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Data-driven simulation of asymmetric hurricane wind fields for community resilience planning

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ABSTRACT:
In community resilience planning, a hurricane wind field of a desired intensity for a community of interest can be used to study the effects on the community infrastructure. This necessitates simulation of the hurricane wind field of a specified intensity with a landfall location specific to that community, even though the community may not yet have experienced a similar event. In this context, this paper proposes a data-driven simulation technique to simulate the temporally and spatially varying hurricane wind fields for the purposes of hindcasting and synthetic scenario analysis based on integrated asymmetric Holland models. The proposed technique successfully overcomes two shortcomings of the existing Holland-type models, i.e. poor representation of wind field in the inner core and the inability to model surface wind speed change due to roughness changes. The performance of the proposed data-driven simulation technique is illustrated in examples of simulations for both historical and synthetic hurricanes.

Keywords: Data-driven hurricane simulation, backward and forward Holland models, inner and outer cores

1. INTRODUCTION

In the context of community resilience planning, typically a scenario (or portfolio of scenarios) analysis is carried out, which eventually facilitates better risk communication with decision-makers and planners. In general, two types of scenario analyses are used, i.e., hindcast analysis and synthetic scenarios analysis. Hindcast analysis uses data from past events to validate the models (e.g. damage and recovery) used in resilience analysis. However, measurements from past events may not include wind field data at a tight enough temporal resolution, while such information may be needed when carrying out time-dependent analysis, e.g. wind, wave, and/or surge for damage and response and early recovery. Whereas, for synthetic scenario analysis, a synthetic hurricane event with a specified strength passing close to the community of interest is needed. This will provide a mechanism for researchers and others to answer the common question that arises: What if hurricane XYZ of a certain strength and duration struck our community? Therefore, wind field modeling with a focus on both historical and synthetic events is needed to enable accurate modelling of the accumulated damage from a hurricane making landfall to the physical infrastructure at the community scale.

In the literature, the axially symmetric parametric vortex models, such as the Holland and Georgiou model (Georgiou, 1985; Holland, 1980), are widely used in engineering applications, due to their high computational efficiency. Recently, researchers have improved these models to capture the asymmetric structure of actual hurricanes (Hu et al., 2012). Despite these improvements, there are still two remaining shortcomings. First, the generalized exponential pressure field model used to drive the parametric wind model may provide a poor approximation of the radial profile in the inner core of some storms, resulting in a less accurate estimation of the wind field in the inner core region. Second, these parametric models cannot model the sudden change of wind field due to the roughness change which occurs when going from water to land.

* Lead presenter

To overcome the aforementioned shortcomings of the existing parametric hurricane models, this paper proposes a novel data-driven simulation technique to simulate the temporally and spatially varying hurricane wind fields. The performance of the proposed data-driven simulation technique is illustrated in wind field simulations for both historical and synthetic hurricanes.

2. METHODOLOGY

This technique is developed based on the Holland-type model (forward Holland model),

$$V_g = \sqrt{\frac{B}{\rho_a}\left(\frac{R_m}{r}\right)^B (p_n - p_c) e^{-(R_m/r)^B} + \left(\frac{rf}{2}\right)^2} - \frac{rf}{2} \tag{1}$$

The parameters of the Holland model are inversely extracted from measurement data included in the H*Wind and best track data using the backward Holland model, i.e. Lambert *W* function,

$$z = f^{-1}\left(ze^z\right) = W\left(ze^z\right) = W\left(-\frac{V_g^2 + V_g \cdot rf}{B \cdot (p_n - p_c)/\rho_a}\right) \tag{2}$$

where $z = -\left(R_m(\theta)/r\right)^B$. It follows that $R_m(\theta) = \exp\left(-\ln z / B\right) \cdot r$. To better capture the asymmetric wind field for various velocity ranges, we can solve for $R_m(\theta^i, V_g^j)$ for specified angles θ^i and velocity contours V_g^j. Then, these data-driven model parameters are interpolated in the time domain and passed back to the forward Holland model to simulate wind fields for a user desired fine temporal resolution. For simulation of synthetic hurricane events, the data-driven model parameters extracted from a real hurricane are used to simulate wind fields that resemble a realistic hurricane, but can also have a synthetic track which is simulated to pass close or through the community of interest. The wind field for inner and outer core regions are modeled separately by two sets of asymmetric Holland models, whose parameters are estimated using two different branches of the Lambert *W* function. In addition, the sudden change of the surface wind speed due to the roughness change from water to land is explicitly modeled using a speed conversion process. In this way, the proposed technique successfully overcomes the two shortcomings of the existing Holland-type models and can achieve a higher simulation accuracy.

