Community Response to Hurricane Threat: Estimates of Warning Issuance Time Distributions

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ABSTRACT: Hurricane evacuation warnings from local officials are one of the most significant determinants of households' evacuation departure times. Consequently, it is important to know how long after the National Hurricane Center (NHC) issues a hurricane watch or warning that local officials wait to issue evacuation warnings. The distribution of local evacuation warning issuance delays determined from poststorm assessment data shows a wide range of warning issuance delay times over an 85-h time span, although the vast majority of times fall within a 40-h window. Nearly 30% of the jurisdictions issued evacuation warnings before an NHC hurricane warning. Only 5% delayed the decision for more than 25 h after the NHC hurricane warning. The curves for warning issuance delays, using both the NHC watch and NHC warning issuance times as reference points, are very different from the warning issuance curves observed for the rapid-onset events. The hurricane data exhibit much more of an "S shape" than the exponential shape that is seen for rapid-onset data. Instead, curves for three different types of storm tracks, defined by a perpendicular/parallel dimension and a straight/meandering dimension, follow three noticeably different logistic distributions. The data also indicate that warnings were issued significantly earlier for coastal counties than for inland counties. These results have direct practical value to analysts that are calculating evacuation time estimates for coastal jurisdictions. Moreover, they suggest directions for future research on the reasons for the timing of local officials' hurricane evacuation decisions.

SIGNIFICANCE STATEMENT: Local officials rely on National Hurricane Center (NHC) hurricane watches and warnings to guide them in issuing evacuation warnings but do not automatically issue evacuation warnings as soon as the NHC issues a watch or warning. Thus, this study constructed a database that contains the timing of NHC hurricane watches and warnings, as well as local evacuation warnings, for 20 hurricanes that threatened 290 U.S. jurisdictions from 1979 to 2008. The data reveal distinct curves for three different types of storm tracks, defined by a perpendicular/parallel dimension and a straight/meandering dimension. These results are of direct practical value to analysts who calculate evacuation time estimates for coastal jurisdictions. Moreover, they suggest directions for future research on the reasons for the timing of local officials' hurricane evacuation warnings.

KEYWORDS: Social Science; Hurricanes; Databases; Communications/decision making; Emergency response; Planning

1. Introduction

Local authorities have long been concerned about deciding when to initiate hurricane evacuation. On the one hand, they want to be sure to clear the risk area before the arrival of hazardous conditions. On the other hand, evacuations in densely populated urban jurisdictions can take up to 36 h or more, so the evacuation decision must be made when it is uncertain if the hurricane will strike their jurisdiction at all. As Fig. 1 indicates, making this decision at the appropriate time requires an understanding of two chains of events—the environmental hazard chain and the community response chain (Lindell et al. 1985; Lindell and Perry 1992; Mileti 1975). In the case of hurricanes, the environmental hazard chain of events can be characterized by the storm's size, intensity, track, and forward speed. Technologies such as satellite imaging have made it possible to assess a hurricane's characteristics and sophisticated computer models make it possible to forecast its behavior with increasing accuracy over time. Thus, for example, track forecast errors have decreased by two-thirds over the past generation (Landsea and Cangialosi 2018).

These technologies make it possible to produce exposure projections that inform local emergency managers, as well as households and businesses, which coastal areas are expected to be affected by extreme wind, storm surge, and inland flooding. In turn, these exposure projections provide the decision information that is used in emergency assessments of the need for protective actions such as evacuation. Once local authorities have decided to recommend protective actions for their jurisdictions, they can use a variety of channels such as broadcast media to disseminate warnings throughout their jurisdictions. Local television and radio were especially common through Hurricane Lili in 2002 (Lindell et al. 2005) and

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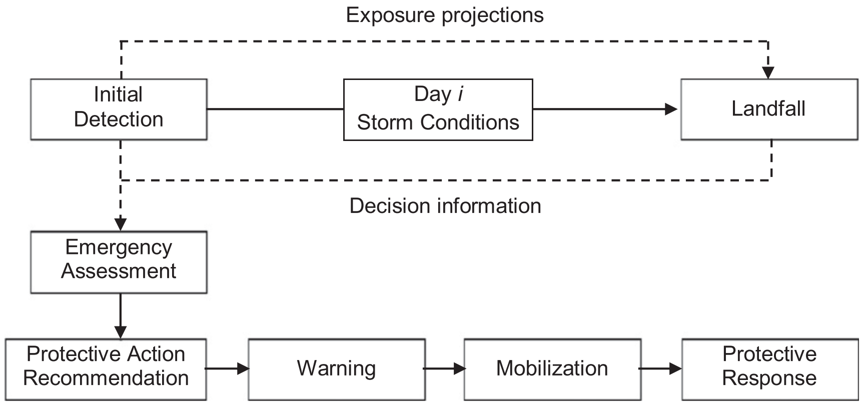


FIG. 1. Chains of events for hurricane and community response [adapted from Lindell and Perry (1992)].

remained so through Hurricane Harvey in 2017 (Lindell et al. 2020). As they receive warnings, households and businesses begin to mobilize their resources (e.g., households install storm shutters, fill gas tanks, and pack bags; Lindell et al. 2020) and subsequently respond by taking personal protective actions, such as evacuation, that directly reduce their risk of injury or death.

