

January 15, 2015. This is an author's manuscript of a paper that has been accepted to appear in the Proceedings of the Western Decision Sciences Institute Annual Meeting Annual Meeting, Mar. 31-Apr. 3, Maui, HI.

## **A HURRICANE DECISION SIMULATOR FOR THE U.S. MARINE CORPS RESERVE FORCES IN NEW ORLEANS**

*Cameron A. MacKenzie, Defense Resources Management Institute, Naval Postgraduate School, 699 Dyer Road, Monterey, CA 93943, 831-656-2224, camacken@nps.edu*  
*Eva Regnier, Defense Resources Management Institute, Naval Postgraduate School, 699 Dyer Road, Monterey, CA 93943, 831-656-2912, eregnier@nps.edu*

### **ABSTRACT**

We build a computer-based tool to help train U.S. Marine Forces Reserve (MARFORRES) decision makers prepare for a hurricane affecting New Orleans. The hurricane decision simulator shows the user simulated hurricane forecasts, including track and wind-speed probability forecasts, stepping through the evolution of a storm. The hurricane forecast is updated at time steps corresponding to six hours of real-world time beginning 120 hours or more before expected landfall, and the user is asked to make decisions regarding preparation and evacuation based on the forecasts.

### **INTRODUCTION**

The U.S. Marine Corps Forces Reserve (MARFORRES) has 1600 personnel working in New Orleans, which is highly vulnerable to hurricanes and tropical storms. Preparing for hurricanes involves high-stakes decisions, especially for a decision maker responsible for people's lives and for mission readiness. While the consequences of failing to evacuate—or of evacuating too late—can be deadly, false alarms can cost millions of dollars and unnecessarily risk traffic fatalities. These high stakes are coupled with multidimensional uncertainty and frequent forecast updates.

MARFORRES decision makers can benefit from a training tool that allows decision makers to practice hurricane-preparation decisions. We construct a computer-based training tool (the hurricane decision simulator) that simulates the track, size, and intensity of hurricanes and associated forecasts. The storm simulations are based on historical hurricane forecast and verification data. The hurricane decision simulator requires emergency managers (users) to make decisions based on MARFORRES operating procedures and the simulated forecasts, stepping through the storm with a new decision opportunity as the forecast is updated. Users receive feedback on the outcomes of their decisions and gain expertise in interpreting forecast uncertainty and appropriately balancing the conflicting objectives of minimizing the cost of preparation and mitigating the consequences of a hurricane.

### **DECISION-MAKING CHALLENGES**

MARFORRES faces several challenges in making high-stakes hurricane preparation decisions. At the lead times that are required for complete preparation (96 hours before the storm), there is considerable uncertainty about the direction and intensity of the storm. The National Hurricane Center's (NHC) 48-hour track forecasts have substantially improved in recent decades, but the average track error still averages about 90 miles [9]. Not only is there uncertainty about whether the storm will impact New Orleans, the time the storm will make landfall is also uncertain. FEMA's decision support tool for

emergency managers displays a point estimate of the time to landfall, but in the 1976-2000 period, the 48-hour forecast erred by more than 18 hours over 20% of the time [10]. Moreover, the NHC updates its forecasts at least every six hours, so the probabilities and time to landfall that are predicted at 0600 will generally change by 1200, further increasing the complexity of the decision environment. Storm intensity and extent of winds are even more difficult to forecast. At 48 hours' lead time, the average intensity forecast error is almost 14 knots [9] which is greater than the difference between a low category 2 hurricane and a category 3 hurricane.

Many high-stakes decisions must also be made within a short time period. All of these factors have been shown to increase the difficulty of the decision problem and decrease both decision quality and the ability to learn through experience [13]. Prior work by Taylor [15] shows that optimal hurricane preparation decisions are not necessarily obvious, and Regnier and Harr [12] suggest that decision makers should sometimes wait to commit to precautions like evacuation until they receive a more accurate forecast.

