landfall point with an X. These perceived tracks (PT) were then compared with the forecast track (FT) from the NHC at the time of the survey, and the NHC official track (OT) using distance

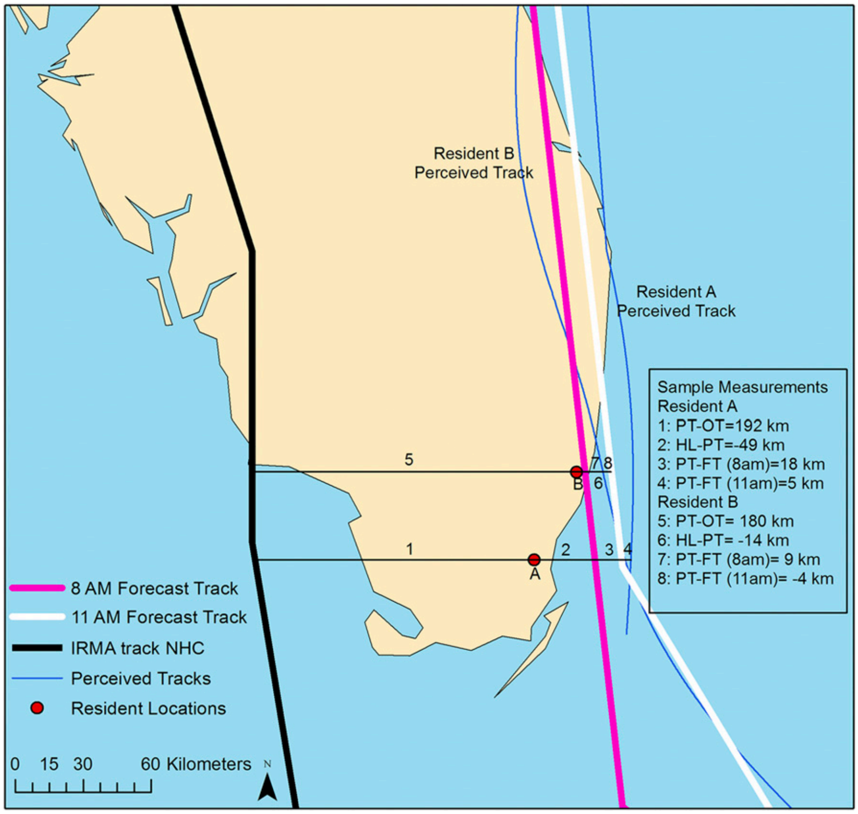

FIG. 1. Sample illustration of track distance measurement methods for perceived track − official track, perceived track − forecast Track, and home location − perceived track for residents A and B. Perceived track − forecast track measurements were taken at two different times. Line segments corresponding to measurements for residents A and B (1–8) are numbered in the legend.

measurements in order to more efficiently assess the track perception error of evacuees (Fig. 1). Negative or positive distance values respectively indicate a PT to the west/south or east/north of FT, OT, and home location (HL) (Table 1) (see Fig. 1). Distance measurements from PT to FT, OT, and HL were made at the latitude of the centroid for each participant's zip code since almost every participant drew a track from the ocean to a location well inland. Therefore, the measurement from PT to each of the three variables could never be in a northwest direction since the measurement was made at the latitude where the PT achieved the same latitude of the participant's home location. Positives and negatives were used because the east/north side of a landfalling hurricane associated with the northeast quadrant has the worst impacts. Absolute values of these measurements were also evaluated concurrently with the positive and negative location results.

A digital map was created and each participant's HL (zip code centroid) was plotted into ArcGIS, versions 10–10.6, depending on the year of each storm. Perceived track lines were drawn onto the map using the "create features" option within the editor tool. This tool allows the user to create new feature classes within a geodatabase. Under construction tools, the freehand option and curved line tools option were used, and each perceived track was manually digitized from the original hand-drawn document. Official tracks and forecast tracks were downloaded from the NHC archives. Distances were then measured for the variables in the preceding paragraph using the measure tool between the two closest points for the tracks at the latitude of the HL while the storm was still classified at least Saffir–Simpson hurricane wind scale (SSHWS) category 1. In the special case of Hurricane Harvey, two of the perceived tracks roughly paralleled the coastline without much inland penetration. For these cases the distance between the track lines was measured to the farthest inland penetration of the perceived track. A brief explanation of each measurement is provided in the following paragraphs.

The PT − FT attempts to measure how well evacuees understood the track forecast at the time they were

TABLE 1. The top section shows track distance perception error comparisons in kilometers using positive/negative and absolute value methods for perceived track (PT), official track (OT), forecast track (FT), and evacuee home location (HL). Positive or negative values respectively indicate that the first variable is east/north or west/south of the second variable in each column. The Hurricane Irma results show the *p* values for day 1 against day 2 using Mann-Whitney tests. There are no test results for Isaac and Harvey because of small sample sizes. The middle section gives Kruskal Wallis test results and means in kilometers for hurricane experience. The bottom section shows Mann-Whitney test results and means in kilometers for evacuation zones. Boldface font indicates statistical significance at the 0.05 level or better.

