Nat Hazards
DOI 10.1007/s11069-009-9457-1

ORIGINAL PAPER

The perceived landfall location of evacuees from Hurricane Gustav

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Received: 30 April 2009 / Accepted: 27 August 2009

Abstract Hurricane evacuations in the United States are costly, chaotic, and sometimes unnecessary. Many coastal residents consider evacuation after viewing a forecasted graphic of where the storm is anticipated to make landfall. During the evacuation process, hurricane tracks commonly deviate from the forecasted landfall track and many evacuees may not pay attention to these track deviations after evacuating. Frequently, a disconnect may occur between the actual landfall track, the official forecasted track, and the perceived track of each individual as they made their evacuation decision. Specifically for evacuees, a shift in track may decrease the hazards associated with a landfalling hurricane since evacuees perceive their threat level to be high at the time of evacuation. Using survey data gathered during the evacuation from Hurricane Gustav (2008) in coastal Louisiana (USA), we calculated a type of *Z*-score to measure the distance error between each evacuee's perceived landfall location and the actual landfall location from each evacuee's home zip code. Results indicate a personal landfall bias in the direction of home zip code for evacuees of three metropolitan regions. Evacuees from the greater New Orleans area displayed the highest error, followed by evacuees from greater Lafayette. Furthermore, we validate the authenticity of the previous results by employing two additional methods of error assessment. A large regional error score might possibly be a predictor of evacuation complacency for a future hurricane of similar magnitude, although there are many other variables that must be considered.

Keywords Hurricanes · Evacuation · Landfall · Error · Complacency · Perception

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Published online: 19 September 2009

1 Introduction

The coastal zones of the United States continue to experience population growth during a period of increased hurricane activity in the Atlantic Basin (Landsea 2005; Webster et al. 2005). The Atlantic and Gulf coasts of the United States have been impacted by approximately six major hurricanes (Saffir Simpson category three or greater) per decade in the historical period, 1851–2006. The period 2001–2007 has already seen seven major United States hurricane landfalls (Blake et al. 2007). With an increase in coastal populations and the potential for increased Atlantic Basin hurricane activity to continue, the threat for more frequent and possibly more chaotic evacuations is a reality. In the days preceding a landfalling hurricane, evacuees are provided with an estimated prediction of both hurricane track and intensity as long as 120 h (5 days) in advance of the storm to 24 h (1 day) prior to landfall. If evacuees deem a forecast to be very inaccurate, they may become more reluctant to trust forecasters during future evacuation scenarios. The current necessity of communicating accurate forecasts with minimal error to potential evacuees is critical to maintain the trust of the public.

The meteorologist's task of predicting the exact landfall location of a hurricane is naturally error-prone and rarely perfect. The National Hurricane Center recently began archiving forecasted track errors for all storms in the Atlantic Basin, calculating the mean 24-hour track error for the 2003–2007 period at 107 km, with track error increasing as lead time increases (National Hurricane Center 2008 October 20th). For a majority of hurricanes, the most intense damage is confined to a narrow swath usually located near the center of the storm, associated with the front right quadrant of United States landfalling hurricanes. Outside of this narrow intensity zone, the conditions and resulting damage are less intense. Due to the small spatial extent of these extreme conditions, greater forecast precision is necessary to convey accurate warnings. Given the narrow spatial extent of this high intensity damage swath, the majority of hurricane evacuees will reside outside of this zone. Furthermore, storm size, which is not currently assessed by the Saffir Simpson scale, exacerbates the uncertainty in predicting where this narrow zone of high intensity will make landfall (Senkbeil and Sheridan 2006). Forecasters have a greater margin of error with a spatially extensive storm (such as Katrina in 2005) than compared to a very small storm (such as Charley in 2004), which resulted in a very narrow extreme damage swath. Regardless of storm size, our research revealed that evacuees generally perceived the storm to be headed somewhere near the vicinity of their home. Due to the challenges of correctly forecasting the landfall location of the most intense part of the hurricane, major discrepancies between expected intensity and actual intensity are possible; especially, for evacuees who anticipated a hurricane threat strong enough to prompt voluntary evacuation. When a discrepancy between actual and expected intensity exists, the possibility for evacuation and threat complacency during subsequent hurricanes of similar magnitude is possible due to the perceived lack of intensity and damage.

In this paper, we surveyed 275 evacuees from Hurricane Gustav, spanning much of coastal Louisiana, with two primary objectives. Our first objective is to assess the degree of error of evacuees in correctly interpreting and predicting forecasted hurricane information. We quantify evacuee error by measuring differences between the evacuees' perceived landfall location of Gustav compared to the actual landfall location, the forecasted landfall location, and the actual track of Gustav. Evacuee error is measured by three different methods, and the results are separated into three regions of Coastal Louisiana. Our second objective is to assess and discuss the potential implications of the results in Louisiana and other regions. Since this paper marks the first time these evacuee error procedures have been attempted, we discuss potential implications of regional error results and how these results may possibly be a meteorologically influenced variable that may complement the numerous social variables influencing evacuation complacency.

2 Related literature

Although no previous research has directly attempted to quantify landfall location or track error from the perspective of the evacuee or coastal resident, Broad et al. 2007 discussed public misinterpretations of the commonly used "Cone of Uncertainty" hurricane warning graphic issued by the National Hurricane Center. Although public misinterpretation involved many elements, one source of concern identified a focus on the black track line in the center of the cone. This line, which indicates the forecasted track of the eye, was especially perceived as hazardous to residents in its path. Likewise, the white cone of uncertainty surrounding the track line was de-emphasized by Florida residents with increasing distance from the track line. The same "Cone of Uncertainty" graphic applies to this research on Hurricane Gustav. The forecasted cone is updated every 3 h and it, or a similar version of it, is the major source for the perceived landfall location of evacuees in this paper. An example of this graphic appears later.

Addressing our second objective, there have been numerous studies on hurricane evacuations, evacuation behavior, and evacuation complacency. Evacuation behavior and possible complacency toward hurricanes has been researched numerous times dating back to the 1950s (Killian 1954; Moore et al. 1963; Wilkinson et al. 1970; Baker 1979, 1991). Windham et al. (1977) was one of the first researchers to describe complacency through repeat experiences and false alarms for veterans of many hurricanes. Dow and Cutter (1998) coined the term "Crying Wolf" for hurricanes by assessing the "Crying Wolf" variable in terms of track error for South Carolina residents in the aftermath of two glancing storms that were predicted to impact South Carolina but made direct hits in North Carolina. Using post-storm face-to-face surveys, they determined that individuals did not assign blame for "Crying Wolf" to any particular set of agencies or officials, but instead sought their own sources of information to assess their personal threat level or the personal consequences of a possible "Cry Wolf" event. Dow and Cutter's "Crying Wolf" scenarios focused on track error increasing the likelihood of future evacuation complacency. An important distinction between Dow and Cutter's research and this research is the emphasis on track error of forecasters versus track error of evacuees. Our results quantify the error of evacuees using both point-and track-based methods.