Warnings from emergency officials are important to this chain because they have a significant influence on people's decisions to evacuate or take other protective actions (Baker 1991). In addition, Dow and Cutter (1998, 2002) supported this result by reporting that about 20% of North and South Carolina coastal residents reported relying on official warnings in their evacuation decisions. More recently, a statistical meta-analysis of factors correlated with evacuation behavior in 21 hurricanes evacuation studies, 19 (90%) reported significant positive correlations, whereas only 2 (10%) reported nonsignificant correlations (Huang et al. 2016).

Although this model is simple and straightforward, its application is complex because many hurricanes have a large impact area that could be devastated by extreme storm conditions. On average, a hurricane's diameter of hurricane-force wind is just over 90 km, but some storms have hurricane-force wind fields that extend over 230 km of coastline (Kimball and Mulekar 2004). The problem posed by a large impact area is compounded by uncertainty about the hurricane's track, so the length of coast subject to a National Hurricane Center (NHC) hurricane warning could be 800 km for a hurricane tracking perpendicular to the coast, as was the case in Hurricane Rita. Uncertainty about the impact area is especially high for a hurricane that is tracking parallel to the coast, as was the case in Hurricane Floyd for which NHC hurricane warnings were issued at one time or another for the entire Atlantic Coast from the southern tip of Florida to Plymouth, Massachusetts, a distance of 2500 km.

Characterization of the community response chain from emergency assessment to response has also proved to be problematic because it involves a complex decision with scientific, economic, and social components. This is exacerbated by the dynamic flow of environmental information and high levels of uncertainty discussed previously. Furthermore, it requires the integration of social science research on household warning response with transportation engineering models of vehicle flows through evacuation route systems to produce evacuation time estimates (ETEs) for each coastal jurisdiction (Lindell et al. 2019b).

Baker's (1991, 2000) summaries have shown that hurricane evacuation studies (HESs) have provided a wealth of data for evacuation decision-making and poststorm assessments have generated valuable insights into the utilization of HES data. A few studies have reported the overall distribution of household evacuation departure times (Lindell et al. 2005; Huang et al. 2012, 2016), and others have sought to predict those departure times (Fu et al. 2007; Gudishala and Wilmot 2017; Koshute 2013; Li et al. 2013; Sorensen 1991). However, departure time distributions can vary from one storm to another and, for a given storm, from one jurisdiction to another. One important factor affecting these distributions is the amount of time it takes local authorities to issue an evacuation warning, but there is very little research on this topic. To remedy this limitation in existing hurricane evacuation research, the following sections will review the ETE components for hurricane evacuations and examine the available empirical data relevant to authorities' warning issuance delay times.

2. Components of household departure times

In most hurricanes, the percentage of the risk area population that evacuates at each successive time interval usually takes the form of an S-shaped curve. As yet there is no consensus about the most appropriate function to model this curve, but there is general agreement about the four components that determine the time it takes a household to clear the risk area. Specifically, the time required for a household to clear the risk area after incident initiation can be defined as a function of four time components (Lindell et al. 2019b; Urbanik et al. 1980),

$$t_T = f(t_d, t_w, t_p, t_e), \quad (1)$$

where t_T is a household's total clearance time, t_d is the authorities' warning issuance delay time, t_w is the household's warning receipt time, t_p is the household's preparation (mobilization) time, and t_e is the household's evacuation travel time. The first three of these time components are behavioral and are estimated from empirical research on household hurricane evacuation to construct a household evacuation departure time curve (''loading function''). The fourth time component (t_e), is estimated by inputting the loading function into a transportation algorithm that models the flow of evacuating vehicles through the evacuation route system.

Warning issuance delay is the time that it takes for decision-makers to reach a decision to issue a warning once they have detected the hazard or have been notified of the hazard by those monitoring it. Sorensen and Mileti (2016) summarized the research on warning issuance delay times for rapid-onset events such as dam or levee failures, as well as toxic chemical releases from fixed-site facilities or during transportation accidents, flash floods, near-field tsunamis, or sudden volcanic eruptions. Most of these rapid-onset incidents involve evacuations immediately before, during, or shortly after hazard impact. Thus, evacuation can take place either pre- or post-warning. In most events studied to date, the time of forewarning is less than 4 h and, at times, is only a few minutes (Sorensen and Mileti 2016).