	Method	PT − OT	*p*	PT − FT	*p*	PT − FT 1500 UTC	*p*	HL − PT	*p*
Hurricane									
Isaac	Positive/negative	107		21				−3	
Isaac	Absolute value	107		38				40	
Harvey	Positive/negative	22		38				−4	
Harvey	Absolute value	29		44				27	
Irma day 1	Positive/negative	155		−12		−24		−106	
Irma day 2	Positive/negative	99	**<0.001**	19	**0.001**	61	**<0.001**	39	**<0.001**
Irma day 1	Absolute value	158		42		46		127	
Irma day 2	Absolute value	100	**<0.001**	37	0.947	65	**<0.001**	48	**<0.001**
Experience level									
None	Positive/negative	139		−6		−4		−80	
Some	Positive/negative	129		5		20		−36	
Experienced	Positive/negative	121	0.384	6	0.412	25	0.147	−10	**0.044**
None	Absolute value	143		43		57		108	
Some	Absolute value	130		38		51		101	
Experienced	Absolute value	122	0.371	38	0.987	58	0.494	64	**0.027**
Evacuation									
Mandatory	Positive/negative	128		−5		5		−68	
Nonmandatory	Positive/negative	127	0.690	9	0.170	25	0.124	−8	**0.012**
Mandatory	Absolute value	132		42		52		123	
Nonmandatory	Absolute value	128	0.686	37	0.448	57	0.354	61	**<0.001**

surveyed. The PT − FT is also a proxy assessment of the level of trust that the evacuee has in the FT. A PT that is highly discrepant with an FT for an individual could indicate a belief that the forecast is wrong. Alternatively, it could also be viewed as an assessment of poor geographic awareness, but questions about their drawn perceived tracks were not asked to avoid introducing bias. Whereas PT − FT attempts to measure forecast comprehension accuracy, PT − OT is an assessment of meteorological forecast accuracy since the OT is unknown to the evacuee when they make their decisions. The PT − OT is important for evacuees in the post-landfall window when they return home and begin to observe and document damage at their residence.

A third distance measurement is between the participant's HL (centroid of their zip code) and the PT of each participant. The centroid of their home zip code was used because to protect individual identities we were not permitted by internal review board (IRB) protocol to ask for street addresses. The HL − PT provides an indication of their expected impacts. If their PT was drawn directly through their home zip code, then that individual expected direct impacts. Conversely, if the PT was drawn at a great distance from an individual's HL then that person did not expect direct impacts. Having evacuees draw their perceived tracks from the ocean extending well inland past the landfall point created a more comprehensive picture of their perception than labeling these items as points.

b. *Hurricane Isaac 2012, data collection*

Hurricane Isaac made landfall on the Louisiana coast west of New Orleans on the morning of 29 August 2012 as a category-1 hurricane on the SSHWS. Isaac was a storm with a consistent track forecast centered on the Louisiana coast with little landfall track deviation 72 h prior to landfall. However, projecting the intensity of Isaac was difficult for forecasters. Conditions were favorable for intensification, but Isaac languished at tropical storm status until 12 h prior to landfall (Berg 2012). The delayed intensification and confidence in post-Katrina flood and surge mitigation measures in the city of New Orleans, as gathered from participant comments, created a small-scale evacuation with steadily flowing traffic in contrast with the large evacuations before Katrina (2005) and Gustav (2008).

Data collection for Hurricane Isaac followed methods from Senkbeil et al. (2010) and Brommer and Senkbeil (2010). A rest area on Interstate Highway 59 on the Mississippi and Louisiana border was selected on the

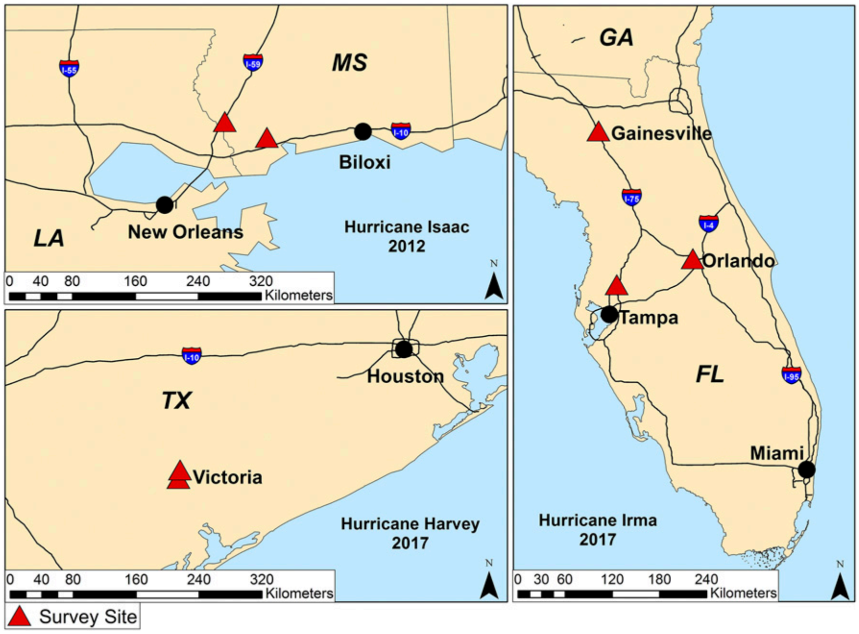

FIG. 2. Survey location sites for data collection during the evacuation of each hurricane.

morning of 27 August 2012 as a data collection site 34–31 h prior to landfall. According to rest area personnel, there were only slightly more visitors to the rest area than a normal day. Thus, the smaller evacuation for Isaac occurred with very little traffic congestion on the major interstate highways. Traffic congestion, or high traffic volume, is a prerequisite to collect a large sample size of participants. Evacuees are more willing to talk candidly about their experiences and answer questions if they feel their evacuation progress is impeded by traffic. The rejection rate was very high at 90%, in comparison with higher acceptance rates in previous research.