Crying Wolf, however, is not limited to hurricanes. Barnes et al. (2007) examined National Weather Service (NWS) severe weather false alarm reports and how people perceive false alarms. The NWS reports the fraction of forecasted events that did not occur in order to verify the accuracy of its weather warnings. Too often events are classified as either a hit or a miss, which does not necessarily reflect public threat perception. If an event was a near hit, public perception generally considers the warning to be a success because the public accepts a small error as reasonable. This is also true for hurricanes, as long as the forecast is reasonably accurate; however, Regnier (2008) noted that false alarm rates are very high for hurricanes. Regnier concluded that, when possible, evacuation lead times should be reduced from 72 to 48 h to reduce uncertainty and save millions of dollars.

Another form of complacency results from hurricane hypoactivity or hyperactivity. Wang and Kapucu (2008) found that during repeat landfalls in the 2004 hurricane season, storm-weary Florida residents began to ignore warnings as the season progressed; however, this fatigue did not extend to evacuation (United States Army Corps of Engineers 2004). Conversely, evidence also supports a prolonged period of hurricane hypoactivity leads to complacency Pielke (1997). Additionally, the National Hurricane Center estimates that the average lingering effect from a hurricane landfall is 7 years. After 7 years, people begin to forget the impacts from a hurricane and become more complacent if hurricane periodicity becomes hypoactive again (Blake et al. 2007). Although individuals may have become saturated with warning frequency in 2004, one or two previous landfalling hurricanes impact the behavior of evacuees during a subsequent hurricane (Dixit et al. 2008; Baker 1991). For example, in Florida a previous landfalling hurricane is often the impetus for reduced damage through better mitigation (Sadowski and Sutter 2008).

Evacuation complacency may also be exacerbated by extenuating circumstances such as traffic congestion and pet ownership, although many communities now make provisions for evacuees with pets. When evaluating evacuation complacency from the personal perspective, an important factor to consider is the unpleasant possibility of becoming mired in prolonged traffic congestion. After the unprecedented devastation of Katrina (a category 3 storm at landfall), residents of the Gulf Coast region were especially liberal with their decisions to evacuate for Rita (also a category 3 storm at landfall) later that same year. The evacuation in advance of Rita was one of the largest evacuations in US history, resulting in frustrating traffic jams across much of southern Texas and Louisiana. Zhang et al. (2007) point out that many evacuees were still stranded on roadways when Rita made landfall, but luckily, most people were out of the path by that time. Given the frustrating evacuation of Rita, it is a concern that many residents may not evacuate as readily for future storms of comparable intensity. To address this concern, Zhang et al. (2007) conducted 120 face-to-face surveys with South Texas residents who had evacuated prior to the landfall of Rita. Their results show that the unpleasant experiences associated with Rita-related evacuations were not enough to keep most ($\sim$90%) residents from evacuating for similar storms in the future. Traffic congestion appears to be a minor factor when assessing evacuation complacency.

Many important studies such as Dow and Cutter (1998, 2000), Zhang et al. (2007), and Baker (1980, 1981, 1986, 1990) have conducted post-storm face-to-face surveys or telephone surveys on various aspects of hurricane evacuation. It is believed that no previous study has conducted surveys in person during the evacuation process with the intent of quantifying landfall error of evacuees for regions that will be impacted by the storm. These data cannot be considered the same as data collected after the storm has impacted the area and affected the subjects' perspectives and priorities. It is likely that vital information is lost regarding the exact time of evacuation and the exact perceived landfall location during a post-storm assessment. These data collected during the evacuation may provide a better understanding as to the uncertainty of public perception of forecasted landfall location and corresponding variability in spatial damage and intensity.

3 Methods

3.1 Data collection

Two teams of researchers from the University of Alabama and Mississippi State University conducted face-to-face surveys of Gustav evacuees at two interstate rest stops over a 2-day period on both sides of the evacuation region (Fig. 1). Interstate rest stops were targeted as locations that would likely contain high numbers of evacuees willing to participate in

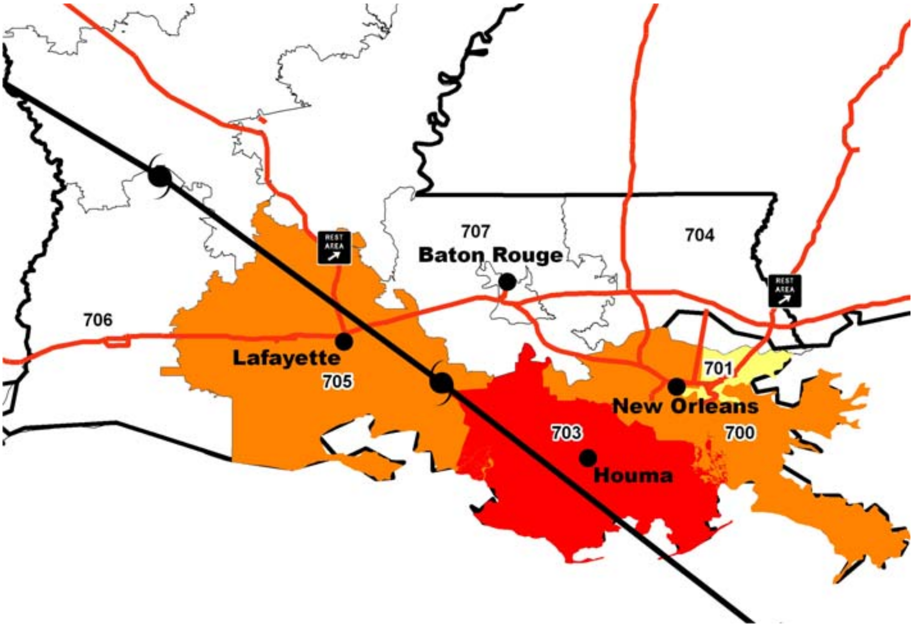

Fig. 1 Map of Coastal Louisiana with impacted three-digit zip code regions and the estimated track of Hurricane Gustav. Survey location sites are indicated by the rest area icons

surveys due to the location of the rest stops along major evacuation routes. On August 30 (a Saturday), 75 evacuees were surveyed over a 3-h period at the Mississippi Welcome Center on Interstate 59 near Picayune, Mississippi. The majority of evacuees were from the greater New Orleans area traveling to destinations in Alabama, Tennessee, or Georgia. The next morning, August 31, we interviewed evacuees at a contra-flow rest stop on Interstate 49 near Opelousas, Louisiana. The majority of the evacuated population on August 31 resided in Houma/Thibodaux and also greater Lafayette, Louisiana. At noon local time on August 31, Gustav was $\sim$21 h from landfall and evacuees were becoming more anxious, thus we ended the survey process at this time even though evacuation traffic was still significant.