Although there is a good conceptual knowledge about organizational decision-making and organizational actor performance during hazard events in general (Ballesteros and Kunreuther 2018; Mileti and Sorensen 1987), as well as the processes of organizational behavior in hurricanes (Lindell et al. 2007), no systematic studies exist to adequately explain how variance in community emergency organizations' structures relate to effective decision-making. More specifically, there is little information about the way in which emergency managers use information from the NHC and local weather forecast offices to formulate their protective action recommendations for coastal residents (Bostrom et al. 2016; Demuth et al. 2012). Some prescriptive decision support aids are available to community decision-makers (Murray-Tuite et al. 2020), but it is unknown whether they are used and, if so, whether they impact the timing of protective action decisions.

As noted earlier, the warning issuance delay distributions for hurricanes are different from those of rapid-onset hazards because the NHC generally detects hurricanes tracking toward the U.S. coast many days in advance, so there is uncertainty about their intensity, size, landfall location, and arrival time. Consequently, local authorities must weigh the probability of being struck, the benefits of a good decision (either correctly deciding to evacuate prior to impact or correctly deciding not to evacuate for a storm that ultimately strikes elsewhere), the costs of a false negative decision (failing to evacuate before the storm strikes), and the costs of a false positive decision (evacuating unnecessarily for a storm that misses) when they reach their evacuation decision deadline (Lindell et al. 2019b, chapter 3). Research on warning issuance delay times for dam and levee failure/breach events benefited from two systematic studies of decision-making for rapid-unfolding chemical accidents (Rogers 1994; Rogers et al. 1990). These studies produced good empirical data on the timing of emergency decisions but did not fully explore why warning issuance delay times varied between communities and events. In contrast, no systematic studies of decision-making processes and timing have been conducted to either develop historical time delay distributions or explain variance in warning issuance delays for slow-onset hazards such as hurricanes. The most relevant attempt to do so was a study that examined local decisions whether or not to issue hurricane warnings (Gudishala and Wilmot 2017). This study found that emergency managers in 45 jurisdictions were more likely to issue evacuation notices in locations that have longer evacuation clearance times and in events that are forecasted to experience a high storm surge. They also found that an evacuation notice was most likely to be issued in the early evening, followed by during the day, rather than in the early hours of the morning between midnight and 0600 LT. The timing of evacuation warning decisions was not significantly related to storm magnitude.

3. Storm data

To assess the distribution of local authorities' warning issuance delay times in past hurricanes, it is necessary to identify when jurisdictions issued a warning to initiate a protective action in a representative sample of hurricanes. This was accomplished by obtaining warning issuance times from available poststorm assessments (PSAs) and poststorm transportation analyses (PSTAs) supported by the Federal Emergency Management Agency (FEMA) and U.S. Army Corps of Engineers (USACE). The set of reports is incomplete because there appears to be no centralized repository of all PSAs and PSTAs that have been performed. Moreover, the warning issuance times within these reports are incomplete because some reports mention only the day on which an evacuation warning was issued. Other cases were excluded because they listed only a vague time reference such as ''evening.'' Nevertheless, these reports are the best available sources and provide data that were collected by a systematic approach. As indicated in the online supplemental material, the protective action warning decision was usually made at the county level, although occasionally it was done by the state for multiple counties or, in rare instances, by a city or town.

To develop consistent measures of warning issuance delay, two reference points were used that are common to all hurricanes. The first of these is the time at which the NHC issued a hurricane watch for the section of coast in which that jurisdiction was located (or in some cases a tropical storm watch if no hurricane watch was issued). The second reference point is the time at which the NHC issued a hurricane warning for the section of coast in which that jurisdiction was located (or a tropical storm warning if no hurricane warning was issued). These two reference points are appropriate because the NHC Glossary (http://www.nhc.noaa.gov/aboutgloss.shtml) defines both types of advisories in terms of their expected time of arrival of storm conditions.

a. Hurricane watch

An NHC hurricane watch is an announcement that sustained winds of 64 kt (74 mi h^{-1} or 119 km h^{-1}) or higher are *possible* within the specified area in association with a tropical, subtropical, or posttropical cyclone. Because hurricane preparedness activities become difficult once winds reach tropical storm force, the hurricane watch is issued 48 h in advance of the anticipated onset of tropical-storm-force winds.

b. Hurricane warning

An NHC hurricane warning is an announcement that sustained winds of 64 kt or higher are *expected* somewhere within the specified area in association with a tropical, subtropical, or posttropical cyclone. Again, because hurricane preparedness activities become difficult once winds reach tropical storm force, the warning is issued 36 h in advance of the anticipated onset of tropical-storm-force winds. The warning can remain in effect when dangerously high water or a combination of dangerously high water and waves continues, even though winds may be less than hurricane force.

Data on warning issuance times were collected from USACE/FEMA PSA and PSTA reports published from 1979 to 2008. In addition to excluding cases if they lacked a date and time for the protective action recommendation (usually an evacuation recommendation), cases were also excluded if they listed a date that was more than 48 h before the NHC hurricane watch date/time or more than 60 h after the NHC hurricane warning date/time. In these cases, the reported date/time was judged to be in error or, in the latter case, was related to disaster recovery activities (i.e., a postimpact evacuation).

