Evacuee Perception of Geophysical Hazards for Hurricane Irma

JASON SENKBEIL

Department of Geography, University of Alabama, Tuscaloosa, Alabama

JENNIFER COLLINS

School of Geosciences, University of South Florida, Tampa, Florida

JACOB REED

Department of Geography, University of Alabama, Tuscaloosa, Alabama

(Manuscript received 27 February 2018, in final form 15 November 2018)

ABSTRACT

Hurricane Irma was one of the strongest Atlantic hurricanes in history before landfall and caused a large evacuation. A total of 155 evacuees at interstate rest areas were asked to rank their concern about damage at their residence for six different geophysical hurricane hazards. Additionally, they were asked about their perceived maximum wind speeds (PMWS) and the wind speeds at which they thought damage would occur (DW) at their residence. These wind speeds were then compared to the actual peak wind gusts (APG) nearest to each resident's location. Results show a significantly greater concern for wind and storm size, compared to other hazards (tornadoes, rainfall/flooding, storm surge, falling trees). The mean PMWS of evacuees was greater than the mean APG, suggesting widespread misperception of wind speeds. Furthermore, the mean APG was less than the mean DW, and the mean PMWS was also higher than the DW. Additional tests found no significant differences in wind perception between residents with previous storm experiences and no experience, and no significant differences between those who resided in mandatory evacuation zip codes and those who did not. These results suggest that wind speed risk is poorly understood, even though it is a high concern for evacuees from hurricanes. The communication of wind speed risk in forecasts should possibly be modified by placing greater emphasis on postlandfall impacts, wind speed decay after landfall, and wind speeds that cause damage to different types of residences.

1. Introduction

Understanding the myriad reasons why people do or do not evacuate from hurricanes is a complicated puzzle with different information and forms of messaging interacting with physical and social stimuli (Morss et al. 2016). 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. Developing a deeper understanding of how evacuees comprehend risk portrayed in forecasts of geophysical hurricane hazards is important for the enhancement of accurate risk communication. Poor familiarity and understanding of geophysical risks from landfalling hurricanes is a possible latent factor contributing to shadow evacuation (Baker 1995; 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. Although the exact economic costs of evacuation vary per storm, Lindell et al. (2011) found that most evacuees use their personal cars to escape, with hotel/motel evacuees spending 55% more per day than those evacuating to stay with friends/family and 27% more per day than those going to shelters. Similar costs were also found by Whitehead (2003), with 71% of that sample using personal cars to evacuate from Hurricane Bonnie. Furthermore, Siebeneck and Cova (2008) found a significant positive relationship between evacuation distance and

Corresponding author: Jason Senkbeil, jcsenkbeil@ua.edu

DOI: 10.1175/WCAS-D-18-0019.1

return time, with over 90% of Hurricane Rita evacuees using personal vehicles. Evacuation can be chaotic, inconvenient, expensive, and frustrating, but evacuation remains the leading option to ensure safety for those living in storm surge risk areas near the coastline or estuaries.

For residents living outside of storm surge risk areas, a shelter-in-place strategy is recommended, especially considering wind-resistant building codes in southern Florida up to 76 $m s^{-1}$ (170 mph; Florida DBPR 2013) for residential structures. Many inland evacuees or shadow evacuees could have stayed home, unless they resided in older and weaker homes or mobile homes built before the HUD manufactured home design code of 1994. Inland transition of a hurricane is often accompanied by a spatial expansion of the wind field as the pressure gradient relaxes, thus reducing wind speed and peak gusts. Sustained winds and wind gusts over land are lower than wind speeds over the open ocean (Sparks 2003). A category 3 on the Saffir–Simpson hurricane wind scale (SSHS) at landfall is often quickly downgraded to a category 1 just two counties inland, but the exponential rate of decay varies according to storm size, storm forward speed, landfall angle, and landfall location (Vickery 2005). Most major landfalling hurricanes weaken below hurricane intensity within 7 h after landfall (Kaplan and DeMaria 1995). Thus, many inland or noncoastal county hurricane evacuees may leave with a perception that their property is going to experience stronger conditions than what it actually experiences—hence, overestimating their risk.

Inaccurate comprehension of meteorological forecasts by the public can sometimes lead to inaccurate perception and action (Dueñas-Osorio et al. 2012). For most hurricanes, the strongest damaging wind impacts are near and just east of the eyewall, occupying a relatively small swath of coastline, compared to the total land area affected by the hurricane (Senkbeil and Sheridan 2006). Basic probability suggests that the odds of a given neighborhood seeing the absolute worst conditions are low and are even lower inland. Unfortunately, in the 4–2-day period (96–48 h) prior to landfall, when most evacuation decisions are made, there is no certainty or guarantee that a given neighborhood will avoid the absolute worst conditions.

Because of the uncertainty, it is acknowledged that forecasters and emergency managers must motivate people to heed warnings and evacuate; however, they must also use messaging and communication methods that avoid overhyping risk to prevent false alarms (Barnes et al. 2007). A near-miss event that is interpreted as a disaster that did not occur may result in inaccurate risk perception for a subsequent disaster event (Tinsley et al. 2012). It is impossible for every forecast to find the perfect balance described by Barnes et al. (2007), but it should be the goal of every forecaster to be as accurate as possible. The use of uncertainty information and communication in forecasts is a possible remedy for this problem (Joslyn and Savelli 2010), but that is not the emphasis of this research. Regardless, overreaction and shadow evacuation from hurricanes is an economic, transportation, and logistics problem that sometimes leads to inaccurate perception of hurricane hazards for future events (Dillon et al. 2014).

The primary goal of this research was to assess the perception of risk from geophysical storm hazards so that future forecasting communication can be enhanced. Questions about hurricane hazards (wind, storm surge, storm size, tornadoes, rainfall/flooding, and falling trees) were included. A novel approach used in this research was the collection of risk-perception data during the evacuation while the meteorological conditions of the storm were being forecast (Senkbeil et al. 2010; Brommer and Senkbeil 2010; Collins et al. 2017). This real-time data collection allows participants to more accurately recount the intricacies of their decision-making process. Baker (1979, 1995) 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.