Later that afternoon, 27 h prior to landfall, a Red Cross hurricane shelter in Kiln, Mississippi, was selected as it was opening. After meeting with the shelter director, permission was granted to speak with shelter inhabitants for a brief period of 30 min. The response rate inside the shelter was 50%. A total of three surveys were completed before our time expired, bringing our total sample from the rest area and the shelter to 16 participants. Ten participants were from the greater New Orleans area, three were from coastal Mississippi, two were from southeastern Louisiana, and one was from coastal Louisiana.

c. *Hurricane Harvey 2017, data collection*

In contrast to the slow and gradual intensification of Isaac, Hurricane Harvey rapidly intensified. On Thursday morning 24 August, Harvey was forecast to become a major hurricane at landfall on Saturday morning 26 August at 0700 local time just north of Corpus Christi, Texas. Subsequent forecasts continued to depict a major hurricane landfall with very minor track fluctuation. The eyewall directly impacted Rockport, Texas, Friday night 25 August as a strong SSHWS category-3 hurricane (130 mi h^{-1}, or 58 m s^{-1}; National Hurricane Center 2017). This rapid intensification and adjustment of the intensity forecast would have been disastrous for a densely populated coastline, or if the storm was only 50–75 km farther south. Fortunately, this stretch of the coastline was not densely populated, allowing residents to efficiently evacuate away from the area or evacuate inland away from the storm surge zone without major traffic impediments.

Procedures for Hurricane Harvey mirrored that of Hurricane Isaac. Therefore, the only differences in methods between the two storms are from the unique challenges of data collection in situations in which it was difficult to successfully recruit participants. There were no major interstate highways or highway rest areas as one travels inland from the Texas coastline in the mandatory evacuation counties (Fig. 2). Victoria, Texas (population 68 000 and 64 km inland), was chosen as the best location to initiate conversations with evacuees. Once again, a Red Cross shelter granted 30 min of time, enabling the completion of three surveys on Friday afternoon 25 August. The remaining 13 surveys were completed in the lobby of the Courtyard Marriott hotel in Victoria on Friday night. The hotel was near full capacity with storm evacuees, and the Bistro Restaurant in the lobby was one of the few establishments open in the city as Harvey was near landfall at that time. Hotel guests from Victoria and coastal towns had evacuated to what they perceived to be more substantial shelter at the hotel. They were more willing to talk with us in a relaxed atmosphere as they ate dinner and asked for news about the storm. A live radar display was set up by our team in the lobby, and the interactions and conversations were beneficial for all parties. The rejection rate at the hotel was 60%, and caution was exercised to ensure that only one person was interviewed from each group.

d. Hurricane Irma 2017, data collection and analyses

Hurricane Irma was one of the strongest storms ever recorded in the Atlantic Ocean (Senkbeil et al. 2019). On the morning of Sunday 3 September, the 5-day COU from the NHC forecast Irma to be over the Bahamas, causing anticipation of a possible Florida landfall as a major hurricane. The evening of Monday 4 September was the first time that the 5-day COU included southern Florida. Evacuations from the Florida Keys began on Tuesday 5 September, and Wednesday 6 September was the first widespread evacuation day from southern Florida, including metropolitan Miami. The evacuation traffic was heavy on Thursday 7 September, and three surveys sites with three separate teams collected data, with a rejection rate ranging between 40% and 70%. A convenience sampling strategy was used and discussed in Collins et al. (2018) and Senkbeil et al. (2019) in which participants were surveyed at interstate-highway rest stops. Evacuation traffic reached its peak volume at our survey site near Orlando, Florida, on Friday 8 September. During this time there were minor fluctuations in forecast track between the east coast of Florida and the interior of Florida. The longevity of major hurricane status prior to landfall, combined with a forecast of a major hurricane impacting a densely populated region, created an unprecedented evacuation. Irma eventually made landfall at Cudjoe Key, Florida, on Sunday 10 September at 0910 local time with $58\,m\,s^{-1}$ ($130\,mi\,h^{-1}$) winds before tracking over Naples, Florida, as it weakened to winds of $51\,m\,s^{-1}$ ($115\,mi\,h^{-1}$) (Cangialosi et al. 2018). Combined between the two days of data collection, a total of 155 Florida residents completed our survey. This brought the total sample size for all three storms to 187.

A brief description of the data-analysis procedures is provided here. Statistical tests were performed comparing the day-1 distance measurement data with the day-2 distance measurement data. In previous storms, data collection occurred in one day. The large multiday evacuation from Hurricane Irma provided an opportunity to assess track perception over two days of data collection. More important, the day-2 data were collected from evacuees from the greater Miami area, thus resembling the more concentrated spatial footprint of Hurricanes Isaac and Harvey, allowing for a better comparison with those storms. Since most of the variables did not have a normal distribution, Mann–Whitney tests were used to assess significant differences in the distance measurements. Additional tests were performed to determine whether previous hurricane experience or residence location within an evacuation zone affected track perception. Three levels of experience were used to divide the sample into those with previous hurricane experience, some hurricane experience, and no previous hurricane experience. Similarly, the sample was divided into those residing in mandatory or nonmandatory evacuation zones. Kruskal–Wallis tests were used to explore significant differences in track distances by three levels of experience, and Mann–Whitney tests were used for two zones of residence location.