The dates and times for the NHC hurricane watches and warnings were obtained from NHC tropical cyclone reports and the National Weather Service natural disaster survey reports for all hurricanes having a USACE/FEMA PSA or PSTA report. Typically, NHC hurricane watches and warnings are issued for a stretch of coastline using geographic locations as boundaries. Each NHC hurricane watch or warning was examined to identify all jurisdictions that were located within the relevant boundaries. All of the relevant jurisdictions (organized by state) were entered into a database for that hurricane along with their corresponding NHC hurricane watch and warning times.

Data were also collected for each storm and jurisdiction for

- wind speed (in knots) for the storm at the time of each watch (WS-Watch) and warning (WS-Warning),
- orientation of the track to the coast—perpendicular (coded as 0) or parallel (coded as 1),
- stability of the track—straight (coded as 0) or meandering (coded as 1),
- whether the jurisdiction was coastal (coded as 0) or inland (no part of the jurisdiction connected to the ocean or an inland waterway, coded as 1), and
- population of the jurisdiction (measured by the closest decennial census).

The classification of storm-track orientation and stability was based on the behavior of the storm from the time that a tropical storm watch was first issued until landfall. Data on storm behavior included the track of the hurricane from the NHC tropical cyclone reports and NHC advisories issued during this time period. Track stability (straight or meandering) was classified as straight if there was no abrupt change in direction in the track or erratic shifts in the projected landfall location during the storm history. If there were changes, it was considered meandering. Track orientation (parallel or perpendicular) was based on the whether the track of the hurricane was moving along the coast for 2 days or longer or moving toward the coast. There was a disagreement between the authors and one of the reviewers on the track classification for 5 of the 18 hurricanes, although, even then, Cohen's (1960) kappa index of interrater agreement was $\kappa = 0.58$. After consideration of the reviewer's rationale, two of the tracks were reclassified, resulting in $\kappa = 0.72$ for the revised classification.

4. Results

As indicated in Fig. 2, approximately 5% of the jurisdictions issued evacuation warnings before the NHC issued a hurricane watch and just over 50% issued evacuation warnings within 20 h after the NHC issued a hurricane watch. However, it took 38 h (just over 1.5 days) after the NHC hurricane watch to achieve 95% warning issuance, and the last evacuation warning was issued approximately 70 h (almost 3 days) after the NHC hurricane watch.

Figure 3 indicates that about 30% of the jurisdictions issued evacuation warnings before the NHC issued a hurricane warning, 75% issued evacuation warnings within 12 h of the NHC hurricane warning, and 95% issued evacuation warnings within 20 h of the NHC hurricane warning. Surprisingly, a few jurisdictions had not issued a warning until 33 h after the NHC hurricane warning—just about the time at which tropical storm wind would ordinarily be expected to arrive at the forecast point of landfall for a storm with a perpendicular straight track. It is unclear why these delays in warning issuance were so long because some of them (e.g., 42 h for Martin County, North Carolina, for Hurricane Floyd in 1999) took place in counties that were near other jurisdictions that had extremely short warning issuance delays (e.g., 4 h for Duplin County, North Carolina) in the same storm.

The substantial variation in warning issuance delay times raises questions about whether there are systematic differences among the storms or jurisdictions that account for this variation. For example, it is possible that local jurisdictions issue warnings earlier for storms that are more intense (higher maximum wind speed and, thus, Saffir–Simpson category), have tracks that are perpendicular (vs parallel) to the coast, or have tracks that are straight (vs meandering). Of course, it is also likely that local jurisdictions issue warnings earlier if they have larger populations (and, presumably, longer ETEs) and are located on the coast. These possible explanations are addressed below.

As Fig. 4 indicates, there were statistically significant differences in the average (across jurisdictions) warning issuance delay times per storm ($F_{17,197} = 3.43$, with $p < 0.001$). The average delays were all positive during the first part of the data series ending in the 1990s. However, there were three storms with negative average delays (Ivan, Gustav, and Ike) that struck in 2004 and 2008. Both Ivan and Gustav were category-4 hurricanes when the NHC first issued hurricane watches for these storms. Ike was only a category-2 hurricane, but it had a storm surge that was more like that of a category-5 storm (Wei et al. 2014). Nonetheless, Table 1 shows that year was not significantly correlated with warning issuance delays for either the NHC watch or warning. Moreover, warning issuance delays

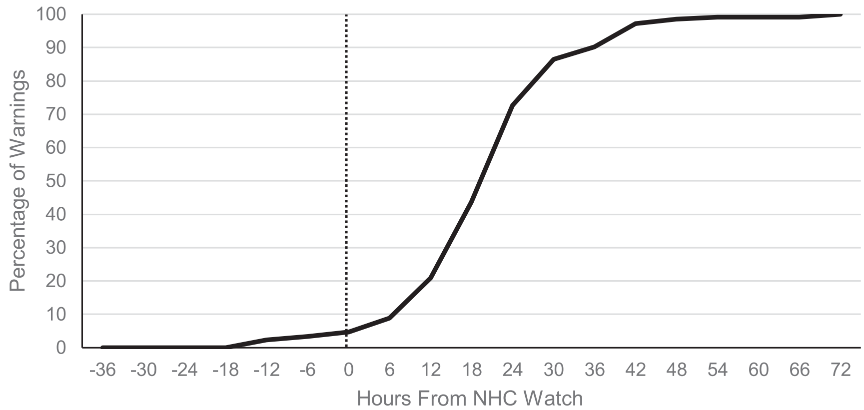


FIG. 2. Local warning issuance delay after NHC hurricane watch.