Brommer and Senkbeil (2010) assessed the accuracy of perception of meteorological hazards associated with Hurricane Gustav using similar methods on data collected during the evacuation. In that research, residents of coastal Louisiana generally had an accurate perception of the hazards that posed the greatest risk at their locations. Residents of lower-lying areas were more concerned about storm surge and rainfall/flooding, whereas residents farther inland were more concerned about wind. Other research has revealed inaccurate risk perception of physical storm hazards. Many Houston-area residents overestimated the risk from wind and storm surge for Hurricane Ike in 2008, especially in proximity to waterways (Dueñas-Osorio et al. 2012). Stein et al. (2010) argued for greater emphasis on neighborhood-level risk communication to resolve discrepancies between evacuation decision influences, particularly those involving wind and storm surge.

Since the SSHS evaluates storm intensity based on wind speed, and wind speed is perceived to be the single most important factor that people consider in evacuation decision-making (Petrolia et al. 2011), the second objective in this manuscript was to ask questions about perceived wind speeds and assess the accuracy of those perceptions by comparing perceived winds against observed winds. Wind was the greatest concern of evacuees, thus justifying its precedence for additional analysis in our objectives.

TABLE 1. Survey questions used for the research involving geophysical hurricane hazards.

Question					
1. What is your age?					
2. What is your gender?					
3. What is your zip code?					
4. What is your race or ethnicity?					
5. Have you ever been in a tropical storm or a hurricane?					
6. Which storms have you previously experienced?					
7. Name all of the sources you used to get hurricane information.					
8. What will be the maximum sustained winds (in mph) experienced at your residence?					
9. At what wind speed do you think you would experience significant damage at your home?					
10. How often did you view hurricane graphics before making a decision to evacuate?					
11. When was the last time that you looked at a hurricane graphic?					
	Categories				
12. There are many hazards of concern in landfalling hurricanes. Please rank your level of concern about the following hazards at your residence	4 = Extremely concerned/worried	3 = Very concerned	2 = Concerned	1 = Somewhat concerned	0 = Not concerned
Sustained winds					
Storm surge					
Tornadoes					
Rainfall/flooding					
Storm size (not intensity)					
Falling trees					

Agdas et al. (2012) used wind tunnel experiments to compare perceived wind speeds versus actual wind speeds and to model how perceived wind speed varies with previous tropical cyclone experience. It is not believed that any previous research has asked hurricane evacuees about their perceived wind speeds and the wind speeds that would cause damage at their residences, in comparison to the actual wind speeds observed near their residences.

Three sections follow the introduction. Section 2 consists of three subsections that describe the data collection procedures and survey design, the specifics of the evacuation from Hurricane Irma, and data analysis. The three subsections of section 3 are divided into geophysical hazard concern, wind speed perception, and how each of these relates to evacuation zones.

2. Methods

a. Data collection and survey design

Data collection procedures targeted evacuees at interstate rest areas during the evacuation, following methods from Senkbeil et al. (2010), Brommer and Senkbeil (2010), and Collins et al. (2017). Rest areas often have high foot traffic with participants that are in relaxed atmospheres, resulting in high response rates. 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.

A 20-question survey, consisting of written responses and Likert-scale answers, was administered (Table 1). 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 responses and six Likert-scale responses).

Pilot studies using the proposed methodology for Hurricane Irma were performed in Hurricanes Isaac

(2012) and Harvey (2017) with small sample sizes of only 16 evacuees for each storm. The total size for the evacuations of Isaac and Harvey were both small. Recruiting participants for surveys during the evacuations of Hurricanes Isaac and Harvey was difficult with high rejection rates; however, this was not true for the large, congested evacuation from Hurricane Irma. Because of the small sample sizes and unique conditions associated with Hurricanes Isaac and Harvey, wind perception and hazard results from these storms are used as ancillary evidence in the discussion of the Hurricane Irma findings in the results and conclusions.

b. *Hurricane Irma evacuation and data collection*

Hurricane Irma was one of the strongest storms ever in the Atlantic Ocean. Irma was remarkable for maintaining its category 5 status longer than any storm in the Atlantic basin while tallying 64.9 points of accumulated cyclone energy (ACE; P. Klotzbach 2018, personal communication) over its 12-day life-span, ranking it second all time in the Atlantic basin behind 23-day Hurricane Ivan in 2004. On the morning of Sunday, 3 September, the 5-day cone of uncertainty from the NHC forecast Irma to be over the Bahamas, causing anticipation of a possible Florida landfall as a major hurricane. Monday evening, 4 September, was the first time that the 5-day cone included south Florida. Evacuations from the Florida Keys began on Tuesday, 5 September, and Wednesday, 6 September, was the first widespread evacuation day from southern Florida and metropolitan Miami. The evacuation traffic was heavy on Thursday, 7 September, and reached its peak volume at our survey site 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, at 1310 UTC on Sunday, 10 September, with $58\,\mathrm{m\,s^{-1}}$ (130 mph) winds before tracking over Naples, Florida, as it weakened to winds of $51\,\mathrm{m\,s^{-1}}$ (115 mph; National Hurricane Center 2017).

The evacuation from Irma was the largest in the history of the United States (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 DOT 2018). The normal Friday traffic flow exiting Florida into Georgia on Interstate 75 from 0500 to 1100 UTC ranges from 2300 to 2700 vehicles. On Friday, 8 September 2017, 23 462 vehicles were counted northbound at this same border crossing from 0500 to 1100 UTC. A Florida Department of Transportation car counter on Interstate 75 near Ocala reported a 1236% increase in cars per hour, compared to the same days the previous year, with very slow speeds during peak traffic hours (Florida DOT 2018).

A total of 155 surveys were administered, with some only partially completed, slightly reducing the sample size for certain questions. The sample was an accurate cross section of southeastern and southwestern Florida, with equal gender balance and representation of all races and ethnic groups. Using the six counties containing the highest number of evacuees, our sample groups (percentages) were white (48%), African American (10%), Hispanic/Latino (20%), Asian (3%), multiple races (9%), and preferred not to answer (10%). The mean percentages for those six counties from the U.S. census were white (55%), African American (14%), Hispanic/Latino (27%), Asian (2%), and multiple races (2%) (United States Census Bureau 2018). The home locations of evacuees are found in Fig. 1.