A sample of the survey is provided in Fig. 2. Efforts were made not to survey more than one representative from each vehicle or party, in the case that several vehicles were traveling together. Survey participants represented a variety of socioeconomic groups, races, and gender. For this aspect of the research, it was important for the participant to answer questions two, six, seven, and ten. If these questions were not answered to completion, the surveys were not included in the analysis.

Over 70 five-digit zip codes were represented by evacuees of coastal Louisiana. Initially, five-digit zip codes were preferred for analysis; however, this process was ineffective due to inadequate sample sizes in each zip code. In order to facilitate analysis, the five-digit zip codes were organized into three-digit zip code regions representing the largest impacted metropolitan areas (Fig. 1). These three-digit zip code regions are 700/701 (greater New Orleans), 703 (Houma/Thibodaux), and 705 (greater Lafayette). Regions 704, 706, and 707 did not have sufficient sample sizes (Fig. 1). Surveys meeting the criteria of answered questions were then sorted manually by selecting all eligible surveys

Please answer the following questions to the best of your ability:

How many years have you lived on the Gulf Coast? (If you do not live on the Gulf Coast, please state that you do not).

At what time and on what day did you make the decision to evacuate?

On a scale of 1-5 with 5 being the most important, please rank how important the following factors were in influencing your decision to evacuate:

	Least Important				Most Important
Wind	①	②	③	④	⑤
Storm Surge	①	②	③	④	⑤
Rainfall	①	②	③	④	⑤
Tornadoes	①	②	③	④	⑤
Storm Size (not strength)	①	②	③	④	⑤

How long (in number of hours) do you expect your home will experience hurricane conditions? (If you do not expect your home to experience hurricane conditions, please also state that.) __________ hours

How long do you expect to be away from your home?

Where (closest to what city) do you expect the hurricane to make landfall?

Was your decision to evacuate affected by Hurricane Katrina? If so, how?

On which of the following sources of information did you rely a great deal to help you decide to evacuate? (check all that apply)

□ A family member
□ An official (e.g., police, fire dept., emergency management)
□ The Weather Channel
□ Local radio station
□ Local National Weather Service website
□ Paging or instant messaging service
□ A friend or neighbor
□ Other cable news channel such as Fox News, CNN or MSNBC
□ Local television station
□ The National Hurricane Center Website
□ Other Internet websites
□ None—did not use any information
□ Other ___________________________________

Was any one of the sources you checked more important than the others in your final decision to evacuate? (Which one)?

What is the zip code of your primary residence? ______________

Does your household have any pets? □ Yes □ No

If yes, which of the following is true?
□ Have all pets with you
□ Left some or all pets at home
□ Left pets with a boarding facility
□ Left pets with a friend or relative

What type of pets do you have? □ Dog(s) □ Cat(s) □ Other(s)

Where do you expect your final evacuation destination to be?

Fig. 2 Blank sample of survey administered at interstate rest stops that answered the desired questions (questions two, six, seven, and ten on the survey Fig. 2). After compiling all eligible surveys, 30 surveys (90 surveys total) from each three-digit zip code region were then randomly selected for the evacuee error procedures. Thirty surveys from each region were randomly chosen to achieve equal group membership before calculating error statistics. Furthermore, the New Orleans region had a larger number of eligible surveys due to its higher population, while Houma/Thibodaux and greater Lafayette had 33 and 35 eligible surveys each. Thus, 30 eligible surveys were retained for analysis in each region.

3.2 Methods of quantifying evacuee error

As previously stated, we examined the discrepancies between where evacuees perceived landfall location compared to the actual landfall location, the forecasted landfall location, and the actual track of Gustav. This research represents the initial attempt at quantifying these discrepancies, thus, we present three methods with each being explained in the following paragraphs.

Our primary interest is the quantification of the difference between perceived landfall location and actual landfall location. A location's proximity to the actual landfall location and corresponding track is ultimately the most important indicator of potential damage. For discrepancies between perceived landfall location and actual landfall location, we calculated a perceived landfall distance error score (PLDE) for evacuees of three metropolitan regions of Coastal Louisiana using a *Z*-score procedure. Participants were asked to provide their home zip code and the exact time and day they made their evacuation decision. For perceived landfall location, we asked participants to name the city where they believed the eye of the storm was to make landfall at the time of their evacuation decision. A map of perceived landfall locations is presented in Fig. 3. The PLDE score is a form of a *Z*-score determining the relationship between perceived landfall and actual landfall. The common *Z*-score equation for a sample is given:

$$z = \frac{X - \overline{X}}{s}$$

where X is the mean perceived landfall distance to the eastern eyewall from the center of the participants' zip codes in that region, $\overline{X}$ is the mean actual distance to the eastern eyewall from the center of the participants' zip codes in that region, and s is the standard deviation of actual distance to the eastern eyewall from the center of participants' zip codes in that region. PLDE scores were calculated for evacuees of each three-digit zip code region, greater New Orleans, Houma/Thibodaux, and greater Lafayette.

Perceived and actual distances to hurricane landfall location were measured using ArcGIS 9.2. The location of the eastern eyewall was determined from radar images from National Weather Service New Orleans (http://www.srh.noaa.gov/lix/html/Gustav08/Radar/). The eastern eyewall of the storm passed 20 km east of Morgan City, Louisiana on Highway 90; this location was used as the official landfall location and was chosen because it represents the initial point at which Gustav encountered "land." The actual landfall of Gustav occurred near Cocodrie, LA in a sparsely populated area (www.nhc.noaa.gov/pdf/TCR-AL072008_Gustav.pdf). A majority of the landscape south of Highway 90 is coastal marsh punctuated briefly by elevations between 0 and 4 meters. For this reason, we selected the eastern eyewall location at Highway 90 as the landfall location since the bulk of the impacted population resides along and north of highway 90.