also had nonsignificant correlations with wind speed at the NHC watch (WS-Watch) and warning (WS-Warning). Figure 4 may also reflect a modernization of the NHC's graphic products in 2002 with the use of images of projected tracks with uncertainty cones and strike probabilities. Such graphical representations of risk may impact the timing of local decisions to evacuate.

As one would expect, warning issuance delays seem to be greater in storms that have more meandering and uncertain tracks than in storms with relatively straight and more certain tracks. Table 2 indicates that there were statistically significant differences in the mean time after the NHC hurricane warning for that local decisions were made to issue evacuation warnings ($F_{2,212} = 6.73$, with $p < 0.001$). It is lowest for storms that have perpendicular straight tracks ($M = 1.62$ h) and not significantly higher for storms with parallel meandering tracks ($M = 5.34$ h), such as Hurricane Floyd. Warning issuance delay is highest for storms with perpendicular meandering tracks ($M = 8.76$ h), such as Hurricane Charley. Although storms with perpendicular meandering tracks are not significantly different from storms with parallel meandering tracks, they are significantly different from storms that have perpendicular straight tracks. However, there were nonsignificant differences in the mean time after NHC hurricane watches ($F_{2,212} = 2.45$, with $p > 0.05$), with an average delay over all tracks of 19.89 h.

It is also unsurprising that inland counties tended to have longer warning issuance delays for hurricane watches and warnings (correlation coefficient $r = 0.21$ for both types of advisories). With the exception of Martin County, Florida, in Hurricane Francis, the counties with the longer warning issuance delays are inland counties, which have a mean issuance time of 11.3 h as opposed to 3.3 h for coastal counties. Surprisingly, however, warning issuance delay is not significantly related to a county's population size ($r = -0.08$), which is related to its ETE, a major component of the jurisdictional warning issuance process.

The finding of differences among the three track types supports the construction of a separate warning issuance delay curve for each of them. Specifically, Fig. 5 shows that storms having *perpendicular straight* (PD/S) tracks toward the coast have a much higher probability of jurisdictions deciding to issue evacuation warnings before the NHC warning (i.e., *early* or

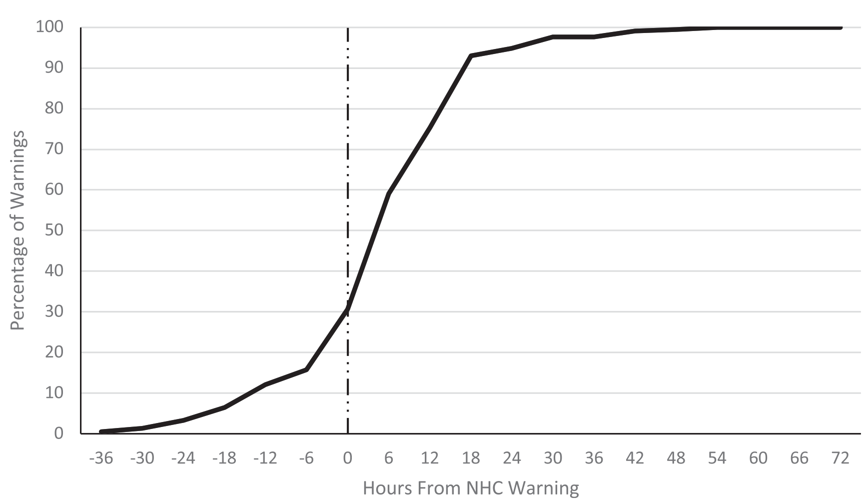


FIG. 3. Local warning issuance delay after NHC hurricane warning.

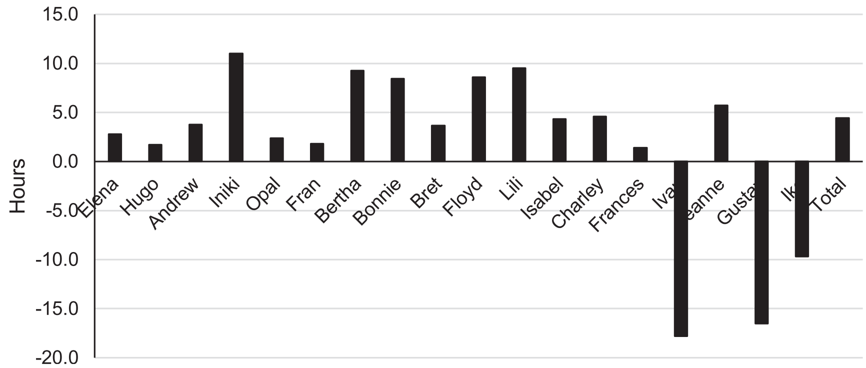


FIG. 4. Average warning issuance delay after NHC warning.