All survey locations were within Florida. On Thursday, 7 September, two teams from the University of South Florida (USF) departed to different interstate rest areas, while a third University of Alabama (UA) team sampled a rest area farther north as that team was traveling into Florida. A northbound rest area on Interstate 75 in Pasco County, just north of Tampa, was chosen by the first group as a site to capture evacuees from the west coast of Florida. For the second group, a northbound rest area (Turkey Lake) on the Florida Turnpike in Orange County, near Orlando, was selected as a location to capture evacuees from southeast Florida and the east coast of Florida. The UA team was arriving into Florida in the late afternoon and attempted to survey evacuees near Gainesville at the Columbia County rest area. Rejection rates at these sites varied by researcher, with a range between 40% and 70%. A total of 48 surveys were conducted north of Tampa on Interstate 75 starting in the early morning, 30 were completed on the Florida Turnpike in Orlando starting in the early morning, and only five were completed in Gainesville in the afternoon. Northbound traffic was heavy and moving slowly Thursday afternoon on Interstate 75 north of the junction with the Florida Turnpike near Wildwood. Rejection rates were 90% in Gainesville in the late afternoon, with many evacuees being visibly disgruntled and frustrated after spending all day in traffic. The teams compared results in Tampa that night, noting that fuel supplies were scarce and all hotels were nearly at full capacity in the Tampa area.

Friday, 8 September, resulted in sustained heavy evacuation traffic. One mixed team of USF and UA researchers departed for the Florida Turnpike Turley

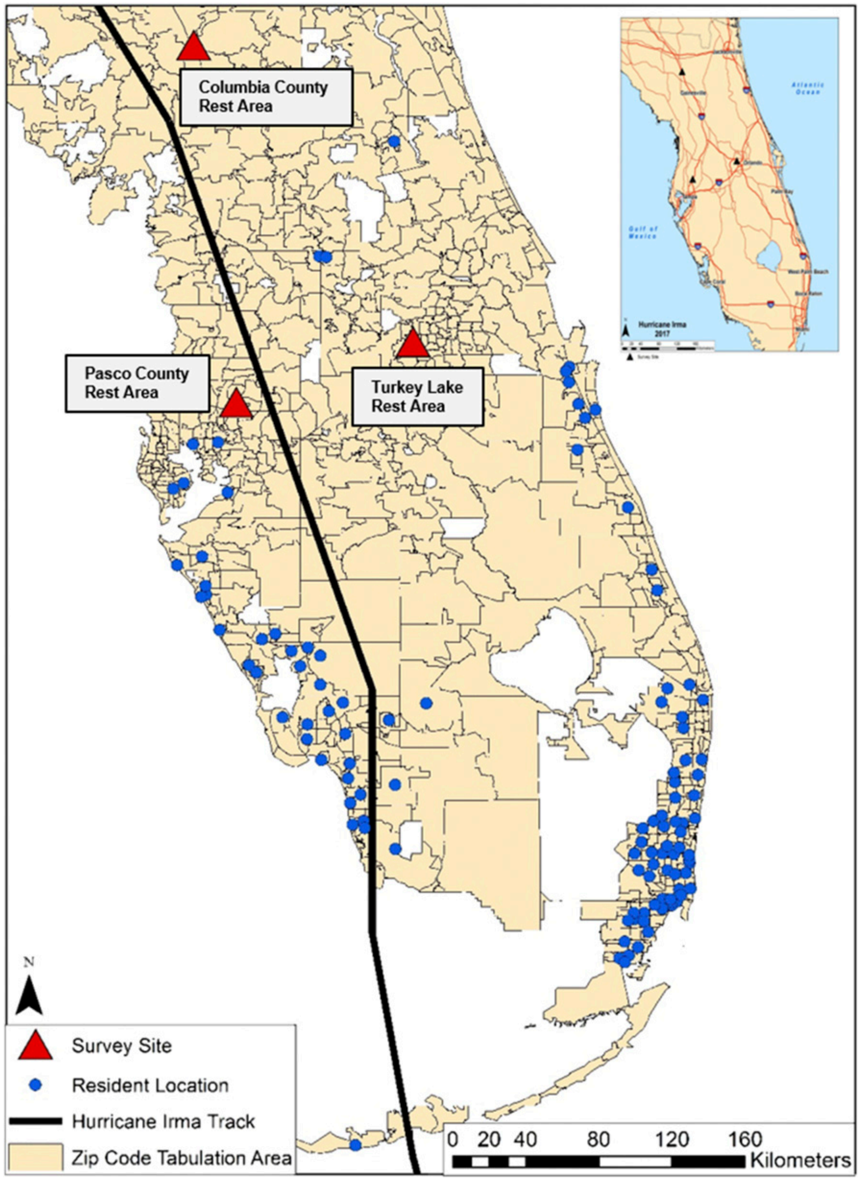

FIG. 1. Hurricane Irma evacuee zip code locations in Florida. The white areas within Florida are occupied by estuaries, lakes, or swamps. Interstate rest area survey sites are marked by red triangles on both the large and inset maps.

Lake rest area since the teams agreed that location offered the best setting to survey a large sample size of evacuees still streaming out of southeastern Florida. The Turkey Lake rest area featured a central service plaza with fuel, restaurants, and other amenities, where most evacuees stopped for between 10 and 45 min. A common strategy was to survey participants as they waited in line for one of the four restaurants or as they sat down to eat lunch. A total of 72 surveys were completed on 8 September, with rejection rates ranging between 30% and 50%, varying for each researcher. All data collection activity was suspended at 1900 UTC on Friday, 8 September, once the shifting track forecast began to emphasize the possibility of direct impacts in Tampa, thus prompting USF team members to attend to their own personal situations, including preparing their houses and executing their hurricane plans, which included evacuation for one of them.

c. *Data analysis*

For our first objective, evacuees were asked to rate their level of concern for each hurricane hazard at their residence on an ordinal scale (0 = not concerned and

4 = extremely concerned). A one-way ANOVA was used with ordinal data to compare the concern level across all six hazards to determine if evacuees were significantly more concerned about certain hazards. Since there is disagreement on the appropriateness of one-way ANOVA with ordinal data, nonparametric Kruskal–Wallis and Mann–Whitney tests were also performed with the Irma data as a way of confirming the robustness of significant ANOVA results.