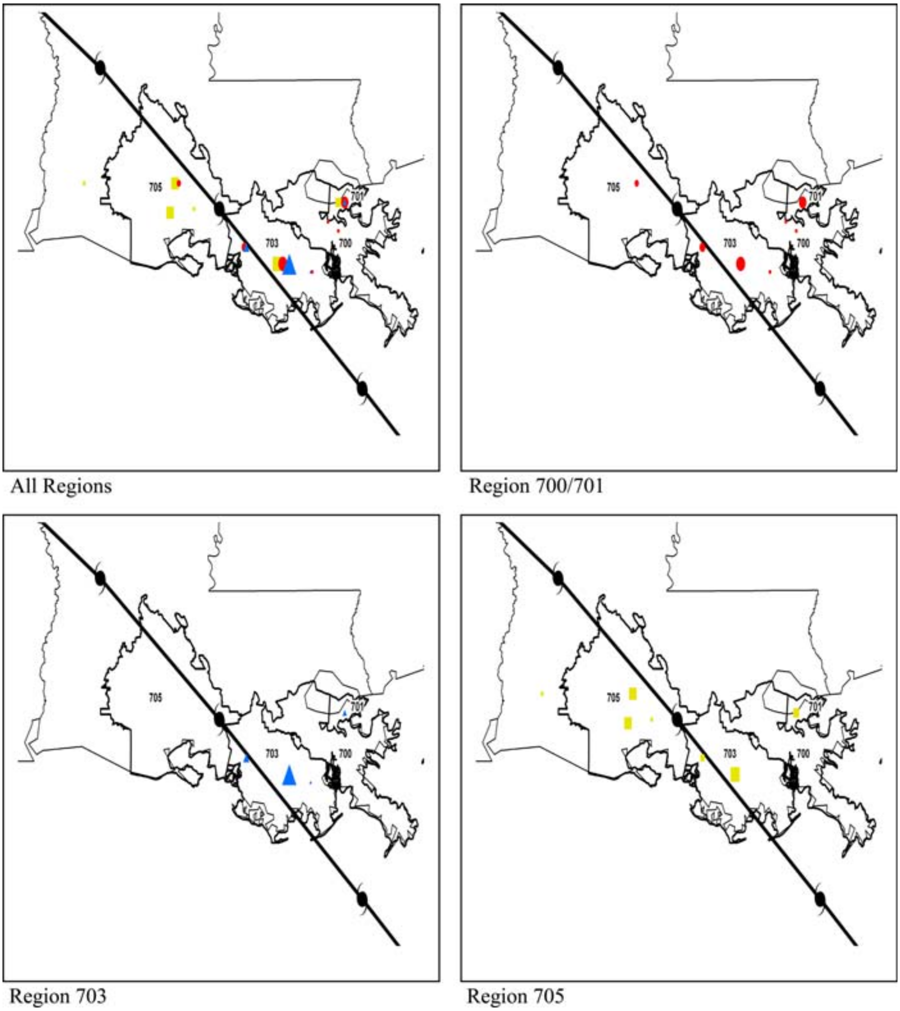

Fig. 3 Perceived landfall locations for each three-digit zip code region. *Larger symbols* represent a greater occurrence of perceived landfall location answers

All actual landfall distances from participant zip codes were measured to this common landfall point 20 km due east of Morgan City Louisiana. All evacuees reside between 29.9 and 30.5°N latitude so any latitudinal measurement error to the common landfall point was minimal.

In determining the difference between home zip code and perceived landfall location, perceived landfall distances were considered positive if they were east of the participant's home zip code and negative if they were west of the participant's home zip code (Table 1). For example, for a participant in the 700/701 region, if the perceived landfall was New Orleans and that participant resided in New Orleans the perceived landfall distance is 0 (zero) km and the actual distance from New Orleans to the eastern eyewall was –100 km (the storm made landfall 100 km west of New Orleans). Therefore, [0 – (−100 km)] = a distance of +100 km. In other words, that individual perceived that the storm was to make

Table 1 Abbreviated sample PLDE table showing a portion of the respondents in each three-digit zip code region ($n = 90$ with 30 in each of the three regions)

Home zip code	City	PLL	HZ–PL	HZ–AL	Difference
Region 700/701					
70003	Metairie	Houma	−75	−90	15
70005	Metairie	New Orleans	10	−100	110
70043	Chalmette	Houma	−80	−115	35
70056	Gretna	New Orleans	15	−95	110
70112	New Orleans	New Orleans	0	−100	100
Region 703					
70364	Houma	Houma	0	−30	30
70342	Glenwild	Houma	45	25	20
70355	Gheens	Houma	−20	−50	30
70359	Gray	Houma	−12	−25	13
70380	Morgan city	Morgan city	0	20	−20
Region 705					
70507	Lafayette	Lafayette	0	115	−115
70506	Lafayette	Houma	140	110	30
70512	Arnaudville	New Orleans	180	120	60
70538	Erath	Morgan city	85	100	−15
70560	New Iberia	Houma	120	100	20

PLL perceived landfall location, *HZ–PL* distance between home zip code and perceived landfall, *HZ–AL* distance between home zip and actual landfall. All distances are in km

landfall 100 km farther east than actual landfall (Table 1). An example from Lafayette is just the opposite. This evacuee perceived landfall in Lafayette so the perceived distance is 0 (zero) km, but the actual landfall distance is +115 km east. Therefore, (0 – 115) = −115, with the difference being −115 since the individual thought the hurricane would make landfall 115 km farther west than it actually did.

Two additional methods were used to assess the authenticity of the PLDE results. A second method of measuring evacuee error is to use forecasted landfall instead of actual landfall, since evacuation decisions are based on forecasted landfall prior to the occurrence of the actual landfall. We asked each participant their exact evacuation time to determine the corresponding forecasted National Hurricane Center landfall location at the time each individual made their decision to evacuate. Forecasted landfall is different than actual landfall because of its migratory location, as the forecasted landfall changes every 3–6 h with new updates from the NHC. Forecasted landfall was taken from the NHC update that most closely matches the evacuation time provided by each participant. Consistent with the PLDE procedure, the forecasted landfall location was marked on the eastern side of the NHC track line at the point the track crossed Highway 90. All forecasted landfall distances were measured to this point and a log was kept to mark the changing forecasted landfall location with each NHC update. We calculated the mean difference between perceived landfall distance and forecasted landfall distance in each region; however, for this procedure our sample size dropped below the requisite ($n = 30$) (Urdan 2005) in each region for a Z-score procedure similar to PLDE. Therefore, the procedure is exactly the same as described previously but the result is not standardized and is reported as a mean distance between perceived landfall distance and forecasted landfall distance. Our sample size was smaller using forecasted landfall due to evacuations greater than 120 h prior to landfall. Greater than 120 h prior to landfall, Gustav was not yet forecasted to make landfall on the National Hurricane Center's 5-day graphic.

A third method of quantifying evacuee error involves the use of the actual storm track instead of a point-based method such as PLDE. Our track-based method is similar to the previous point-based examples, albeit the track method has unique challenges of measuring to a track line oriented from the southeast toward the northwest as Gustav came onshore. For our track method, we repeated the second procedure described previously and reported the results as a mean distance between perceived landfall location and track location. Although we did not specifically ask evacuees to predict Gustav's track, we asked for a perceived landfall location. It is assumed that Gustav's perceived landfall location is a point along Gustav's hypothetical perceived track; therefore, the perceived landfall location is used as a proxy point to estimate Gustav's hypothetical perceived track. We measured the shortest radial distance from home zip code to the eastern side of the actual track line. This method estimates the difference between the hypothetical perceived track and the actual track in the vicinity of the perceived landfall location; however, it loses its applicability with increasing distance from the perceived landfall location. Although it is not directly assessed, the track procedure provides an alternative method that helps to elucidate the results and better evaluate PLDE scores.