negative warning issuance delays) and a noticeably flatter slope than the other two types of storms. By contrast, storms that have *perpendicular meandering* (PD/M) or *parallel meandering* (PL/M) tracks have a similarly low probability of warning issuance through about 6 h after an NHC warning. From 6 to 18 h, however, storms with PL/M tracks have a higher probability of later (positive) warning issuance times. After 18 h, the curves for the three types of tracks are indistinguishable from each other.

5. Modeling warning issuance delay times

There are many different probability distributions that have been used to characterize the timing of decisions in emergencies. In particular, a Rayleigh model of the type suggested by Southworth (1991) and Tweedie et al. (1986), and discussed in Lindell and Prater (2007a), has been proposed as a suitable distribution for authorities' warning issuance times. The cumulative distribution function for this distribution is defined by

$$P_t = 1 - \exp\{-(t^2)/[2(\beta^2)]\}, \qquad (2)$$

where P is the cumulative probability of issuing a protective action warning at time t (in hours), "exp" is the base of the natural logarithm, and β is a constant that determines the central tendency of the distribution. As β increases, the total amount of time to complete the initiation of a protective action warning increases.

Figure 6 compares the observed distribution of warning initiation delay times after the NHC hurricane warning from Fig. 1 with a simulated curve with $\beta = 32$. This parameter estimate provides the best fit to the data by minimizing the variance of the deviations of the actual observations from the values estimated using Eq. (2). In this figure, the x axis is the time at which a protective action warning was issued in a given jurisdiction and $t = 0$ represents the time at which a hurricane watch was issued for that jurisdiction. The y axis is the cumulative probability of a local warning being issued.

Inspection of Fig. 6 indicates that a Rayleigh distribution tends to overestimate the percentage of earlier warnings and underestimate the percentage of later warnings. However, it provides an excellent prediction of the median value (the 50th-percentile value) and the lower extreme value (the 5th-percentile value). The estimated distribution provides a moderately good fit to the 95th-percentile value (50 h for the estimated distribution vs 40 h for the actual distribution). This latter value is conservative in the sense that the estimated value predicts that a warning will be issued later than it is likely to actually occur.

A well-known alternative to the Rayleigh distribution is the logistic distribution, which has the capability of modeling distributions with a more steeply accelerated response (Lindell and Prater 2007a). The cumulative distribution function for this distribution is defined by

$$P_t = 1 - e^{-at^b}, \qquad (3)$$

where, as with the Rayleigh distribution, P is the cumulative probability of issuing a protective action warning or at time t (in hours) and e is the base of the natural logarithm. However,

TABLE 1. Means (M), standard deviations (SD), and intercorrelations (r_{ij}) among variables. Note that $r_{ij} \geq 0.15$ are significant at $p < 0.05$ and $r_{ij} \geq 0.20$ are significant at $p < 0.01$.

	M	SD	1	2	3	4	5	6	7	8
1. Year	1999.05	5.04								
2. WS-Watch	99.74	17.26	0.17							
3. WS-Warning	101.97	12.41	−0.07	0.76						
4. ParallelTrack	0.29	0.45	−0.10	0.40	0.26					
5. MeanderingTrack	0.49	0.50	−0.26	0.12	0.11	0.65				
6. Inland	0.17	0.38	−0.06	0.04	0.16	0.26	0.17			
7. Population (1000s)	181.18	293.87	0.03	0.00	0.14	−0.12	−0.09	−0.15		
8. Delay/watch	19.89	11.96	−0.08	0.03	0.10	0.15	0.09	0.21	0.10	
9. Delay/warning	4.44	12.68	−0.12	−0.10	0.10	0.22	0.23	0.21	−0.08	0.55

TABLE 2. Mean issuance time for public warnings after NHC warning (Hr). Values with the same superscript are *not* significantly different from each other.

	Storm-track characteristic	
Storm-track direction	Straight	Meandering or changing
Perpendicular to coast	1.62[a]	5.34[ab]
Parallel to coast	—	8.76[b]

in the logistic distribution, a is the distribution's mean M and b is its standard deviation. Increases in a shift the distribution to the right, whereas increases in b make the distribution flatter. As $b \to \infty$, the curve approximates a uniform distribution and, thus, a horizontal straight line.

Figure 6 also compares the observed distribution from Fig. 3 with a simulated curve with $a = 40$ and $b = 6$. These parameter estimates provide the best fit to the data by minimizing the variance of the deviations of the actual observations from the values estimated using Eq. (3). Inspection of Fig. 6 indicates that a logistic distribution (the dashed line) provides a much better fit to the actual data than does the Rayleigh distribution. Indeed, the logistic distribution fits the actual data almost perfectly.

