August 27-31, 2023
FLORENCE - ITALY
16th International
Conference on
Wind Engineering
ICWE 16

Large eddy simulation of extreme nonstationary hurricane winds via a hurricane boundary layer model

Tianqi Ma[1], Chao Sun[1], Paul Miller[2]

[1]*Department of Civil and Environmental Engineering, Louisiana State University, Baton Rouge, United State, csun@lsu.edu*
[2]*Department of Oceanography and Coastal Sciences, Louisiana State University, Baton Rouge, United State, pmiller1@lsu.edu*

SUMMARY:
Extreme tropical cyclones (hurricanes) induced winds are always nonstationary and more turbulent than atmospheric boundary layer winds. In this study, a large eddy simulation based hurricane boundary layer (HBL) model is developed to model the wind field at the target location under the moving of the hurricane center by considering the changing of large-scale kinematic and thermodynamic conditions. An asymmetric model is adopted to obtain the gradient wind velocity, the wind direction, and the distance from the hurricane center. The large-scale thermal conditions are obtained by extracting the hourly profiles of air temperature and relative humidity from generated Proxy soundings. Then, the wind field at Arana airport during Hurricane Harvey's passage is simulated for 12 hours and compared with observations collected by FCMP T2. The 10-min averaged wind speed, turbulence intensity, and wind direction at 10 m elevation are consistent with the observed data. Research results show that the developed model can predict wind turbulence and wind gust well. The simulated longitudinal and lateral wind spectrum agrees well with the observed results and has higher energy at lower frequencies than that predicted by the Kaimal spectrum model for non-hurricane winds. In summary, the developed nonstationary HBL model can capture the main characteristics of hurricane winds.

Keywords: hurricane boundary layer, large-eddy simulation, spectral density

1. INTRODUCTION

Extreme hurricanes caused extensive damages to critical civil infrastructure. The extreme hurricane winds are always non-stationary and more turbulent than the neutral atmospheric boundary layer(ABL) winds. Recent studies have developed LES models for HBL wind fields in a relatively small domain of $O(5)$ km instead of the entire tropical cyclones (Worsnop et al., 2017, Ma and Sun, 2021). Mesoscale tendency terms are included in the governing equations to maintain the mean wind profiles as that of an entire tropical cyclone in a much smaller field. Worsnop et al. analyzed the simulated wind turbulence characteristics in HBL and found that peak power shifts to higher frequencies than the peaks in the Kaimal spectrum model, and the spectral coherence is higher than that predicted by the IEC coherence model (Worsnop et al., 2017). Ma and Sun applied the LES-generated hurricane wind fields to analyze the structural response of a power transmission system and found that the spatial variance of the HBL flow field causes large unbalanced wire axial forces acting on the tower(Ma and Sun, 2021). These models are derived for simulating wind fields with fixed large-scale conditions. The along-wind direction is always in the x direction. However, the wind speed and direction change as the hurricane center moves. To simulate non-stationary hurricane characteristics within a long duration (e.g., hours) at a specific location, the model for HBL needs to be generated in a fixed global coordinate. In addition, these models neglected the effects of thermodynamics and moist processes. However, the water vapor near the hurricane eye and away from the hurricane center is different. To address these limitations, a nonstationary HBL LES solver is developed in the present study by considering the changing of large-scale kinematic and thermodynamic conditions.

2. MODEL DESCRIPTION

2.1. Hurricane Boundary Layer Model

An LES model of HBL for a moving hurricane is derived, as shown in Fig. 1. Governing equations of HBL wind fields at a specific location with a distance R from the hurricane eye are derived in the reference (Ma and Sun, 2021). The X-coordinate is in the direction of gradient velocity U_g, which varies with time because the hurricane center moves. In this work, the global x axis points east, the y axis points north. The new global coordinate is rotated counter-clockwise by an angle, θ, from the initial local coordinate system. The mesoscale terms in the global coordinate are

$$M_x^{\mathrm{gl}} = \left(V\frac{\langle U\rangle}{R} + V\frac{\partial\langle U\rangle}{\partial R}\right)\cos(\theta) + \left(-V\frac{\langle V\rangle}{R} - \langle U\rangle\frac{U}{R} + \frac{U_g^2}{R} + \Omega_3 U_g\right)\sin(\theta) \tag{1}$$

$$M_y^{\mathrm{gl}} = -\left(V\frac{\langle U\rangle}{R} + V\frac{\partial\langle U\rangle}{\partial R}\right)\sin(\theta) + \left(-V\frac{\langle V\rangle}{R} - \langle U\rangle\frac{U}{R} + \frac{U_g^2}{R} + \Omega_3 U_g\right)\cos(\theta) \tag{2}$$