People make a number of systematic errors when making decisions and other judgments in conditions of uncertainty, even when quantitative probabilistic forecasts are provided [2]. The challenge is amplified when there is complexity such as the need to synthesize uncertainty about multiple dimensions, in this case timing and impact. Furthermore, the probabilities are changing over time, which adds ambiguity (uncertainty about probability) to the decision context. The literature shows that most people are uncomfortable with ambiguity and it can lead to worse decisions [1].

Experience can improve intuitive judgment, but the factors that make the decision challenging—many environmental variables, frequent forecast updates, substantial irreducible environmental uncertainty, high-stakes decisions, and time pressure—also make it more difficult for people to learn through experience [13]. The number of tropical storms that a typical emergency manager will experience is far too few to develop high-performing intuitive judgment based on their personal experience. On average, there are fewer than 10 tropical cyclones per year in the North Atlantic, and only about 60% will make landfall [5]. Most of these will not become hurricanes, and only about one or two will be category 3 or higher [4], which is considered the threshold for evacuating New Orleans. On average, one category 3 or larger hurricane makes landfall at New Orleans every 19 years [8].

## **HURRICANE DECISION SIMULATOR**

Our hurricane decision simulator seeks to address these decision-making challenges by giving users the opportunity to experience many simulated storms. The hurricane decision simulator provides the following:

- the opportunity for users to experience and react to dozens of (simulated) storms;
- realistic forecasts of track and wind-speed probabilities updated at regular intervals;
- a realistic decision model specific to the MARFORRES context; and
- decision feedback consisting of a realistic description of outcomes associated with user choices and the simulated hurricane.

The simulator has three principal components: the storm simulator, decisions selected by the user, and outcomes based on the decisions and the storm.

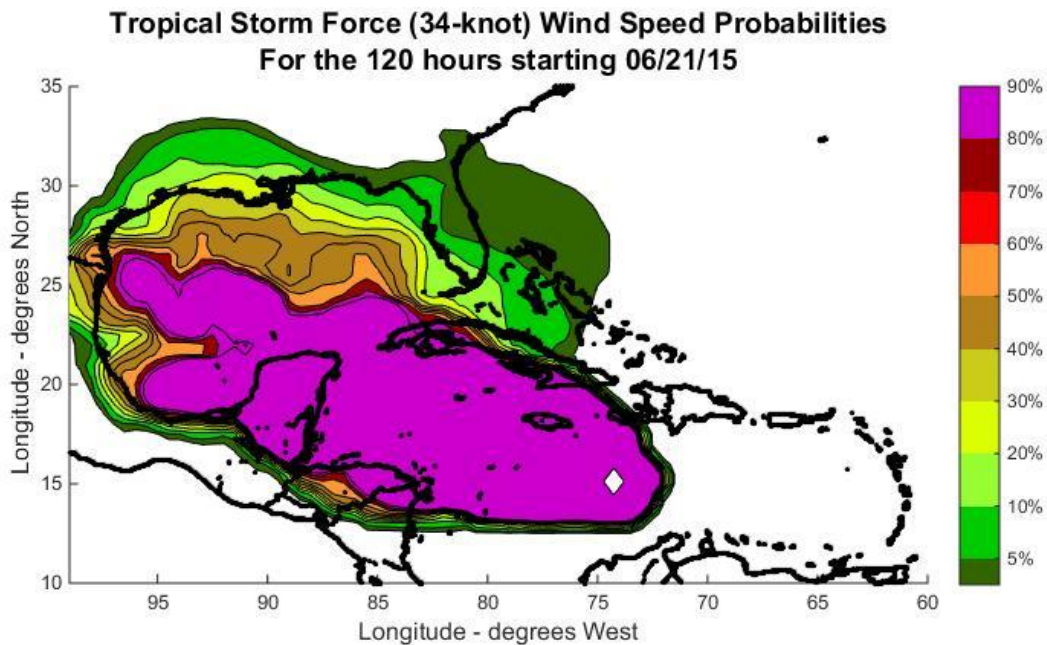
### **Storm Simulator**

The storm simulator is a probabilistic model of the center position, intensity (maximum sustained wind speed), and radius of maximum winds, and is used to calculate the probability of winds exceeding the 34, 50, and 64-knot thresholds, which correspond to the NHC's wind-speed probability product. The simulator updates the storm variables at discrete intervals corresponding to six hours of storm time.