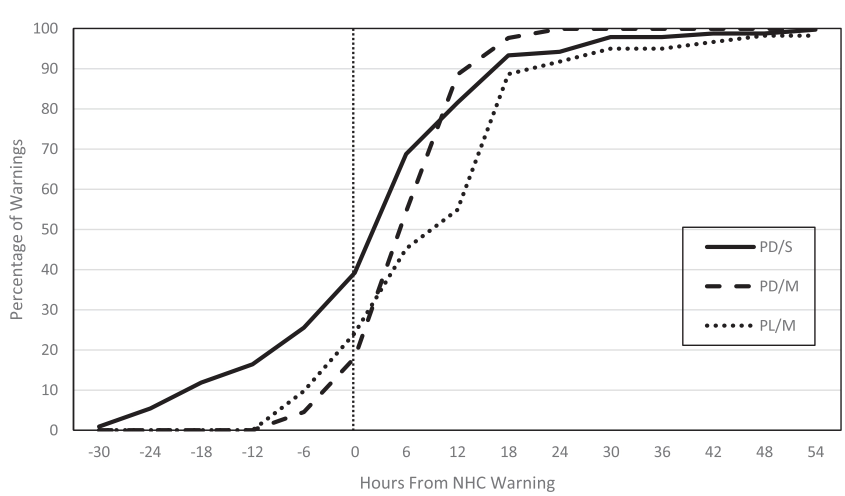
6. Discussion

The issuance curves developed from PSA data show a wide distribution of warning issuance delay times over about an 85 h time span, although the vast majority of times fall in approximately a 40-h window. Nearly 30% of the jurisdictions issued evacuation warnings before the NHC posted a hurricane warning. Only 5% delayed the decision for more than 25 h after an NHC warning was issued. Overall, these curves are better characterized as logistic distributions than Rayleigh distributions.

Examination of the correlates of issuance times after the NHC warnings revealed that storm-track type, defined by a perpendicular/parallel dimension and a straight/meandering dimension, produced noticeably different warning issuance curves. In addition, jurisdiction location is also related to warning issuance times; warnings were issued significantly earlier for coastal counties than for inland counties. However, warning issuance times were not significantly related to the year in which a storm occurred, a jurisdiction's population, or a storm's intensity at the time of the NHC watch or warning.

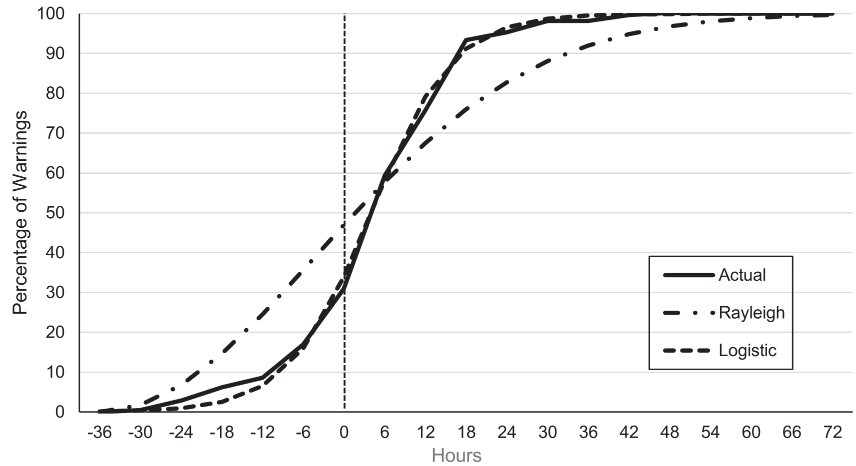
The overall curves for warning issuance delay times, using both the NHC watch and NHC warning points as reference points, are very different from the warning issuance curves observed for rapid-onset events (Lindell and Perry 2004; Lindell and Prater 2007a; Sorensen and Mileti 2016). Specifically, they exhibit much more of an "S shape" than the exponential shape of rapid-onset hazard warning issuance curves. The difference from rapid-onset events is also reflected in the curves for three types of storm tracks displayed in Fig. 5. Thus, the empirical model used in describing warning issuance times for rapid-onset events would be inappropriate for use for most hurricanes, although it is likely to be appropriate for hurricanes with late changing tracks or late intensification. However, it is important to note that, in such cases, a logistic distribution with a very small mean and standard deviation will produce a warning issuance curve that is quite similar to those observed for the rapid-onset events. This is because the logistic distribution shifts to the left as the average warning issuance delay $a \to 0$. Moreover, the distribution approaches a step function as the standard deviation of the warning issuance delays $b \to 0$. Both of these features are the distinctive characteristics of rapid-onset hazard warning issuance curves.