For our second objective, evacuees were asked about the perceived maximum wind speeds (PMWS) they expected to occur at their residences and the wind speeds at which damage (DW) would occur to their residences. The actual peak gust (APG) recorded at the nearest weather station closest to each evacuee's residence was used to assess error in PMWS (NWS Miami Hurricane Irma local report and summary; https://www.weather.gov/mfl/HurricaneIrma). A map and table of Irma wind speeds across southern Florida is available at this site. These three variables were directly compared to determine the mean differences among PMWS − DW, PMWS − APG, and APG − DW. APG represents the highest wind gust that was experienced near each residence, which is what evacuees answered to question 8 in Table 1. There were likely small inconsistencies in the height of the wind measurement for APG at each station, and exact station specifications are not available. The stations from the NHC Irma summary represent a mixture of official ASOS, FAA, mobile field research, and RAWS with privatized Weatherbug and Weatherflow stations. There were a total of 92 weather stations across the six peninsular counties of southern Florida, creating a resolution where all representative gusts were near evacuee zip codes. Wind gusts were evaluated and verified against surrounding stations to ensure consistency and minimize error. The use of APG as an error verification for PMWS and DW is a more conservative approach than using sustained winds, which would have artificially inflated the error. These comparisons revealed if respondents over- or underestimated the threat of wind hazards. Statistical tests were conducted to determine the possible impacts of gender, age, and previous hurricane experience on wind speed perception. These included independent sample t tests and Pearson correlations.

A final analysis divided the sample into evacuees residing in zip codes that were at least partially under a mandatory evacuation order and evacuees from zip codes that were not under a mandatory evacuation. Since we were not allowed to collect personal addresses, it was impossible to determine where inside each zip code each evacuee resided, thus necessitating a partial mandatory evacuation zip code coverage criterion for dividing the sample. Geophysical storm hazard perception and wind speed perception were assessed as previously described, comparing the split sample of mandatory evacuees against nonmandatory evacuees. Mann–Whitney U tests were used for the ordinal paired comparisons between the evacuee groups for each hazard type and each measure of wind perception.

3. Results and discussion

a. Concern for geophysical hazards

All the evacuees in our sample indicated that they used multiple sources of information when making their evacuation decisions. Most used television weather, social media, and weather websites, checking multiple times per day. Therefore, any changes to potential hazards at their location were fresh in their minds. A one-way ANOVA was used to test for significant differences in concern for each hurricane hazard at the residence of the evacuee. Wind had the highest mean score of 3.37, followed by storm size at 3.29 (Table 2). Wind was the most common reason why people decided to evacuate among the physical variables in this research and the social variables in Collins et al. (2018). Concern for wind was significantly higher than every other hazard, except for storm size. A possible explanation for wind being the greatest concern is the ubiquitous prominence of wind and current SSHS category across all types of media in each forecast update. Further reinforcing wind as the greatest concern, Petrolia et al. (2011) found that wind and landfall timing were the only significant factors influencing hypothetical evacuation decisions. Storm size concern was significantly higher than storm surge, tornadoes, and falling trees. Researchers were careful to explain that storm size referred to the size of the storm and not the intensity. Larger storms are accompanied by a greater volume of storm surge over a larger spatial area of the coastline (Irish et al. 2008), especially after considering the forward speed of the storm (Rego and Li 2009). Additionally, larger storms can impact more area and more people, resulting in greater chances for economic loss. Irma was a large hurricane, and the narrow geography of peninsular Florida provided little opportunity to escape the impacts if the storm followed its forecast tracks. Concern for tornadoes was significantly lower than every other hazard, except storm surge (see Table 2). Storm surge was surprisingly ranked fifth out of six hazards, which contrasts with the Hurricane Harvey pilot study results in Texas and previous research in Louisiana (Brommer and Senkbeil 2010). The majority of Irma evacuees were from coastal counties in southeastern or southwestern Florida (see Fig. 1), with an estimated 42% residing in zip codes

TABLE 2. (top) Mean concern scores for each hazard for Hurricane Irma. (middle) One-way ANOVA results for paired comparisons among the different hazards for Hurricane Irma. Boldface indicates significance at $p < 0.05$. (bottom) Mean and median values for PMWS, DW, and APG nearest the evacuee's residence.

Hazard concern	Sustained winds	Storm surge	Tornadoes	Rainfall/flooding	Storm size	Falling trees
	3.37	2.51	2.25	2.92	3.29	2.84

Irma hazards	Storm surge		Tornadoes		Rainfall/flooding		Storm size		Falling trees	
	Mean difference	*p*	Mean difference	*p*	Mean difference	*p*	Mean difference	*p*	Mean difference	*p*
Sustained winds	**0.85**	**<0.01**	**1.12**	**<0.01**	**0.45**	**0.04**	0.07	1.00	**0.53**	**<0.01**
Storm surge			0.26	1.00	−0.40	0.11	**−0.78**	**<0.01**	−0.33	0.44
Tornadoes					−0.67	<0.01	**−1.04**	**<0.01**	**−0.59**	**<0.01**
Rainfall/flooding							−0.38	0.18	0.08	1.00
Storm size									**0.45**	**0.04**

Irma m s^{-1}	PMSW		DW		APG	
	Mean	Median	Mean	Median	Mean	Median
	57	63	55	54	37	36
	PMSW − DW		PMSW − APG		APG − DW	
	Mean	Median	Mean	Median	Mean	Median
	2	0	20	24	−18	−17

that contained mandatory evacuation orders (Fig. 2). It is possible that surge concern was lower with this sample because surge in southern Florida is not as hazardous as surge on the northern coast of the Gulf of Mexico (Irish et al. 2008). Furthermore, many of the evacuees in this sample did not live in a direct coastal zip code bordering the ocean, despite living in a coastal county (see Figs. 1 and 2). In unprompted conversations, there were some evacuees who lived in high-rise condominiums who were not concerned about storm surge. A more detailed personal assessment of hazard concern accuracy for participants is a subject for future research.