3. EXAMPLES ON HURRICANE EVENT SIMULATION

The efficacy of the data-driven model was initially evaluated by comparing the simulated wind field to H*Wind data for historical events. The wind field of Hurricane Andrew was used as an example. A comparison result shows that the simulated velocities in the inner core region (marked by squares) are much more accurate when the wind fields in this region are explicitly modeled (Fig. 1b), compared to the case where the inner core region was not explicitly modeled (Fig. 1a). In addition, when comparing the velocity contours between the simulated results and the H*Wind (Fig. 1c), it is seen that the staggered feature of velocity contours due to the sudden change of surface roughness was successfully reproduced by the proposed data-driven model. In addition, a synthetic Category 5 hurricane event was simulated for the city of Orlando, FL. The data-driven model parameters were extracted from Hurricane Andrew. A synthetic track was simulated according to the user-specified landfall location as well as the initial direction for the hurricane heading. One snapshot of the simulated wind field, as well as the track for the synthetic event are shown in Fig. 2. The staggered pattern of the velocity contours was successfully simulated, which reflected the effect of velocity reduction on land.

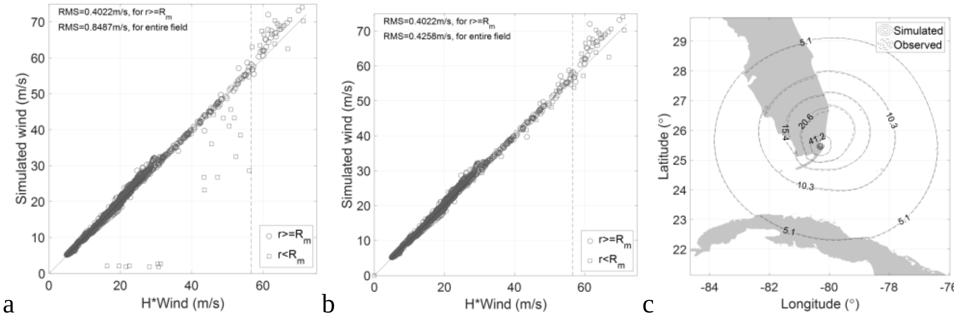

Figure 1. Comparison of simulated and observed velocities: (a) absolute value (without explicitly modeling the wind field in the inner core region), (b) absolute value (with explicitly modeling the wind field in the inner core region), (c) contours.

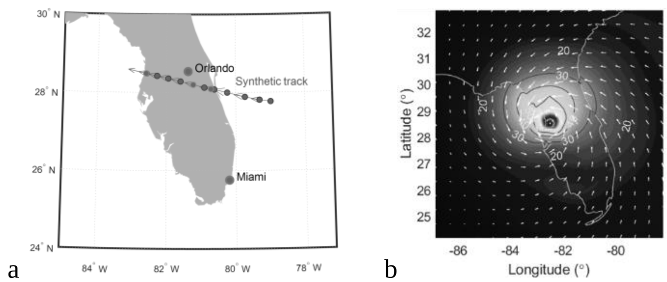

Figure 2. Simulated track and wind field for synthetic hurricane event: (a) track, (b) wind field.

4. CONCLUSIONS

To facilitate community resilience analysis which begins with the simulated hazard event, i.e. hurricane, a novel data-driven hurricane wind field model based on integrated asymmetric Holland models is proposed in this paper to simulate the temporally and spatially varying hurricane wind fields for hindcast and synthetic scenario analysis. The results presented in this paper demonstrated the efficacy of the proposed technique. Specifically, the simulation of the inner core region of hurricanes was significantly improved by separately and explicitly modeling the wind field in this region using the model parameters estimated by the lower branch of the Lambert W function. Then, by introducing a water-land based wind speed conversion process, the staggered pattern of the realistic hurricane wind field due to a sudden roughness change was successfully simulated.

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