3.3 Evacuation time

Using the same 90 randomly selected surveys (30 in each region), mean evacuation time was calculated for each three-digit zip code region from the responses to survey question number two. The mean evacuation times for each region were compared to the archived National Hurricane Center's 5-day track forecasts that corresponded with the mean evacuation times. Evacuation time was determined in number of hours prior to landfall with a range extending from 0 (zero) to 120 h. Hour 120 corresponds with the 8 am CDT (1300 UTC) Wednesday morning update from the National Hurricane Center on August 27, 2008. The 0 (zero) hour was Monday morning, September 1 at 8 am CDT (1300 UTC). The eye of Hurricane Gustav began to impact the coastal marshes of Louisiana shortly after 9 am CDT (1400 UTC) on September 1. If the participant simply answered the estimated time of day they decided to evacuate (morning, afternoon, evening, etc.) but did not provide an exact time, the midpoint of that particular time of day was used. For "morning" answers 10 am CDT was used, 2 pm CDT for "afternoon", and 6 pm CDT for "evening."

4 Results and discussion

4.1 PLDE scores

Mean PLDE scores were calculated for the three-digit zip code regions containing the highest numbers of evacuees, 700/701 (greater New Orleans), 703 (Houma/Thibodaux), and 705 (greater Lafayette). Results indicate a perceived landfall bias closer to each participant's home zip code region, indicating a majority of evacuees across coastal Louisiana perceived Gustav to have a greater impact on their location than what actually occurred (Fig. 4). The greater New Orleans area (zip codes 700/701) displayed the highest PLDE score of the three regions at 3.3. New Orleans and its suburbs dominated the

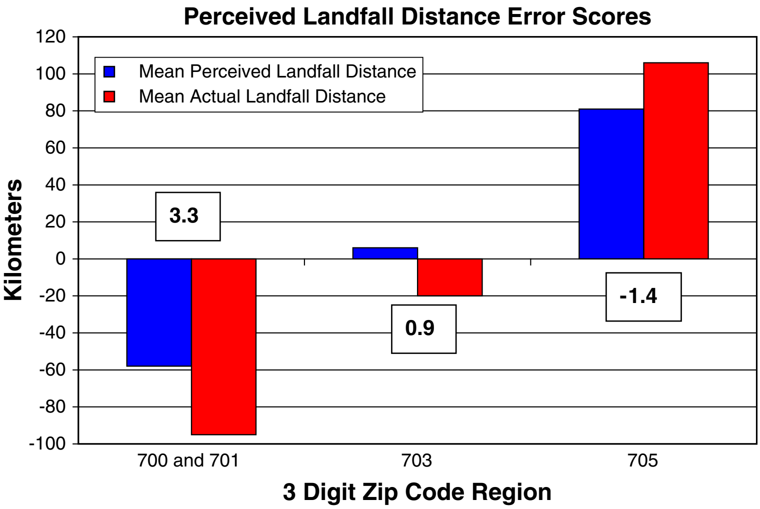

Fig. 4 PLDE scores for each three-digit zip code region. A positive (negative) value indicates a perceived landfall distance farther east (west) than the actual landfall distance

representation of the 700/701 region. The mean perceived landfall distance for a resident of this region was 59 km west while the mean actual landfall distance was 95 km west.

Greater New Orleans residents correctly perceived the landfall location to be west of their residences, thus placing them on the more dangerous eastern side of the hurricane. The problem, however, is that Gustav's sustained hurricane force winds extended 60–100 km to the east of the eyewall, placing the city of New Orleans and its suburbs in the tropical storm-force wind zone. The highest recorded wind gust in New Orleans was 55 kts with many adjacent stations recording lower values (Hurricane Gustav Post Storm Report, http://www.srh.noaa.gov/lix/html/Gustav08/psh_gustav.htm; National Weather Service New Orleans). New Orleans did not receive a direct hit that evacuees anticipated from Gustav. Although we included an internet link on our survey for voluntary post-storm assessments, we received few responses. Unfortunately, at this time we can only use the PLDE score as one of many estimators of potential evacuation complacency.

The New Orleans metropolitan area was evacuated and marshal law enforced beginning 18 h prior to landfall. This region had the earliest mean evacuation time of the three regions at 63 h prior to landfall. The official National Hurricane Center Track at 63 h lead time (from the 4 pm CDT, 2100 UTC update on Friday 29 October) (Fig. 5) displayed a landfall near Atchafalaya Bay, due south of Patterson, Louisiana. This location is ~40 km west of the actual landfall. Ninety percent of respondents throughout all zip code regions indicated that the Weather Channel or local television was their main source of information. These two sources primarily base their forecasted graphics on the latest official track from the National Hurricane Center (NHC). Therefore, 90% of the evacuees were paying attention to a graphic that resembled a facsimile of the NHC "Cone of Uncertainty" at the time they decided to evacuate. Even with the forecasted track displaying a slight westward jog, greater New Orleans residents still anticipated Gustav to make landfall much closer to their locations. Approximately 24 h later, at 40 h lead time, New Orleans mayor Ray Nagin proclaimed Gustav to be "The mother of all storms" (Williams 2008) as it attained category 4 strength prior to crossing Cuba. At this time, mandatory evacuation

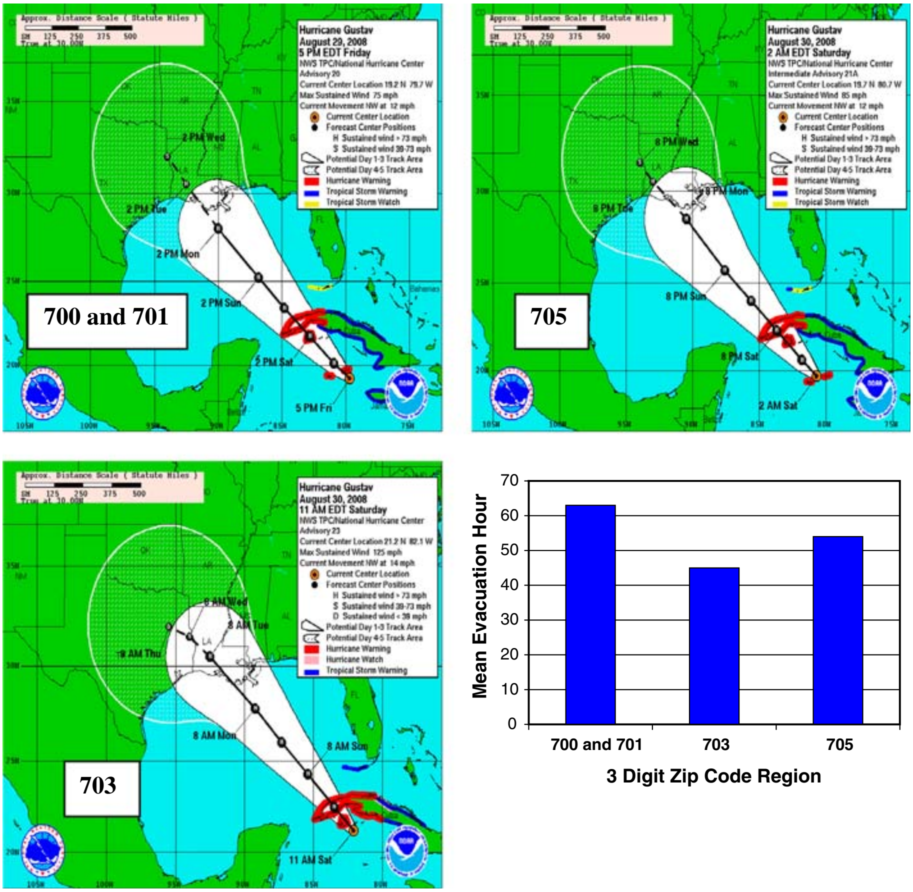

Fig. 5 Official National Hurricane Center forecasts at the time of the mean evacuation hour in each three-digit zip code region. *Source*: http://www.nhc.noaa.gov/archive/2008/GUSTAV_graphics.shtml

