A Computational Model of Hurricane Evacuation Decision

Extended Abstract

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ABSTRACT

Hurricanes are devastating natural disasters. In deciding how to respond to a hurricane, in particular whether and when to evacuate, a decision-maker must weigh often highly uncertain and contradictory information about the future path and intensity of the storm. To effectively plan to help people during a hurricane, it is crucial to be able to predict and understand this evacuation decision. To this end, we propose a computational model of human sequential decision-making in response to a hurricane based on a Partial Observable Markov Decision Process (POMDP) that models concerns, uncertain beliefs about the hurricane, and future information. We evaluate the model in two ways. First, hurricane data from 2018 was used to evaluate the model's predictive ability on real data. Second, a simulation study was conducted to qualitatively evaluate the sequential aspect of the model to illustrate the role that the acquisition of future, more accurate information can play on current decision-making. The evaluation with 2018 hurricane season data shows that our proposed features are significant predictors and the model can predict the data well, within and across distinct hurricane datasets. The simulation results show that, across different setups, our model generates predictions on the sequential decisions making aspect that align with expectations qualitatively and suggests the importance of modeling information.

KEYWORDS

Modelling for agent-based simulation; Validation of simulation systems; Decision-making; Hurricanes

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1 INTRODUCTION

In the past three years, there have been at least five major hurricanes affecting the United States, including Hurricane Harvey, Irma, Florence, Michael, and Dorian, causing immense flooding, many casualties, and more than hundred billion dollars of damage [9].

To help mitigate damage and casualties, effective and efficient evacuation and emergency management plans are needed. The crucial part of such plans is an ability to predict and influence people's decision-making, whether to evacuate or stay in their home. One way to achieve this is to build a model of human decision-making that captures important factors of the evacuation decision and can accurately predict and explain decisions.

There has been much existing research on hurricane evacuation decisions [8], [3], [6], [7]. These studies have identified important features that are associated with the evacuation decision. These features include risk perception, information about the hurricane, official notice, household location, expectations of impacts to personal concerns, and observations of social cues. However, other demographic characteristics have either minor or inconsistent associated with evacuation decisions.

This research provides a sound basis for modeling but also does not take into account the sequential nature of the information people receive about hurricanes. The unfolding of a hurricane event, from formation to landfall, can span several days. People who stay repeatedly face the evacuation decision as they receive or seek out new information. Affected individuals must reason under the uncertainty associated with the state of the hurricane because the hurricane's path and impact cannot be forecast with high certainty [11]. They may consider not only the current information but also future information that is more accurate and could help resolve uncertainty. Different individuals may have different goals and concerns. Similarly, people may have different prior beliefs about the hurricane and the trustworthiness of various sources of information. In short, people with their own beliefs and concerns have to decide whether stay or evacuate would lead to outcomes that they prefer more and take into account the uncertainty of the event and the future information.

There are also many existing Agent-Based Models on evacuation behaviors ranging from decision tree, different variants of logistic regression, and dynamic influence diagram [5], [10], [13], [12]. However, these models broadly include features with limited explanatory power or relationship to the decision as established by prior research and further operate under the assumption that people only consider the current conditions at each time interval, but not the expected future conditions.

To capture all these aspects in the hurricane situation, we propose a process model of human decision making based on a Partial Observable Markov Decision Process (POMDP) which is a general framework capable of modeling sequential decision making under uncertainty and reasoning about information. The model is driven by existing theories and finding on human evacuation decisions.

We evaluate the model in two ways: quantitatively using questionnaire data collected from regions after two 2018 major hurricanes, and qualitatively using simulation. Empirical results show that our model can predict both hurricane data sets well and outperforms other baselines. Simulation results show that the model

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that considers the future information is qualitatively closer to evacuation decisions in our data than the model that doesn't, and reveal what factors might influence this impact of future information.

2 THE MODEL

The hurricane evacuation decision is a sequential decision-making task under uncertainty. People consider not only the impact of the hurricane and the cost of evacuation but also the potential benefit from future, more accurate information. This motivates us to model the evacuation decision using a POMDP, a general and widely-used framework for sequential decision-making under uncertainty [2].

POMDP consists of State (S), Observation (Ω), Observation function (O), Action (A), Transition function (T), Reward (R).