3. Results and discussion

a. Sample characteristics and information sources

The small sample of 16 participants for Hurricane Isaac consisted of 12 females and 4 males, with ages ranging from 22 to 68 and a mean age of 56. The Hurricane Isaac sample was mostly White with one Asian, one African American, and two participants who did not indicate their race or ethnicity. This was not an ideal sample of the population of coastal Louisiana and Mississippi. All of the participants had previously experienced hurricanes, and major historical hurricanes Katrina (2005), Betsy (1965), and Camille (1969) were the only storms mentioned that influenced their decision making, in that order of precedence. Most of the participants were from Louisiana, which explains the hierarchy of influence from past storms. Although local television was the most common source of information, 10 of the participants cited multiple sources that were used in conjunction with television. These sources included Internet weather sites, radio, and The Weather Channel by frequency of count. None of the participants mentioned a type of social media as an information source. All of the evacuees had checked an update on storm information within six hours prior to being interviewed.

The sample of 16 participants from Hurricane Harvey was evenly split between males and females with similar age variance to the Hurricane Isaac sample, but with a slightly younger mean age of 45. The Hurricane Harvey sample was an accurate representation of Central

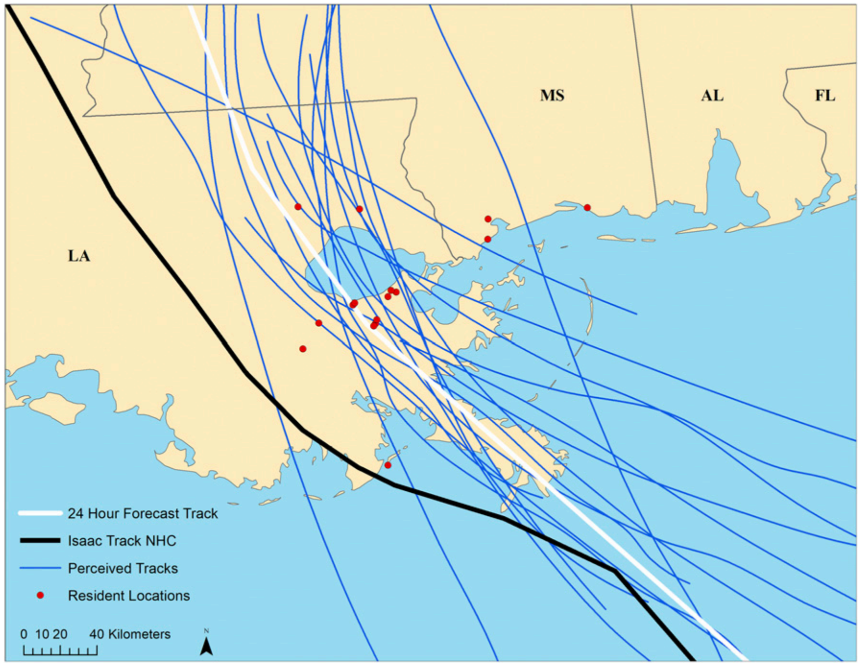

FIG. 3. Perceived tracks of evacuees of Hurricane Isaac in comparison with the official track and 24-h forecast track, along with participant home location.

Texas Gulf Coast residents with eight White, four Hispanic/Latino, one African American, and three participants indicating other or multiracial. Eleven of the participants had previously experienced hurricanes, and recent hurricanes Rita (2005), Ike (2008), and Claudette (2009) were the most frequently mentioned storms that influenced their decision-making. However, Rita (2005) and Ike (2008) did not directly impact their locations with hurricane force conditions. Most of the participants were from Victoria or coastal cities within 100 km of Victoria. Television and social media were the most common sources of information, with many participants listing Internet sources and friends and family. Participants were using multiple sources of information in conjunction with social media and also were checking for information updates more often than participants did in 2012, regardless of age.

The evacuation from Irma was the largest in U.S. history (Bousquet and Klas 2017). Estimates indicate more than 6.5 million residents had been under a mandatory evacuation order (Held 2017), and Florida Department of Transportation vehicle count numbers were at record levels exiting the state (Florida Department of Transportation 2018). Our sample of 155 evacuees resembled the demographic composition of southeastern and southwestern Florida, with equal gender balance and representation of all races and ethnic groups and a mean age of 50 (Senkbeil et al. 2019). Similar to Harvey, participants were using multiple sources of information in conjunction with social media, and also checking for information updates constantly. Most participants had checked the current forecast track for Irma 1 h or less before being surveyed. Of the 132 evacuees who answered the question about previous hurricane experiences, 19% had no previous experience, 57% had experienced at least one hurricane, and 24% had experienced multiple hurricanes.

b. Hurricane-track perception error

HURRICANES ISAAC AND HARVEY

The small samples from Hurricanes Isaac and Harvey were combined in this section for discussion and evaluation. Since the samples of 16 evacuees for each storm were too small for statistical analysis, the results from these storms served as pilot studies to create hypotheses for future storms with larger sample sizes. Although Isaac and Harvey were different in intensity, both had relatively consistent track forecasts, allowing for the storms to be concurrently discussed and their results placed in perspective.