The storm position model is a Markov Chain model fitted to historical tracks and NHC forecasts, using NHC data for storms since 1954 [6]. Each observation corresponds to a post-storm verified best-track position and the official forecast issued at that time. The states in the Markov model are defined using a k-means clustering algorithm. The distance measure is the great-circle distance between positions in an observation and the center of each cluster, plus the sum of squared distances for the remaining predictors, with all predictors including normalized distances. The predictor variables include two positions—best-track latitude and longitude and 48-hour forecast latitude and longitude—and both prior (last six hours) and future (next six hours) storm speed and bearing, as well as an indicator of whether the position is over land.

Each cluster defines a state in the model, and the transition probabilities are equal to the observed frequency of transitions among the states within the data set. The mean intensity and radius of maximum winds are calculated for each cluster, and used to estimate the radius of winds of for each of the three thresholds, using a Rankine profile with parameter 0.5 outside the radius of maximum winds [3].

**Figure 1 Hurricane decision simulator depicting the hurricane forecast**



The simulation updates in a matter of seconds, which corresponds to six hours of storm time. As depicted in Figure 1, a map of the Gulf Coast depicts the hurricane, and contour lines show different probabilities that the hurricane will strike an area within a 120-hour period. We also calculate the expected time the hurricane will strike New Orleans if it does strike New Orleans.

### User Decisions

The decision model is based on a review of official decision timelines from MARFORRES and interviews with MARFORRES emergency managers and operational decision makers. MARFORRES has an official “Decision Support Matrix” that describes six key decisions for the MARFORRES commander to make before a hurricane, beginning 96 hours before landfall. The decisions are strictly time-based, meaning that each decision is supposed to be taken at a specific time before landfall. Although the timeline appears reasonable if the commander knows a hurricane will strike New Orleans, the uncertainty of the hurricane forecasts may create situations where the timeline is compressed.

The six key decisions are:

1. Deploy the advance emergency relocation staff to the alternate headquarters at 96 hours before landfall;
2. Deploy liaison officers to local municipalities' emergency operations centers at 96 hours;
3. Deploy the rest of the emergency relocation staff to the alternate headquarters at 72 hours;
4. Activate a remain behind element at 72 hours;
5. Order evacuation or shelter in place at 60 hours; and
6. Transfer command and control to alternate headquarters at 48 hours before landfall.

When the expected time to landfall reaches each of these triggering lead times in the hurricane decision simulator, the simulator asks the user if or she would like to take that action based on the current hurricane forecast. If the user replies “Yes,” the simulator records the decision and incorporates that decision in determining the outcome of the simulation. If the user replies “No,” the simulator repeats the question at the next forecast update. In this way, the user can choose to compress the timeline if the forecast changes and the hurricane appears more likely to strike New Orleans than during the previous forecast. The timeline may also be compressed if the storm approaches more quickly than originally forecast, which is a realistic occurrence.

The simulation also provides the user information about MARFORRES actions—some of which are based on the user's decisions—and local and state decisions. This information provides a richer context, and the user learns what other preparation actions are occurring that may affect MARFORRES outcomes. For example, an evacuation by the city of New Orleans will dramatically slow the progress of MARFORRES' evacuation. The city will initiate a mandatory evacuation if New Orleans is within a category 3 hurricane's “cone of uncertainty” about 72-84 hours before landfall. The center of the storm will remain within the cone of uncertainty 60-70% of the time [7]. If the city begins an evacuation, it will begin evacuating its less mobile citizens about 60 hours before landfall.