State (S): State is a sufficient statistic of what occurred in the past, such that what will occur in the future only depends on the current state. State features include features related to what people are concerned about and can be changed if the hurricane would hit or people decide to evacuate (safety, flood condition, outage, and money), as well as features that represent the predicted state of a hurricane at the time it reaches the agent's area (i.e., hurricane category). We assume people maintain the predicted state of a hurricane at the time when it reaches their area.

Observation (Ω) and the Observation function (O): The observation that people receive at each time step is the news about the expected category of the hurricane when the hurricane reaches their area. The observation function is the accuracy of the news.

Action (A) and Transition Function (T): We focus on two actions: stay and evacuate. If the agent chooses to stay, it moves to the next time step and receives new observation/news about the hurricane. If the next state is at the time when the hurricane hits, the dynamics of stay action will result in changing the other features related to the impact of the hurricane. The evacuate action results in paying the cost of evacuation which includes traveling cost and evacuated place cost, and moving to the new location.

Reward (R): Reward function maps a state to a real number summarizing how good or bad the given state is. We assume that the reward function is a linear sum of the weighted state's features, where weights reflect how un/desirable the feature is. These weights can vary based on individuals or groups of individuals.

3 SIMULATION

The main objective of the simulation study is to investigate and demonstrate the influence of the sequential aspect of the model on evacuation decisions. Specifically, we explore how the model performs when it expects that a) there will be future more accurate information on the hurricane path and impact, and b) delaying evacuation will increase the cost of evacuation.

Therefore, we are interested in comparing the difference in the evacuation prediction between the model with and without this expectation or lookahead. For the model without lookahead, the agent only uses its current beliefs on the impact of the hurricane to calculate the expected reward of the stay action.

Further, we manipulate three important factors that can influence an evacuation decision when considering future information: prior beliefs about the strength and the impact of this hurricane, the expected accuracy of the future information, and the reward value.

The simulation study shows that the model with lookahead generally predicts evacuation probability in early time steps to be lower than the model without lookahead, reflecting possible gains from future information. These predictions from the model with lookahead are closer to what we observe in the two hurricane data that we collected. Further, the simulation shows a relationship between prior beliefs on the hurricane and the expected accuracy of the information where prior beliefs influence evacuation decisions more when the accuracy of information is low (early information).

4 EMPIRICAL EVALUATION

We created a new questionnaire that includes three main types of questions: 1) demographic characteristics, 2) news, official notice, and prior experience, and 3) model-related questions concerning what subjects thought would happen before the hurricane hit including safety, flood condition, outage, evacuation expenses.

To collect the data, we use the Amazon Mechanical Turk to recruit participants in the states affected by the hurricane. We collected data from two major hurricanes in 2018: Florence affecting South Carolina and North Carolina, obtaining 747 responses, and Michael affecting Florida and Georgia, obtaining 700 responses.

We compare the model-related features with three other baseline sets of features in the questionnaires: 1) intercept only, 2) demographic features, and 3) demographic features plus information features. The data was fitted using Bayesian Logistic Regression [1] with these different sets of features to predict evacuation decisions.

Additionally, to test the assumption that different people may have different reward weights, we fit the data using Hierarchical Bayesian Logistic Regression [4] in which the (reward) weights can vary depending on other features reflecting that different groups of people could have different weights.

The results show that all 95% credible intervals of features' weights do not include 0 except the outage in Florence, and the sign of all weights is in the expected direction. Safety and evacuation costs are negatively associated with evacuation decisions while flooding and outage are positively associated with the decisions.

Using only features from the models outperforms other sets of features in terms of accuracy and F-1 scores (calculated from cross-validation) for both datasets. The hierarchical model outperforms all other models for both datasets, achieving relatively high accuracy (94.9% for Florence and 93.2% for Michael where the best baseline is at 90.5% for Florence and 88.9% for Michael) and F1-score (.8 for both). When training on one hurricane to predict another hurricane, using only model-related features outperforms other sets of features and the hierarchical model outperforms all other models for both datasets, achieving relatively high accuracy (93.0% for Florence and 92.4% for Michael) and F1-score (.8 for both).

In conclusion, the empirical and simulation results show that our model is capable of predicting human decisions well both qualitatively and quantitatively across different hurricane situations.

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