The PT − FT and PT − OT results for Isaac and Harvey share similarities. The FT and OT for Hurricane Isaac had a greater range since it unexpectedly stalled for several hours at landfall before briefly moving west and resuming a northwest track (Fig. 3). Therefore, for Isaac, the FT was east of the OT, creating some forecast

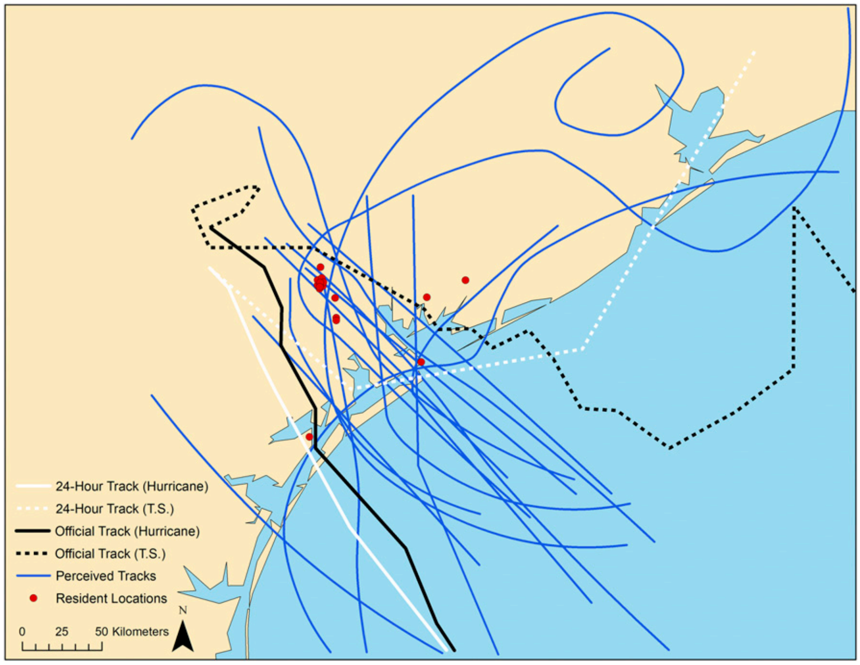

FIG. 4. Perceived tracks of evacuees of Hurricane Harvey on the Texas coast in comparison with the official track and 24-h forecast track, along with participant home locations. The dashed lines indicate an intensity downgrade to tropical storm status.

error. This westward movement resulted in a mean PT − OT of 107 km and a range of 29 to 215 km (see Table 1). Most of the participant locations were well removed from the decaying eyewall of Isaac. For Hurricane Harvey, the mean PT − OT was a closer distance of 22 km, reflecting an OT that went slightly farther north on the Texas coast than the forecast track, thus bringing it closer to most participant locations (Fig. 4). For both storms the PT was positive, indicating a perception of a track farther east or farther north than the official track while still in the direction of the majority of participant locations. For Hurricane Isaac the mean PT − FT was only 21 km, with a range from −56 to 129 km. Hurricane Harvey had a larger PT − FT mean of 38 km and a more concentrated range from −20 to 47 km (see Table 1). Similar to the OT results, the FT results also show a PT closer to the home locations than what was forecast to occur. Tracks that were consistently drawn closer to the HL could be an indication of impact bias. Impact bias is a psychological term to describe the overestimation of affective reactions to future events and decisions (Sevdalis and Harvey 2009) or overestimating the intensity and duration of emotional reactions to future events in affective forecasts (Morewedge and Buechel 2013). This could possibly be a sign of an impact bias for evacuees who perceived a track closer to their home locations than what actually occurred, but the sample size is too small to make inferences about the total population of evacuees. This possible indication of an impact bias is further evaluated by analyzing the HL–PT results.

For Hurricanes Isaac and Harvey, the HL − PT means were −3 and −4 km, respectively. This result seems to suggest that participants anticipated a storm that would directly hit or come very close to their home location; however, the large positive and negative ranges for each storm created a misleading picture. The absolute values of HL − PT for each storm were 40 km for Isaac and 26 km for Harvey. For both storms, the spatial clustering of participants was concentrated within the forecast hurricane impact zone, thus reducing the influences of spatial dispersion on the results (see Figs. 3 and 4). Although the majority of the perceived tracks are closer to the evacuees' home zip codes as well as east of the forecast track and official track for both hurricanes, it is inconclusive to say that an impact bias effect was clearly observed. These hypotheses of possible impact bias were further investigated in Hurricane Irma.

c. *Hurricane Irma*

1) DAY 1 (7 SEPTEMBER) VS DAY 2 (8 SEPTEMBER)

The sample size was almost evenly divided between evacuees on days 1 and 2. Since the forecast track changed from day 1 to day 2, PTs from each day were directly compared with the OT, FT, and HL using both positive/negative and absolute values. Day 1 represented an almost equal split between evacuees from southeastern Florida and southwestern Florida. The geographical split between the evacuees on the western and eastern coasts of Florida combined with shifting tracks (Fig. 5) necessitated the use of both positive/negative and absolute value distance measures. Results for both metrics are found in Table 1.

The OT was farther west than the FT for both days data were collected. This resulted in a large positive value and significant difference between days 1 and 2 for PT − OT since the PT and FT were both much farther east than the OT. The exact placement of the OT was difficult for forecasters that were trying to anticipate the influences and exact timing of a trough that would turn Irma abruptly northward. Thus, the PT − OT differences were due to inevitable forecast error from an uncertain and difficult meteorological forecast.