The state of Louisiana's evacuation plan is also time dependent and Louisiana's evacuation occurs in phases at 50, 40, and 30 hours before landfall. The hurricane decision simulator provides this information to the user at the appropriate times. If the user waits to order an evacuation of MARFORRES 30-40 hours before landfall, MARFORRES personnel will be caught in traffic, and their arrival to the alternate headquarters in Fort Worth, Texas may be delayed by 24 hours or more.

As the user makes decisions within the hurricane decision simulator, the simulator also reveals the actions taken by MARFORRES as a result of these decisions. For example, if the user decides to deploy the advance emergency relocation staff, the simulation will tell the user these people arrive at the alternate headquarters and have begun to establish communications 12 hours later. MARFORRES has a list of about 100 actions to take beginning 120 hours before landfall, and many of them focus on

preparing for a possible evacuation. The simulation describes these actions to the user in order to mirror what would be occurring in reality.

## **Simulation Outcomes**

After the storm makes landfall or dissipates, the hurricane decision simulator concludes and provides feedback, indicating whether the hurricane strikes New Orleans and whether there is a storm surge. The simulation also lists the user's decisions and the timing of each of those decisions relative to the eventual landfall. Thus, the user can begin to understand the uncertainty in the relationship between the expected time to landfall and the actual time to landfall.

As part of its feedback, the simulator describes in a narrative form the consequences that result from the user's decisions and the storm. Decisions about hurricane preparation should depend on two kinds of costs: (1) the direct costs incurred by taking preparation action and (2) the mitigable portion of the consequences of the hurricane impact (equivalently the benefit of taking protective action). Thus, the simulation returns these two kinds of costs as the consequences from the hurricane.

We developed the consequence descriptions based on our discussions with MARFORRES subject matter experts, including representatives from the personnel, operations, logistics, and communications departments in MARFORRES. Each decision can incur monetary costs, disrupt normal operations, or create difficulties for MARFORRES to complete other missions. The earliest decisions, such as deploying the emergency relocation staff to the alternate headquarters and the liaison officers to the local emergency operations centers, cost relatively little. The emergency relocation staff does receive entitlement pay. The largest monetary cost is incurred by an evacuation. It costs \$250,000 to \$300,000 for each day that MARFORRES is evacuated, and an evacuation typically lasts for 7-14 days if a hurricane strikes New Orleans. However, the funds for evacuation do not come from MARFORRES' budget, and it is debatable how much this monetary cost should factor into MARFORRES decision making. Perhaps the largest cost to an evacuation is the disruption to normal operations.

The benefits of preparation in the simulator focus on how these decisions mitigate the consequences of a hurricane. It is important to estimate the costs, lives, and mission readiness saved by evacuating and other preparation actions. However, the portion of consequences that cannot be mitigated by preparation, such as flood damage to facilities, is not a critical factor in decisions taken 96 hours before a hurricane because such decisions cannot reduce this damage.

The benefit of deploying the emergency relocation staff is that it can set up the alternate headquarters and establish communications. The remain behind element assesses the damage to MARFORRES facilities and estimates the number of days until MARFORRES can return to New Orleans. An evacuation may save lives if a hurricane occurs, and it allows MARFORRES to continue to perform mission essential functions. Although the MARFORRES facilities have backup electric generators and can purify their own water, if the city is without power and the schools are closed, MARFORRES personnel will not be able to work very effectively if they had remained in New Orleans.

## **BENEFITS OF HURRICANE DECISION SIMULATOR**

The simulator does not evaluate whether or not the user made good or bad decisions. Rather, the simulator provides feedback on what the user decided, winds experienced in New Orleans, and the resulting consequences. Future iterations may ask the user to think about what he or she would have

done differently, but we think it is important to have the user assess whether the decisions were good or bad within the uncertain decision context.