b. *Wind speed perception*

The most direct measure of wind perception was to compare the PMWS to the APG nearest the participant's location. The mean PMWS − APG for Irma was 20 m s^{-1} (see Table 2). The small samples collected for Hurricanes Harvey and Isaac also showed positive mean PMWS − APG, albeit a slightly smaller range than Irma. The vast majority of storms weaken soon after landfall, unless latent heat energy is available over land (Andersen et al. 2013). These positive PMWS − APG results suggest that misperception of wind speeds after landfall is possibly widespread and common for hurricane evacuees, but such a conclusion could only be reached through a larger sample size from several landfalling hurricanes. Based on these results, it is hypothesized that inland wind decay after landfall is poorly understood by the public.

It is recognized that the intensity of the storm in the prelandfall period at the time of the survey could have had an influence on the PMWS and PMWS − APG misperception. It could have also contributed to cognitive dissonance as a way to rationalize an evacuation decision. For example, an evacuee might have held a belief that evacuation was such a hassle that they would never evacuate; however, Irma was so powerful that they thought it best to evacuate. This could have possibly influenced some of the higher PMWS answers (Fig. 3). The Hurricane Irma data were collected on Thursday, 7 September, and Friday, 8 September, but landfall did not occur in the Florida Keys until Sunday, 10 September. At the time of our data collection on Thursday, the winds from Irma were 77 m s^{-1}, and only dropped to 67 m s^{-1} on Friday for our second day of data collection (National Hurricane Center Data Archive 2018). The mean PMWS value of 57 m s^{-1} is not a particularly erroneous estimation since the official Friday morning forecast for landfall was 64 m s^{-1}. The high winds and large storm size concern for Irma noted in the previous section also undoubtedly contributed to the high PMWS values for Irma. Irma's interaction with a trough and associated shearing began to weaken the storm as it turned north toward the Florida peninsula before landfall. Although the trough interaction was forecast to occur, there was not enough certainty to forecast a rapid decrease in wind speed and cause confidence of weakening among the public. Thus, the PMWS − APG mean of 20 m s^{-1} paints a picture of overestimation that is mitigated by the potential of what Irma could have been. Agdas et al. (2012)

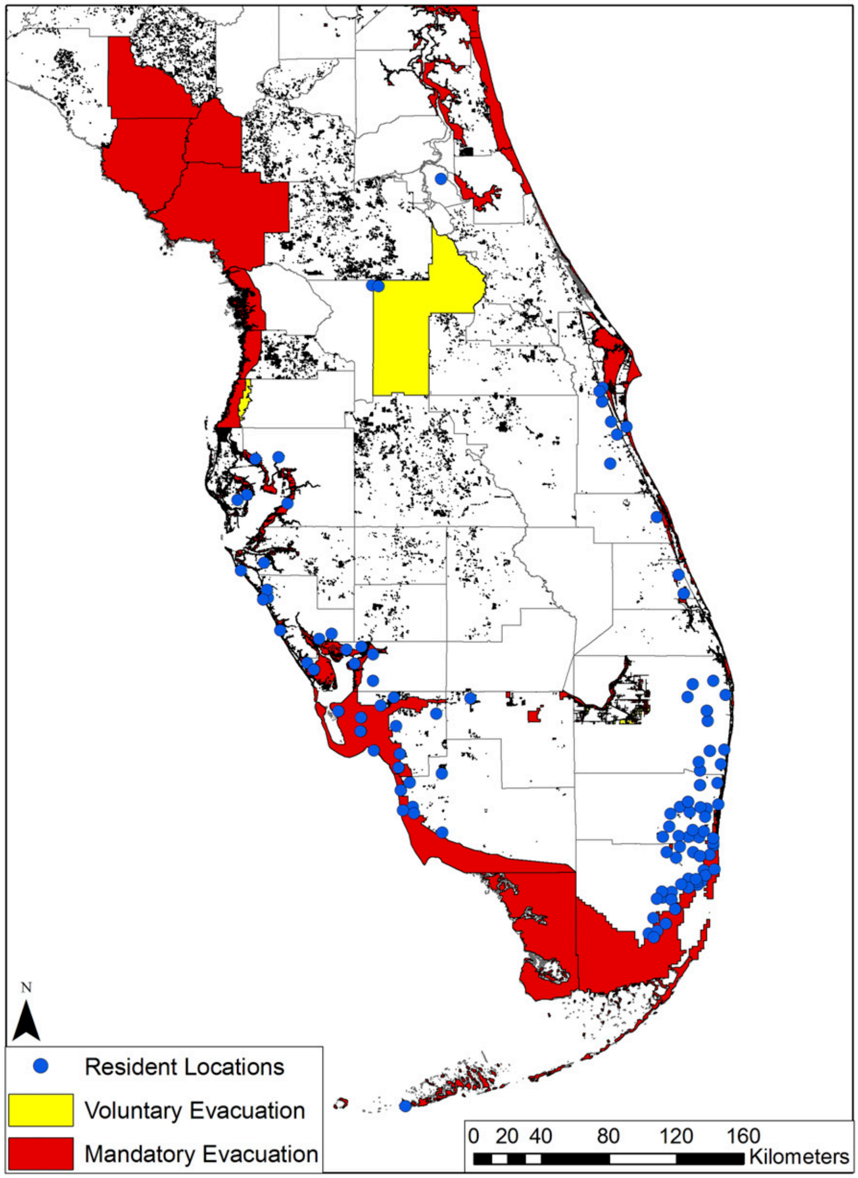

FIG. 2. Hurricane Irma mandatory (red) and voluntary (yellow) evacuation zones. The thin black lines are county borders.

also found an overestimation of wind speed with increasing velocity in simulations, but that result was possibly mediated by participants who had previous tropical cyclone experience. Statistical tests were run to determine the influence of previous hurricane experience, gender, and age on PMWS. Using a variety of tests, only one of these relationships was significant at the 0.05 level. Age was inversely correlated with PMWS ($r = -0.22$, $p = 0.012$), showing that as age increases, there is a tendency for PMWS to be less inflated and positive, compared to APG.