The FT used for each day had times at 1200 and 1500 UTC since data collection occurred starting in the morning and continuing into the afternoon. Evacuees were paying very close attention to the latest forecast track. The most common response to our question about when evacuees last checked for storm forecast information was within the last 30 min. The FT on day 1 at both 1200 and 1500 UTC was near or over the greater Miami metropolitan area (see Fig. 5). On day 2, the FT had shifted westward on a track into the interior of Florida, and the 1500 UTC shifted even farther west, also into the middle of Florida. The differences in PT − FT between days 1 and 2 were small and insignificant for 1200 UTC, but these differences were significant for 1500 UTC (see Table 1). Most evacuees drew a perceived track very close to the forecast track at the time that they were surveyed on day 1; however, on day 2 there appeared to be a lag behind the shifting FT. As the FT shifted westward and more inland on day 2, many people were still drawing their PT over the greater Miami area. This explains the significant differences for 1500 UTC between the two days (significance level $p < 0.01$) while possibly providing ancillary evidence for an impact bias effect.

This possible effect is best analyzed through HL − PT differences, but the HL − PT differences between days 1 and 2 were largely controlled by evacuees either residing in southwestern Florida or southeastern Florida. The mean day-1 distance of −106 km was heavily influenced by the evacuees from southwestern Florida who expected the storm to go east of their homes. Therefore, any comparisons between days 1 and 2 for HL − PT could be misleading. If only the day-2 distances were used, it controls for regional location and makes the comparison more similar to that for hurricanes Isaac and Harvey, which were collected on a single day. The day-2 HL − PT distances of evacuees only from southeastern Florida support the 1500 UTC differences in PT − FT discussed above. Although the day-2 FT shifted into the middle of Florida, The HL − PT track was 48 km, indicating that evacuees perceived a track closer to their residences than what it was forecast to be on day 2. This result does not confirm an impact bias effect, but is another piece of tangential evidence. Coupled with the Harvey and Isaac results, it suggests that most evacuees anticipated a more direct impact at their residence than was forecast to occur. This possible impact bias effect is further supported by the overestimation of wind speeds as reported by Senkbeil et al. (2019).

2) Previous hurricane experience

Previous hurricane experience may have played a role in the psychology and comprehension accuracy of track perception for evacuees. Three levels of experience were used to divide the sample into those with previous hurricane experience (three or more storms) ($n = 43$), some hurricane experience (one or two storms) ($n = 50$), and no previous hurricane experience ($n = 29$). The track distance variables discussed in the prior section were used with Kruskal–Wallis tests for experience, but the test for experience was not divided into days for this analysis. Only HL − PT had significant results. Using both positive/negative methods (mean −10 km; $p = 0.04$) and absolute values (mean 64 km; $p = 0.03$), evacuees with previous hurricane experience perceived that a storm track would be closer to their homes than did evacuees with some experience (−36 and 101 km) or no experience (−80 and 108 km) (see Table 1). Furthermore, evacuees with some experience perceived a storm track significantly closer to their homes than evacuees with no experience ($p = 0.02$). These results align with the HL − PT track result for day 2 and the results for Harvey and Isaac about a possible impact bias effect. Does this suggest that those with previous storm experiences are possibly dwelling on past examples, or does it suggest that they are using memories of noteworthy past storm tracks as benchmarks? It may also suggest that evacuees with traumatic past hurricane experiences were possibly expecting greater impacts than what was forecast. Is there an impact sentiment, where people believe that because they were impacted in the past that it will happen again? These questions cannot be adequately answered with our data collection. Ideally, an equally sized sample of nonevacuees would be used to evaluate how robust the track perception results are for differing levels of hurricane experience.