Of course, this study does have some limitations. The classification of storms into differing track types was relatively simplistic and could be refined in any future efforts to understand the relationship between hurricane characteristics and protective action decisions. One promising line of research would be to present a systematically varying set of hypothetical



Note: PD/S = perpendicular straight, PD/M = perpendicular meandering, PL/M = parallel meandering

FIG. 5. Local warning issuance delay after NHC hurricane warning, by storm track.



Note: Rayleigh β = 32; Logistic M = 40, SD = 6.0

FIG. 6. Approximations of local warning issuance delay after NHC hurricane warning.

hurricane tracks to emergency managers and ask them to indicate when they would initiate protective actions for different population segments in their jurisdictions. For example, Wu et al. (2015a,b) used DynaSearch, an online program for studying dynamic decision-making to monitor experiment participants tracking four different hurricanes over six forecast advisories (Lindell et al. 2019a). Huang et al. (2017) subsequently analyzed participants' protective action recommendations to see how they responded to changes in hurricane conditions. However, the DynaSearch studies did not systematically address the three types of tracks studied here or use actual emergency managers, so further research is needed.

In addition, as noted earlier, there were differences in warning issuance delay for Ivan, Gustav, and Ike from hurricanes earlier in the 1979–2008 time period. Although these did not establish a statistically significant trend, this is quite possibly due to the small number of hurricanes in the latter portion of the database. Consequently, future research should reexamine this issue when more hurricane data become available. However, future analyses of warning issuance delay times will require the systematic collection of such data, perhaps through the resumption of USACE/FEMA PSAs.

Moreover, there are other measures of storm threat that might predict evacuation warning issuance delays but were not included in this analysis due to limitations in the available data. For example, it is possible that evacuation warning issuance delay times could be predicted more precisely with the addition of data on the predicted landfall location and time and predicted Saffir–Simpson category over the history of the storm. This additional information could address the issue of *slack time*, in which authorities set a warning trigger and wait until environmental conditions meet the trigger before initiating warnings (Cova et al. 2017).

In addition, the analysis could be improved by knowing the ETE for each jurisdiction at the time of the hurricane. Unfortunately, there appear to be no historical records of ETEs, so it is not possible to use these data in a retrospective analysis such as the present study. Instead, as is the case with warning issuance delay times, any future analyses of ETEs would need to construct a database by collecting these data from all coastal jurisdictions every year. Until a comprehensive database of ETE data is constructed, population size will need to serve as the best available proxy.

A more comprehensive understanding of warning issuance delays is needed because there were cases in which nearby counties in the same storm ranged from 4 to 42 h in their warning issuance delay times. It is clearly not feasible to explain this variation after the fact because the hurricanes in this database struck from 12 to 42 years ago. Consequently, there is no realistic likelihood of obtaining records about individual jurisdictions' decision processes. However, this understanding could be achieved in future research that measures important warning issuance factors and analyzes their significance in explaining variance in issuance times. These factors include formalization of planning and implementation procedures (e.g., warning triggers have been established), performance and interpersonal relations (e.g., communicating personnel across organizations know each other), system performance factors (e.g., redundant/failsafe communications are in place), and situational factors (e.g., day or night).

7. Conclusions

This study contributes to the development of a more complete empirical foundation for computing hurricane ETEs. Specifically, incorporating distributions of warning issuance delay times from Fig. 5 into Eq. (1) along with data on households' warning diffusion time distributions and households' evacuation preparation time distributions will improve the accuracy of hurricane ETEs. In turn, this will allow coastal emergency managers to define better *evacuation triggers* (Cova et al. 2017) that balance tradeoffs between false negatives, which fail to evacuate the entire population before a hurricane strikes, and false positives, which evacuate the population for a hurricane that fails to strike (Lindell et al. 2019b, chapter 3; Lindell and Prater 2007b; Regnier 2008).

Moreover, the data collection methods and data analyses conducted in this article are not limited to hurricane evacuations. In principle, they can also be used in the computation of ETEs for other hazards as well. One of the challenges for the development of evacuation management decision support systems for other hazards will be the difficulty of collecting data on warning initiation delays. As the present study shows, such analyses will require a substantial amount of data collection for hazards ranging in frequency from wildfires (which strike the United States many times per year) to tsunamis (which strike the United States perhaps a few times per century).

There is also a need to incorporate uncertainties about warning initiation delay time distributions, as well as about warning dissemination time distributions and household evacuation preparation time distributions, into ETE analyses. One method for displaying such uncertainties is a tornado diagram that shows the sensitivity of ETE estimates to a plausible range of uncertainty about each of the evacuation model input parameters (e.g., see Lindell 2008). However, future research will need to determine if emergency managers are able and willing to use these displays.

Last, we note that it is unfortunate that there are so many inconsistencies in the way in which the data were collected and recorded, as well as that the data series ended with Hurricane Ike in 2008. Resuming the production of USACE/FEMA PSA and PSTA reports—ideally for all hurricanes, but at least for major hurricanes—would add significantly to the existing database and extend the base of scientific knowledge about hurricane evacuation warning issuance times.

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