The mean DW speed results followed a pattern similar to PMWS. Hurricane Irma evacuees had a mean DW of $55\,\mathrm{m\,s^{-1}}$. These values resulted in a mean PMWS − DW of $2\,\mathrm{m\,s^{-1}}$ for Irma. The mean DW for Hurricanes Isaac and Harvey was 45 and $42\,\mathrm{m\,s^{-1}}$, respectively. For Irma, these wind speeds correspond roughly with category 3 SSHS winds and category 2 EF-scale winds for tornadoes. The wind speed at which damage would occur has great variability depending on the type of residential structure. The relationships between PMWS and DW raise questions about how well people understand housing construction and the wind speeds at which their residence would begin to experience significant damage. We did not ask questions about housing type, unless that

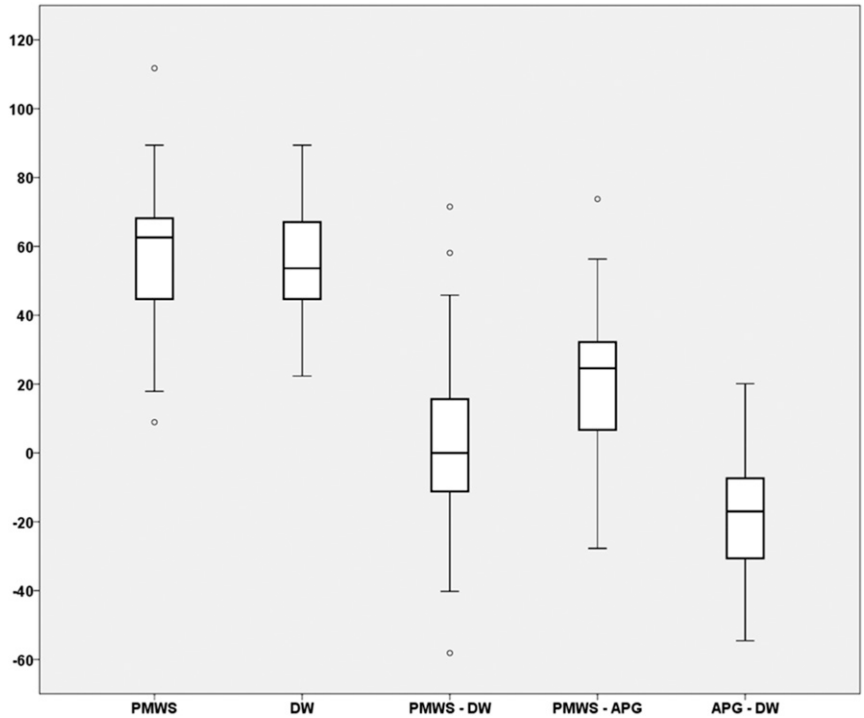

FIG. 3. Boxplot of wind perception values in m s^{-1}. The boxes represent the 75th and 25th percentiles. The horizontal line within the box is the median. The T bars extend to the 95th and 5th percentiles with outlier values represented by circles.

information was volunteered by evacuees who wanted to chat with us about damage potential. During these casual conversations, it was revealed that many metropolitan Miami evacuees lived in high-rise buildings. A few evacuees from more rural areas lived in mobile homes. We were denied expedited IRB permission to ask any questions about personal identity, personal information, home addresses, and associated details. Questions about housing type will hopefully be included in future research to better understand the possible disconnect between wind perception and housing safety.

Another piece of evidence for wind speed overestimation comes from APG − DW (see Fig. 3). Following the results in the previous paragraph, Hurricane Irma had a mean APG − DW of $-18\,\mathrm{m\,s^{-1}}$ (see Table 2). Hurricanes Isaac ($-13\,\mathrm{m\,s^{-1}}$) and Harvey ($-6\,\mathrm{m\,s^{-1}}$) also once again demonstrated supporting consistency in wind overestimation. The overwhelming majority of evacuees received winds considerably lower than the winds they thought would cause damage to their homes. This does not indicate that hurricane evacuees are foolish, nor does it indicate that hurricane evacuations are unnecessary. However, it does provide some of the first direct evidence that the methods of wind speed communication and the comprehension of that message by the public must be improved and better understood to avoid confusion. What are the long-term effects of consistently overestimating wind speed, evacuating, and then returning home and not seeing the anticipated damage? These and other questions can only be answered with time and with future research to determine how robust wind speed overestimation is among evacuees across a variety of storm types, housing type, and regions of hurricane activity.

c. *Hazard and wind speed perception by evacuation zones*

An evacuee's location within a mandatory evacuation zone could have influenced their decision-making. Evacuees were divided according to their residences within zip codes that contained mandatory evacuation zones (42%) and zip codes that did not (58%; see Fig. 2). Mann–Whitney U tests were used for paired ordinal comparisons for the six geophysical hazards and the three measures of wind speed perception. The only statistically significant hazard difference was a higher concern for tornadoes ($p = 0.03$) among evacuees who resided in nonmandatory zip codes. This greater concern for tornadoes in nonmandatory evacuation zones is accurate, as most tornadoes in major landfalling hurricanes occur in both coastal and inland counties in feeder bands away from the storm center (Moore et al. 2017).

Twelve hours to a day after landfall, inland tornadoes in nonmandatory zones are more common with a decaying tropical storm or remnant low system closer to the remains of the central storm structure (Rhodes and Senkbeil 2014). None of the measures of wind perception were significant among the evacuee categories, providing further support for pervasive overestimation of wind throughout Florida regardless of residence location.