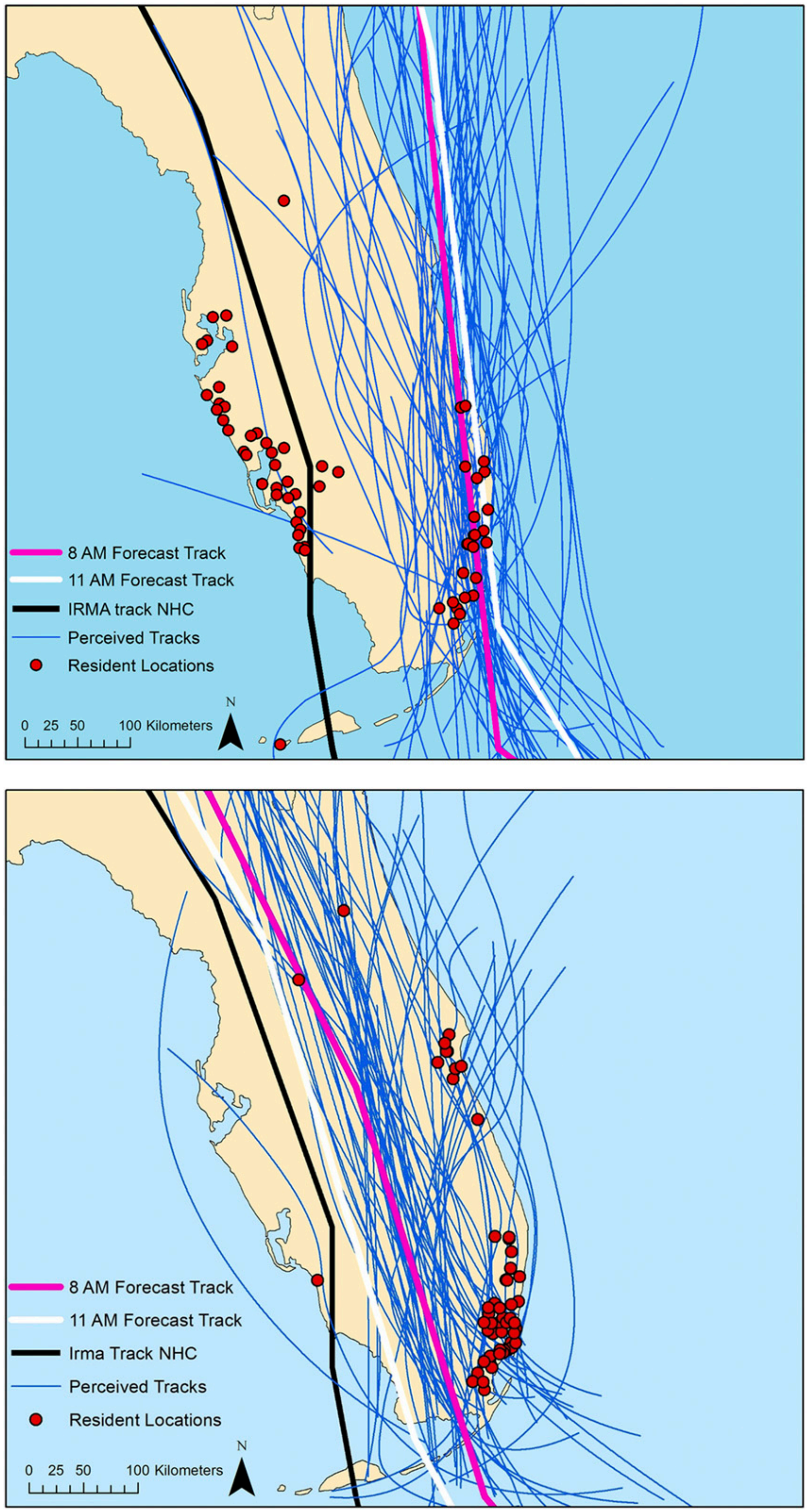

FIG. 5. Perceived tracks of evacuees of Hurricane Irma in Florida in comparison with the official track and forecast track for (top) day 1 (7 Sep 2017) and (bottom) day 2 (8 Sep 2017), along with participant home locations.

3) Evacuation zones

The location of an evacuee's residence within or outside a mandatory evacuation zone could have played a role in the psychology and comprehension accuracy of track perception for evacuees. Each evacuee's home zip code was mapped and the mandatory evacuation zones for Florida were overlaid onto the zip codes using GIS. This method allowed for the identification of evacuee zip codes that were either totally within, bisected, or partially intersected by mandatory evacuation zones (Fig. 6). If a zip code was at least intersected by a mandatory evacuation zone, then it was coded as mandatory. Permission to collect personal addresses and other personal information from evacuees was denied by the IRB; therefore, exact locations of residences within mandatory evacuation zones cannot be determined.

The sample was divided into either mandatory ($n = 50$) or nonmandatory ($n = 69$) evacuees. A Mann–Whitney test was used. Like the experience results, only HL − PT was significant. Using both positive/negative (−68 km; $p = 0.01$) and absolute values (−8 km; $p < 0.01$), evacuees from nonmandatory evacuation zip codes perceived a storm track closer to their homes than evacuees from mandatory evacuation zones (123 and 61 km) (see Table 1). This likely contributed to high shadow evacuation numbers. This result both supports and contradicts the results from other sections. If an impact bias was present, then those within mandatory evacuation zones should have perceived tracks closer to their homes. Contrarily, if people were unaware that they resided in a mandatory evacuation zone this becomes irrelevant, and we do not know how many participants in our sample were unaware. It is also possible that evacuees from nonmandatory zones subconsciously drew their perceived tracks closer to their homes as a way of justifying their decision to evacuate. Combined with overestimation of wind speed (Senkbeil et al. 2019), this result suggests that the majority of evacuees in the sample expected a track that would at least cause some damage to their residence. The evacuees from nonmandatory zones expected a track closer to their homes, and this was generally accurate since the nonmandatory zones are primarily farther inland and the forecast tracks and official track shifted into the middle of Florida. The massive number of shadow evacuees across Florida likely expected strong storm impacts and persistent inconveniences after the storm even though the conditions were not life-threatening in these zip codes.