One iteration of the simulator may not provide very many learning opportunities for the user, and we intend that MARFORRES emergency managers will practice this simulator many, many times. The goal is to help them learn how to interpret probabilistic forecasts and how to use those forecasts to make better decisions. Because of the randomness in the simulation, learning can only occur through multiple runs of the hurricane decision simulator. Given that one simulation takes about 10 minutes, a user should be able to experience several storms in one sitting. As we further refine this simulator, we hope to be able to record and store the ongoing results of individual users in order to ascertain if their decisions have improved and to provide more detailed feedback to the user.

## REFERENCES

- [1] Camerer, C. & Weber, M. Recent developments in modeling preference: Uncertainty and ambiguity. *Journal of Risk and Uncertainty*, 1992, 5 (4), 325-370.
- [2] Gilovich, T., Griffin, D. & Kahneman, D. *Heuristics and Biases: The Psychology of Intuitive Judgment*. Cambridge, U.K.: Cambridge University Press, 2002.
- [3] Holland, G.J, Belanger, J.I. & Fritz, A. A revised model for radial profiles of hurricane winds. *Monthly Weather Review*, 2010, 138, 4393-4401.
- [4] Landsea, C.W. A climatology of intense (or major) Atlantic hurricanes. *Monthly Weather Review*, 1993, 121, 1703-1713.
- [5] Landsea, C.W. Counting Atlantic tropical cyclones back to 1900. *Eos Transactions American Geophysical Union*, 2007, 88 (18), 197-202.
- [6] National Hurricane Center. Automated tropical cyclone forecast (ATCF): Archive data files. Accessed January 11, 2015. <ftp://ftp.nhc.noaa.gov/atcf/archive/>.
- [7] National Hurricane Center. Definition of the NHC track forecast cone. National Weather Service. Last modified March 4, 2014. <http://www.nhc.noaa.gov/aboutcone.shtml>.
- [8] National Hurricane Center. Introduction to storm surge. National Weather Service. Accessed January 11, 2015. [http://www.nhc.noaa.gov/surge/surge\\_intro.pdf](http://www.nhc.noaa.gov/surge/surge_intro.pdf).
- [9] National Hurricane Center. Official NHC 5-year average forecast errors (2009-2013). National Weather Service. Last modified February 12, 2014. [http://www.nhc.noaa.gov/verification/pdfs/OFCL\\_5-yr\\_averages.pdf](http://www.nhc.noaa.gov/verification/pdfs/OFCL_5-yr_averages.pdf).
- [10] Powell, M.D. & Abernethy, S.D. Accuracy of United States tropical cyclone landfall forecasts in the Atlantic basin (1976-2000). *Bulletin of the American Meteorological Society*, 2001, 82 (12), 2749-2767.
- [11] Regnier, E.D. Public evacuation decisions and hurricane track uncertainty. *Management Science*, 2008, 54 (1), 16-28.
- [12] Regnier, E.D. & Harr, P.A. A dynamic decision model applied to hurricane landfall. *Weather and Forecasting*, 2006, 21 (5), 764-780.
- [13] Shanteau, J. Competence in experts: The role of task characteristics. *Organizational Behavior and Human Decision Processes*, 1992, 53 (2), 252-266.
- [14] Stewart, T.R., Moninger, W.R., Heideman, K.F. & Reagan-Cirincione, P. Effects of improve information on the components of skill in weather forecasting. *Organizational Behavior and Human Decision Processes*, 1992, 53 (2), 107-134.
- [15] Taylor, B.J. Eastern North Carolina Marine Corps Forces and Installations (ENCMCFI) High Intensity Hurricane (HIH) Evacuation Decision Support—A Dynamic Decision Model under Uncertainty and Risk. M.S. Thesis, Naval Postgraduate School, 2007.