4. Conclusions

In this research, Hurricane Irma evacuees were asked to rate their concern for six different hurricane hazards and to also answer questions about wind speeds at their residence. A novelty of this research was the collection of evacuee perception data during the evacuation, when storm characteristics were fresh in the minds of evacuees. The large evacuation in Florida for Hurricane Irma created an environment with traffic gridlock where survey data collection was possible. The first objective was to gain a better understanding of which geophysical hurricane hazards generate the most concern for evacuees. The second objective was to determine how well evacuees perceived the risk from wind by comparing perceived winds to actual wind gusts.

The evacuees from Hurricane Irma were significantly more concerned about wind and storm size and less concerned about tornadoes and falling trees. The extreme wind intensity of Irma at the time the surveys were conducted and its large size created a perception of a violent storm targeting the entire state of Florida, with little chance of avoiding its extreme impacts.

Since wind was such a high concern, it was given priority for additional analysis. The perceived maximum wind speeds (PMWS) were greater than the actual peak gusts (APG) and also greater than the wind speeds at which perceived damage would occur (DW). The APG was less than the DW for each storm. These results suggest widespread overestimation of wind speeds after landfall, and this is only further exacerbated by using the APG for comparison. If the sustained wind speeds over land were used, then the overestimation of wind speed would be even greater. Communication of wind speed forecasts postlandfall should consider methods to better convey wind speeds and the wind speeds at which damage occurs to different types of residential structures. This is especially important, considering the state of Florida's building codes requiring category 1 buildings (low occupancy) to be capable of withstanding 3-s gusts up to 67 $m s^{-1}$ (150 mph) for the majority of the state and 76 $m s^{-1}$ (170 mph) for the Miami area and part of the Florida Keys (Florida DBPR 2014). Furthermore, concern for storm surge was comparatively low, and storm surge potential is the most important factor when delineating mandatory evacuation zones. Forecast communication may also consider methods to address wind speed decay after landfall so that people have a more accurate estimate of the wind speeds they may encounter at their residence. Another area where forecast communication could be improved is specific messaging targeting the reasons why people should evacuate from hurricanes. Currently, agencies such as FEMA and the CDC offer advice on how and when to evacuate and what to pack, but not why people should evacuate or shelter in place.

Despite the evidence for overestimation of wind speeds and the greater concern for wind compared to other hazards in this sample, evacuations may not be determined or affected by one expected attribute of the hurricane. Hurricane evacuation will continue to be a complicated relationship among physical, social, economic, population, infrastructure, and geographic factors with storm-specific variables and local attributes exacerbating decision-making. Future research will continue to assess hazard concern and wind perception during hurricane evacuations, with an emphasis on identifying areas where communication can be enhanced to improve decision-making.

Acknowledgments. The Hurricane Irma research was sponsored by NSF RAPID Grant BCS-1760235. We also would like to acknowledge members of the USF hurricane team, especially Emily Cerrito, Amy Polen, Michelle Saunders, and Saurav Chakraborty, for their field work in Hurricane Irma.

REFERENCES

Agdas, D., G. D. Webster, and F. J. Masters, 2012: Wind speed perception and risk. *PLOS ONE*, **7**, e49944, https://doi.org/10.1371/journal.pone.0049944.

Andersen, T. K., D. E. Radcliffe, and J. M. Shepherd, 2013: Quantifying surface energy fluxes in the vicinity of inland-tracking tropical cyclones. *J. Appl. Meteor. Climatol.*, **52**, 2797–2808, https://doi.org/10.1175/JAMC-D-13-035.1.

Baker, E. J., 1979: Predicting response to hurricane warnings: A reanalysis of data from four studies. *Mass Emerg.*, **4**, 9–24.

——, 1995: Public response to hurricane probability forecasts. *Prof. Geogr.*, **47**, 137–147, https://doi.org/10.1111/j.0033-0124.1995.00137.x.

Barnes, L. R., E. C. Gruntfest, M. H. Hayden, D. M. Schultz, and C. Benight, 2007: False alarms and close calls: A conceptual model of warning accuracy. *Wea. Forecasting*, **22**, 1140–1147, https://doi.org/10.1175/WAF1031.1.

Bousquet, S., and M. E. Klas, 2017: Millions of Floridians who fled Irma are eager to get home. *Miami Herald*, 11 September, http://www.miamiherald.com/news/weather/hurricane/article172603391.html.

Brommer, D. M., and J. C. Senkbeil, 2010: Pre-landfall evacuee perception of the meteorological hazards associated with

Hurricane Gustav. *Nat. Hazards*, **55**, 353–369, https://doi.org/10.1007/s11069-010-9532-7.

Collins, J. M., R. L. Ersing, and A. Polen, 2017: Evacuation decision-making during Hurricane Matthew: An assessment of the effects of social connections. *Wea. Climate Soc.*, **9**, 769–776, https://doi.org/10.1175/WCAS-D-17-0047.1.

——, ——, ——, M. Saunders, and J. Senkbeil, 2018: The effects of social connections on evacuation decision making during Hurricane Irma. *Wea. Climate Soc.*, **10**, 459–469, https://doi.org/10.1175/WCAS-D-17-0119.1.

Cuite, C. L., R. L. Shwom, W. K. Hallman, R. E. Morss, and J. L. Demuth, 2017: Improving coastal storm evacuation messages. *Wea. Climate Soc.*, **9**, 155–170, https://doi.org/10.1175/WCAS-D-16-0076.1.

Dillon, R. L., C. H. Tinsley, and W. J. Burns, 2014: Near-misses and future disaster preparedness. *Risk Anal.*, **34**, 1907–1922, https://doi.org/10.1111/risa.12209.

Dueñas-Osorio, L., B. Buzcu-Guven, R. Stein, and D. Subramanian, 2012: Engineering-based hurricane risk estimates and comparison to perceived risks in storm-prone areas. *Nat. Hazards Rev.*, **13**, 45–56, https://doi.org/10.1061/(ASCE)NH.1527-6996.0000053.

Florida DBPR, 2013: Florida building codes. Florida Department of Business and Professional Regulation, https://floridabuilding.org/bc/bc_default.aspx.

——, 2014: FBC wind maps—Resources. Florida Department of Business and Professional Regulation, http://www.floridabuilding.org/fbc/Wind_2014/2014_Wind_Maps.htm.