orders were issued for much of greater New Orleans. Gustav made landfall approximately 100 km west of New Orleans and had weakened to category 2 hurricane strength. The lingering impacts of Hurricane Katrina undoubtedly contributed to the mandatory and early evacuation of New Orleans. Participants in the survey were also asked if Hurricane Katrina influenced their decision to evacuate. The greater New Orleans region had the strongest response to this question with 21/30 (70%) participants indicating that Hurricane Katrina impacted individual evacuation decisions in region 700/701 (Fig. 6).

The Houma/Thibodaux region (zip code 703), immediately west of the greater New Orleans metro region, received the brunt of Gustav, producing a much lower PLDE score of 0.9. This region had the latest mean evacuation time (45 h) even though the region was forecasted to be directly impacted in all updates from the National Hurricane Center. The forecasted landfall location at 10 am CDT (1500 UTC) on September 30 was very close to the actual landfall location (Fig. 5). Since this region is less populated and traffic is less of a concern, it is hypothesized that evacuee mobilization time is not as important as it is in the New Orleans metro area. The mean perceived landfall distance for a resident from this region was 6 km east (essentially a direct hit), while the mean actual distance was 19.5 km

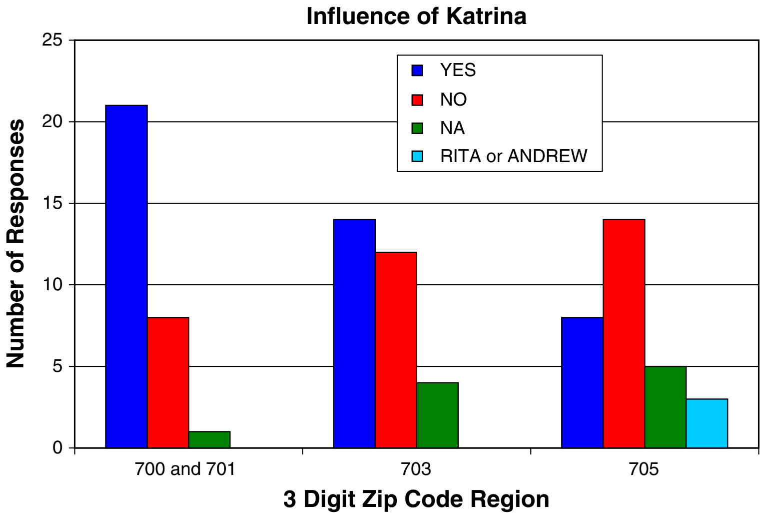

Fig. 6 Influence of Hurricane Katrina on the evacuation decisions of participants in each three-digit zip code region

west. Since the PLDE score is a form of a *Z*-score, values between -1 and 1 were considered normal. With a PLDE score of 0.9, residents of region 703 expected a direct hit and received it.

The Lafayette region 705 is located west of the Houma/Thibodaux zip code region. This region displayed a westward bias toward participant zip code with a PLDE score of -1.4. The mean perceived landfall distance for residents of this region was 81 km east, while the mean actual landfall distance was 106 km east. The mean evacuation time for the Lafayette region was 54 h. It is interesting to note that the official forecast at 54 h displayed a slight westward jog in Gustav's track closer to the population core of this region (Fig. 5). This may explain some of the westward bias for this region. Another important point about this region is that Gustav made landfall in zip code region 703 and then tracked inland northwest along the eastern border of zip code region 705 (Fig. 3). This admittedly adds difficulty in calculating a PLDE score for this region. The procedure established in this article for calculating the PLDE score implies that this method works best when a hurricane makes landfall more perpendicular to the coastline. The track of Gustav is measured at a 43° angle to the coastline. If a hurricane such as Gustav makes landfall more parallel to the coast, the PLDE score becomes more unreliable due to the complications of measuring perceived and actual landfall distance to a fixed point when the track is less than 45° as the storm moves inland. For this reason, two additional methods of assessing evacuee error are presented in the following sections.

In zip code region 705, several cities were west/northwest of the initial landfall location, after which Gustav eventually passed closer to these locations as a weak category 1 hurricane or tropical storm with a decaying eye structure. However, based on personal interactions with the evacuees, the authors are confident that most residents feared extreme damage (Zhang et al. 2007) rather than the threats associated with a category 1 or 2 hurricane. Therefore, the evacuees of zip code region 705 evacuated with a perceived threat of a stronger hurricane. Furthermore, most of the locations in zip code region 705 were at nearly the same latitude as regions 703 and 700/701 so the PLDE score for this region may prove to be reliable. This marks the first time this procedure has been attempted, limiting the comparison with previous landfalling hurricanes.

4.2 Perceived landfall compared to forecasted landfall and actual track

Two additional methods of assessing evacuee error are presented in this section to evaluate the authenticity of the PLDE procedure. In order to make direct comparisons between all three methods, mean distances between perceived landfall distance (PLD) and either the actual landfall distance (ALD), forecasted landfall distance (FLD), or actual track distance (ATD) were calculated for each method in each three-digit zip code region.

Region 700/701 displays a positive perceived landfall distance in all three methods (Fig. 7). The PLD–ALD and PLD–ATD are almost identical. The overwhelming majority of respondents of 700/701 (93%) reside in a home zip code within metropolitan New Orleans creating minimal variability in results in both procedures. Furthermore, the actual landfall location was southwest of New Orleans and the shortest radial distance to the actual track line happened to be in nearly the same spot as the actual landfall location for most New Orleans zip codes. The PLD–FLD is the largest among the three regions; greater New Orleans, Houma/Thibodaux, and Greater Lafayette, which provides evidence to suggest that evacuees of the Greater New Orleans region evacuated without regard to 3–6 hourly updated changes in forecast track from the National Hurricane Center. It should be noted that since the sample size is smaller for the FLD procedure ($n = 24$), the mean perceived landfall distance changed from −58 to −56 km. Evacuees of region 700/701 perceived a landfall location/track farther east and closer to their home zip codes than what actually occurred or was forecasted to occur. These results suggest that the large PLDE score (3.3) for Greater New Orleans is genuine and that PLDE may possibly be a variable worth considering if the region is faced with a future hurricane of similar magnitude.