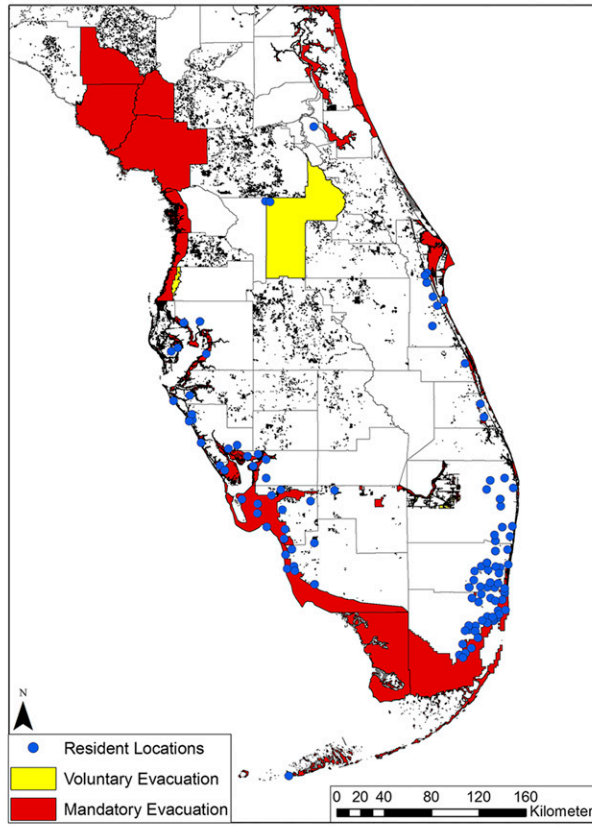

FIG. 6. Locations of evacuee zip codes in relation to mandatory evacuation zones in Florida (Source: GIS Division of the Florida Department of Emergency Management).

4. Conclusions

The primary goal of this research was to assess the perception accuracy of forecast hurricane tracks from hurricane evacuees. Specifically, were evacuees perceiving storm tracks that closely resemble the forecast storm tracks from the NHC? Evacuee perception of storm tracks was assessed for three different landfalling hurricanes via three different metrics. There were common factors of hurricane-track perception among all three hurricanes, despite the differing characteristics of each storm. The small samples for hurricanes Isaac and Harvey both showed a tendency for evacuees to perceive a storm track closer to their homes than the official track and forecast track. This result was also seen with Hurricane Irma evacuees after controlling for regional location using only the day-2 results. The day-2 Irma track shifted inland. Even though evacuees were closely monitoring changing track forecasts, most of the perceived Irma tracks were located farther east near the greater Miami metropolitan area on day 2. Therefore, this research appears to show emerging evidence that evacuees are anticipating a storm track closer to their homes than what was forecast to occur and what actually occurred. This is a possible indication of an impact bias effect; however, that cannot be proven with the data collected so far. For incontrovertible evidence of such a result, a perception comparison between a large sample of evacuees and nonevacuees would be required. Such data would be difficult to collect with a sample of nonevacuees immediately before or immediately after a major hurricane landfall. It is likely that such a study would be conducted weeks or months after the event at the expense of losing ephemeral decision-making data captured during the evacuation or nonevacuation.

The second question asked about the role of external variables on the perception of storm tracks. Additional risk perception results from evacuees were found by dividing the Hurricane Irma participants into levels of hurricane experience and evacuation zones. Those with extensive hurricane experience and participants with some hurricane experience expected a track closer to their home locations than participants with no experience. It is unknown what would cause those with experience to perceive a closer track, but several ideas were previously mentioned. Does a traumatic past storm experience trigger the expectation that there is a high chance that history will repeat itself? Do people anticipate hurricane tracks and perceive some hurricane characteristics in a similar way to tornado folklore (Klockow et al. 2014)? These questions cannot be adequately answered with our data collection, but provide avenues to pursue in future research in coordination with psychological expertise.

Hurricane Irma participants from zip codes that were associated with nonmandatory evacuation zones perceived a track closer to their homes. Shadow evacuation from Irma was a huge contributor to the largest evacuation in U.S. history. The overestimation of wind speeds that evacuees thought they would experience at their homes supplied evacuees in nonmandatory zones with motivation to also evacuate (Senkbeil et al. 2019). The inconveniences of possibly being without power for up to 2 weeks may have been just as or more important when analyzing the thought processes of shadow evacuees (Bostrom et al. 2018). Regardless, targeted communication and distribution of existing messages on inland impacts and hazards from National Weather Service (NWS) offices and the NHC should be given high emphasis in future storms to combat excessive shadow evacuation.

Hurricane-track forecast accuracy skill from the NHC is reliable and errors are decreasing over time. Despite this fact, this research suggests that many evacuees are making errors in perceiving the spatial locations of track forecasts. How can forecasts be tailored to better reach the public audience? The NHC currently has a video on their website describing the COU and how to use it. NWS offices and the NHC are constantly evaluating how to best serve their constituents. Some of their existing products and experimental products will undoubtedly help in coming years. In addition to those ideas, a few more suggestions are briefly mentioned here.

Perhaps greater geographic specificity with place names should be applied to the COU graphic in the 72 h prior to landfall. Map-reading skills are eroding over time, and this could possibly reduce confusion that is potentially related to any spatial or geographic misinterpretation. In our survey mapping exercise, it often took the participant about 30 s to find their home location on a map as they flipped the map in several different directions trying to understand where they were. This is despite a clear north arrow and clear text labels for cities and interstate highways. The predicted path of the storm could be zoomed in for scale across each greater metropolitan region with a focused emphasis on hazards specific to and within each region. The NHC storm surge unit is already using this approach on the metropolitan region scale. With a reduced map extent in urban areas, perhaps forecast hurricane hazard uncertainty information for the size of the wind field, wind gusts, rainfall ranges, and tornado potential could also be presented in addition to storm surge on this scale. Many NHC products need better promotion from broadcast meteorologists to inform more people about these resources. Continued social science feedback on how people use forecast information from warning graphics is also imperative to facilitate communication of the intended message. These ideas and others may help to alleviate current gaps (Bostrom et al. 2018) in hurricane hazard perception between meteorological forecasters and their pubic audiences.

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