Florida DOT, 2018: Hurricane Irma: Emergency evacuation report and recommendations. Florida Department of Transportation Rep., 39 pp., http://www.fdot.gov/info/CO/news/newsreleases/020118_FDOT-Evacuation-Report-Appendix.pdf.

Held, A., 2017: As Irma shifts west, powerful winds batter Florida Keys. National Public Radio, 9 September 2017, https://www.npr.org/sections/thetwo-way/2017/09/09/549704585/-the-storm-is-here-floridians-window-to-evacuate-shrinks-as-irma-bears-down.

Huang, S.-K., M. K. Lindell, and C. S. Prater, 2016: Who leaves and who stays? A review and statistical meta-analysis of hurricane evacuation studies. *Environ. Behav.*, **48**, 991–1029, https://doi.org/10.1177/0013916515578485.

Irish, J. L., D. T. Resio, and J. J. Ratcliff, 2008: The influence of storm size on hurricane surge. *J. Phys. Oceanogr.*, **38**, 2003–2013, https://doi.org/10.1175/2008JPO3727.1.

Joslyn, S., and S. Savelli, 2010: Communicating forecast uncertainty: Public perception of weather forecast uncertainty. *Meteor. Appl.*, **17**, 180–195, https://doi.org/10.1002/met.190.

Kaplan, J., and M. DeMaria, 1995: A simple empirical model for predicting the decay of tropical cyclone winds after landfall. *J. Appl. Meteor.*, **34**, 2499–2512, https://doi.org/10.1175/1520-0450(1995)034<2499:ASEMFP>2.0.CO;2.

Lindell, M. K., J. C. Lu, and C. S. Prater, 2005: Household decision making and evacuation in response to Hurricane Lili. *Nat. Hazards Rev.*, **6**, 171–179, https://doi.org/10.1061/(ASCE)1527-6988(2005)6:4(171).

——, J. E. Kang, and C. S. Prater, 2011: The logistics of household hurricane evacuation. *Nat. Hazards*, **58**, 1093–1109, https://doi.org/10.1007/s11069-011-9715-x.

Moore, T., N. Sokol, and R. Blume, 2017: Spatial distributions of tropical cyclone tornadoes by intensity and size characteristics. *Atmosphere*, **8**, 160, https://doi.org/10.3390/atmos8090160.

Morss, R. E., J. L. Demuth, J. K. Lazo, K. Dickinson, H. Lazrus, and B. H. Morrow, 2016: Understanding public hurricane evacuation decisions and responses to forecast and warning messages. *Wea. Forecasting*, **31**, 395–417, https://doi.org/10.1175/WAF-D-15-0066.1.

National Hurricane Center, 2017: Hurricane Irma local report/summary. NHC, accessed 8 August 2018, https://www.weather.gov/mfl/HurricaneIrma.

National Hurricane Center Data Archive, 2018: Tropical cyclone advisory archive. NHC, accessed 17 February 2018, https://www.nhc.noaa.gov/data/#advisories.

Petrolia, D. R., S. Bhattacharjee, and T. R. Hanson, 2011: Heterogeneous evacuation responses to storm forecast attributes. *Nat. Hazards Rev.*, **12**, 117–124, https://doi.org/10.1061/(ASCE)NH.1527-6996.0000038.

Rego, J. L., and C. Li, 2009: On the importance of the forward speed of hurricanes in storm surge forecasting: A numerical study. *Geophys. Res. Lett.*, **36**, L07609, https://doi.org/10.1029/2008GL036953.

Rhodes, C. L., and J. C. Senkbeil, 2014: Factors contributing to tornadogenesis in landfalling Gulf of Mexico tropical cyclones. *Meteor. Appl.*, **21**, 940–947, https://doi.org/10.1002/met.1437.

Senkbeil, J. C., and S. C. Sheridan, 2006: A postlandfall hurricane classification system for the United States. *J. Coastal Res.*, **22**, 1025–1034, https://doi.org/10.2112/05-0532.1.

——, D. M. Brommer, P. G. Dixon, M. E. Brown, and K. Sherman-Morris, 2010: The perceived landfall location of evacuees from Hurricane Gustav. *Nat. Hazards*, **54**, 141–158, https://doi.org/10.1007/s11069-009-9457-1.

Siebeneck, L. K., and T. J. Cova, 2008: An assessment of the return-entry process for Hurricane Rita 2005. *Int. J. Mass Emerg. Disasters*, **26** (2), 91–111.

Sparks, P. R., 2003: Exaggeration of wind conditions in Hurricane Floyd and other tropical cyclones. *Nat. Hazards Rev.*, **4**, 27–35, https://doi.org/10.1061/(asce)1527-6988(2003)4:1(27).

Stallings, R. A., Ed., 2002: *Methods of Disaster Research*. Xlibris, 524 pp.

Stein, R. M., L. Dueñas-Osorio, and D. Subramanian, 2010: Who evacuates when hurricanes approach? The role of risk, information, and location. *Soc. Sci. Quart.*, **91**, 816–834, https://doi.org/10.1111/j.1540-6237.2010.00721.x.

Tinsley, C. H., R. L. Dillon, and M. A. Cronin, 2012: How near-miss events amplify or attenuate risky decision making. *Manage. Sci.*, **58**, 1596–1613, https://doi.org/10.1287/mnsc.1120.1517.

United States Census Bureau, 2018: American fact finder. U.S. Census Bureau, accessed 17 February 2018, https://factfinder.census.gov/faces/nav/jsf/pages/index.xhtml.

Vickery, P. J., 2005: Simple empirical models for estimating the increase in the central pressure of tropical cyclones after landfall along the coastline of the United States. *J. Appl. Meteor.*, **44**, 1807–1826, https://doi.org/10.1175/JAM2310.1.

Whitehead, J. C., 2003: One million dollars per mile? The opportunity costs of hurricane evacuation. *Ocean Coastal Manage.*, **46**, 1069–1083, https://doi.org/10.1016/j.ocecoaman.2003.11.001.