The results from region 703 are very similar to region 700/701. The PLD–FLD for region 703 is also higher than the PLD–ALD as was the case in region 700/701, although the range between the two is much smaller for region 703. The PLD–ATD is smaller in region 703 than it is in region 700/701 (Fig. 7). The result is explained by the proximity and orientation of the track to several zip codes in region 703. The radial distance from home zip code to the eastern side of the track line for many locations was shorter than the more linear east to west distance to the actual landfall location. Nevertheless, Region 703

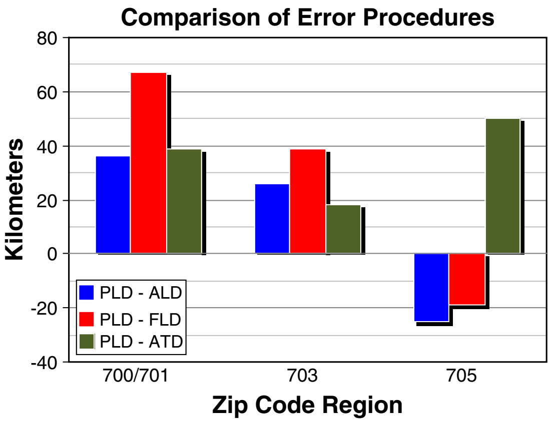

Fig. 7 Comparison of error procedures in each three-digit zip code region. *PLD* Perceived landfall distance, *ALD* Actual landfall distance, *FLD* Forecasted landfall distance, *ATD* Actual track distance

exhibits a positive value for all three methods. The people of this region perceived a landfall/track slightly east of the actual landfall/track resulting in minimal error. The PLDE score for Region 703 is also likely genuine and this suggests that evacuees may respond appropriately to a future threat of similar magnitude.

The results from region 705 are the most difficult to understand (Fig. 7). First an explanation is provided for ALD and FLD. The PLDE score from this region is −1.4 indicating a perceived landfall distance farther west (negative) than the actual landfall distance. The PLD is also farther west than the FLD, although this region has the smallest range between PLD and FLD at only −19 km. Compared to the other two regions, evacuees of region 705 appear to have responded to the forecasted landfall updates more closely. As stated earlier, the mean evacuation time for region 705 was 54 h prior to landfall at a time when the official NHC warning graphic depicted a westward jog in Gustav's track (Fig. 5). Residents of Coastal Louisiana are very familiar with tropical cyclones as evidenced by the Tropical Hazard Index scores for this stretch of coastline (Keim et al. 2007). Most residents of the Gulf Coast know from experience that the western side of the storm is not as severe; therefore, it is likely that many evacuees from this region responded to the westward track updates on Friday evening 29th August and Saturday morning 30th August.

Both the PLD–ALD and PLD–FLD are negative for Region 705. The PLD–ATD is positive making this the only region to have an opposite result from the PLDE procedure. The most obvious explanation is the orientation and proximity of most 705 zip codes to the landfalling track in a southeast to northwest trajectory. For Region 700/701, the ALD and ATD were essentially identical because the track of Gustav made its closest approach to greater New Orleans adjacent to the same point as the actual landfall location. In Region 705, the actual landfall location is significantly east of the closest approach of the track as Gustav tracked northwest after landfall. The PLDE score is based upon the measurement to the actual landfall occurring 20 km east of Morgan City. The eastern side of the track line passed within 50 km of every zip code in Region 705 making the mean actual track distance 50 km farther west than the perceived landfall distance. Although most zip codes in greater Lafayette did not experience the brunt of Gustav compared to Houma/Thibodaux, many locations near Lafayette still experienced minimal category 1 hurricane conditions. Evacuees of region 705 perceived a landfall location west of the actual landfall location and the forecasted landfall location indicating a perception that Gustav would be closer to their region. In this aspect, the PLDE score is valid for Region 705, although it is reported with caution, because Gustav ultimately transited the region thus minimizing evacuee error. Compared to region 700/701, evacuees of 705 had a smaller degree of error in predicting landfall location, but that success was convoluted by a storm track with a 43° angle to the coastline. The discrepancies between PLDE and PLD–ATD for Region 705 illustrate the need for more track perception research. The authors recognize the limitations in making conclusions about PLDE and wish to incorporate track-based methodologies with point-based methodologies in future research.

5 Summary and conclusions

In this research, we quantify the error of evacuees correctly interpreting and predicting the landfall location/track of Hurricane Gustav. It is important to quantify the degree of error in evacuee interpretation and prediction of landfall location/track to understand evacuee perception of the hurricane's damage and intensity in the post-landfall window. Upon returning home, evacuees may observe damage that is greater than or less than expected depending on their proximity to the actual landfall location. Since the extreme conditions of a landfalling hurricane are felt over such a small area, the majority of evacuees return home to find less damage than expected. This may lead to future evacuation complacency if the evacuee feels they have evacuated unnecessarily. Significant evacuee error in misinterpreting or predicting the actual landfall location/track of a hurricane may possibly be a variable to consider for future hurricane evacuations, along with numerous social variables that are not discussed in this paper.

Evacuation error was quantified via three methods. First, a Perceived Landfall Distance Error (PLDE) score was calculated with the intention of quantifying the potential disconnect between the actual landfall location and the perceived landfall location of evacuees. The PLDE score is calculated in each region by a *Z*-score procedure using the differences between mean perceived landfall distance and mean actual landfall distance from each survey participant's home zip code in that region. Perceived landfall distance and actual landfall distance were determined from responses of face-to-face survey questions conducted at two interstate rest stops during the evacuation of Hurricane Gustav. PLDE scores were spatially summarized into three-digit zip code regions representing the largest metropolitan areas to facilitate analysis. In Hurricane Gustav, there were three major zip code evacuation regions in coastal Louisiana. Region 700/701 represented greater New Orleans, region 703 comprised the Houma/Thibodaux area, and Region 705 characterized greater Lafayette.

Of the three regions, greater New Orleans experienced the largest PLDE score at 3.3. A score of this magnitude indicates that the residents of New Orleans who evacuated anticipated Gustav to make landfall closer to their location. It is hypothesized that this PLDE score for New Orleans may be a predictor of evacuation complacency for a future hurricane of similar magnitude. Residents of New Orleans may possibly feel as if the well-coordinated evacuation before Gustav was overreaction. Greater Lafayette encountered a negative PLDE score of -1.4. Residents of this region also expected Gustav to hit closer to their location, albeit to the east. A PLDE score of -1.4 is hypothesized to generate a slight level of future evacuation complacency. Houma/Thibodaux expected a near direct hit with a PLDE score of 0.9 and this region bore the brunt of Gustav. It is hypothesized that residents of this region will be less complacent compared to other regions in the future due to a direct hit.

Since this research marks the first known attempt at employing a procedure such as PLDE, the authenticity of PLDE scores were evaluated by using two additional methods. The actual landfall location is important for a final evaluation of error, but the forecasted landfall location may be of greater importance as evacuees make their decisions. For this reason, the mean forecasted landfall distance was calculated for each region and the results were directly compared to the actual landfall results. The third method involved using the actual storm track. While the first two methods were both point-based, the third track-based method elucidated the results and helped to verify the PLDE score for each region.

There were minor differences between actual landfall location and forecasted landfall location in each region. The forecasted landfall distance was farther west than the actual landfall distance for Regions 700/701 and 703. This suggests that evacuees from these regions paid little attention to changes in the official forecast track of Gustav. In Region 705, forecasted landfall was closer to perceived landfall indicating that Region 705 possibly had a greater response to forecasted information.

Results from the actual track distance mirrored that of the actual landfall distance for Regions 700/701 and Region 703. In region 703, the actual track distance was closer to several zip codes than the actual landfall location. In region 705, the results were drastically different. Region 705 is the only region to have both positive and negative distances for evacuee error methods. The track of Gustav passed within 50 km of all zip codes in Region 705 as Gustav traveled northwest causing the track results to contrast sharply with PLDE results. Results suggest that PLDE scores are reliable for Regions 700/701 and 703, but questionable for Region 705. If a hurricane, such as Gustav, makes landfall at less than a 45° angle to the coastline, several evacuee error methodologies should be employed before conclusions are made. The authors also suggest that a greater variety of track-based methodologies may help to resolve some of the discrepancies between methods. In future research, PLDE scores will be used in conjunction with experimental track techniques.

The results from all three methods contain valuable information regarding hurricane evacuation decisions for individuals in the projected path of a significant, landfalling hurricane. Data collected during the evacuation of Gustav is of great utility compared to previous research due to the unique time window in which the data were collected from the evacuees. Data collected in this research from Hurricane Gustav provides a baseline so that the methods presented here may be used as a variable to evaluate potential evacuation complacency in other coastal regions. Future research will attempt to establish PLDE scores in coastal regions with both higher and lower hurricane frequencies to determine if these values are unique to Louisiana. Furthermore, future research will also use PLDE scores to evaluate communication of warning graphics and forecast information to the public. Finally, it should be emphasized here that the respondents to this survey were all evacuees. It would be interesting to conduct a similar study on both evacuees and non-evacuees to determine whether differences in PLDE could account for any of the differences in evacuation likelihood.

Acknowledgments This research was supported by the National Science Foundation, Grant 0852549.

References

Baker EJ (1979) Predicting response to hurricane warnings: a reanalysis of data from four studies. Mass Emerg 4:9–24

Baker EJ (1980) Public response to hurricane Frederic: variation within the warning area. Environmental Hazards Center, Florida State University, Tallahassee

Baker EJ (1981) Evacuation of Galveston in Hurricane Allen. Environmental Hazards Center, Florida State University, Tallahassee

Baker EJ (1986) Warning and evacuation in Hurricanes Elena and Kate in Panama City, Florida and Pinellas County, Florida. Environmental Hazards Center, Florida State University, Tallahassee

Baker EJ (1990) Evacuation decision making and public response in Hurricane Hugo in South Carolina. Natural Hazards Research Center, University of Colorado, Boulder

Baker EJ (1991) Hurricane evacuation behavior. Int J Mass Emerg Disasters 9:287–310

Barnes LR, Gruntfest EC, Hayden MH, Schultz DM, Benight C (2007) False alarms and close calls: a conceptual model of warning accuracy. Weather Forecast 22:1140–1147

Blake ES, Rappaport EN, Landsea CW (2007) The deadliest, costliest, and most intense tropical cyclones from 1851 to 2006 (and other frequently requested hurricane facts) NOAA Technical Memorandum NWS TPC-5

Broad K, Leiserowitz A, Weinkle J, Steketee M (2007) Misinterpretations of the “cone of uncertainty” in Florida during the 2004 hurricane season. Bull Am Meteorol Soc 88(5):651–667

Dixit VV, Pande A, Radwan E, Abdel-Aty M (2008) Understanding the impact of a recent hurricane on mobilization time during a subsequent hurricane. Transp Res Record 4:9–57

Dow K, Cutter SL (1998) Crying wolf: repeat responses to hurricane evacuation orders. Coast Manage 26:237–252

Dow K, Cutter SL (2000) Public orders and personal opinions: household strategies for hurricane risk assessment. Global Environ Change Part B: Environ Hazards 2(4):143–155

Keim BD, Muller RA, Stone GW (2007) Spatiotemporal patterns and return periods of tropical storm and hurricane strikes from Texas to Maine. J Clim 20(14):3498–3509

Killian LM (1954) Evacuation of Panama city before hurricane Florence. National Research Council Disaster Study, National Academy of Sciences, Washington, DC

Landsea CW (2005) Meteorology—hurricanes and global warming. Nature 438(7071):E11–E13

Moore H, Bates F, Layman M, Parenton V (1963) Before the wind: a study of the response to hurricane Carla. National Academy of Sciences, Washington, DC

National Hurricane Center Season Archives (2008) http://www.nhc.noaa.gov/pastall.shtml. Accessed 20 October 2008

National Weather Service New Orleans Hurricane Gustav Radar Images (2008) http://www.srh.noaa.gov/lix/html/Gustav08/Radar/. Accessed 20 October 2008

Pielke R (1997) Reframing the US hurricane problem. Soc Nat Res 10(48):5–499

Regnier E (2008) Public evacuation decisions and hurricane track uncertainty. Manage Sci 54:16–28

Sadowski NC, Sutter D (2008) Mitigation motivated by past experience: prior hurricanes and damages. Ocean Coast Manage 51:303–313

Senkbeil JC, Sheridan SC (2006) A postlandfall hurricane classification system for the United States. J Coastal Res 22:1025–1034

United States Army Corps of Engineers Post Storm Assessment Archive (2004) 2004 Hurricane assessments. http://chps.sam.usace.army.mil/USHESdata/Assessments/2004Storms/2004_hurricane_season_page.htm. Accessed 15 April 2009

Urdan TC (2005) Statistics in plain english. Routledge ISBN: 0805852417, 9780805852417, 184 pp

Wang X, Kapucu N (2008) Public complacency under repeated emergency threats: some empirical evidence. J Pub Admin Res Theory 18:57–78

Webster PJ et al (2005) Changes in tropical cyclone number, duration, and intensity in a warming environment. Science 309(5742):1844–1846

Wilkinson KP, Posey EI, Ross PJ, Spencer BG (1970) Citizens' response to warnings of hurricane Camille. Social Sciences Research Center, Mississippi State University, Mississippi

Williams L (2008) Nagin orders evacuation in face of 'mother of all storms'. New Orleans Times, Picayune

Windham GO, Posey EI, Ross PJ, Spencer BG (1977) Reactions to storm threat during hurricane Eloise. Social Sciences Research Center, Mississippi State University, Mississippi

Zhang F, Coauthors (2007) An in-person survey investigating public perceptions of and responses to hurricane Rita forecasts along the Texas Coast. Weather Forecast 22:1177–1190