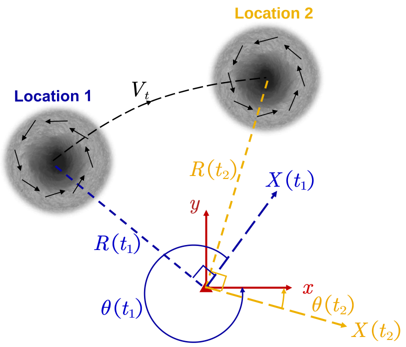


Figure 1. Conceptual schematic of the model.

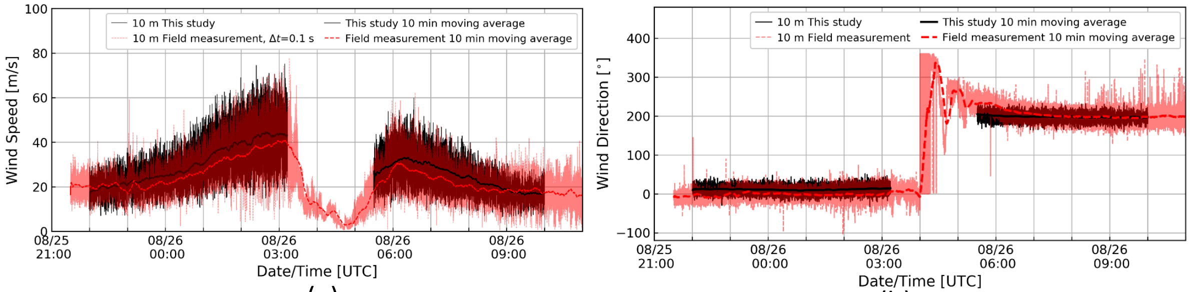
where the M_x^{gl} and M_y^{gl} are the mesoscale terms introduced to the momentum equations in x and y directions. The angle brackets represent a horizontal average at a certain height. The U, V, W represent the wind components in the local coordinate system (X, Y, Z), and the u, v, w represent the wind components in the global coordinate system (x, y, z). U_g is the gradient wind speed and Ω_3 is the rotation velocities in the Z directions. In this work, the specific humidity (q_v) is considered. The source terms S_ϑ and the S_{q_v} are introduced to maintain specified vertical profiles of potential temperature (ϑ_r) and mixing ratio of water vapor (q_{vr}).

2.2. Large-scale Conditions

In the governing equations of nonstationary hurricane wind, R, θ, and U_g are input parameters in this study. An asymmetric hurricane wind model is adopted to estimate the U_g (Xie et al., 2006). The $R_{max}(\alpha)$ is computed from the wind radii reported in the NHC forecast guidance. To further enhance the asymmetric model, the parameters B and R_{max} are optimized using various available real-time dropsonde data. Using this method, the large-scale conditions, U_g, R, and θ are obtained. The large-scale thermodynamic conditions, ϑ_r and q_{vr}, are estimated by extracting the hourly profiles of air temperature and relative humidity from generated Proxy soundings. proxy soundings were generated using meteorological conditions from ERA5 reanalysis for each ERA5 grid cell containing the TC center and all contiguous grid cells.

3. CASE STUDY AND RESULTS

Using the developed model, a case study is conducted. The wind field at Arana airport during Hurricane Harvey's passage is simulated for 12 hours and compared with observations collected by FCMP T2. Fig. 2(a) shows the surface wind speed of Hurricane Harvey at the Aransas County Airport from August 25th at 21:00 to 26th at 10:00. The black line denotes the simulated wind speed at a selected point (1250, 1250, 10) m. The red line denotes the instantaneous (10 Hz) recorded wind speeds collected by the FCMP T2 (Fernández-Cabán et al., 2019). The simulated wind turbulence intensity is around 20%, close to the observed result. The simulated maximum 3-s gust wind speed is 62.4 m/s before and 51.9 m/s after Hurricane-eye passage. The observed maximum 3-s gust wind speed is 61.3 m/s before and 46.9 m/s after Hurricane-eye passage. Overall, Fig. 2(a) indicates that the model can predict the 10-min averaged wind speed, turbulent wind, and gust wind well. Fig. 2(b) shows the wind direction of Hurricane Harvey simulated in this study and measured by the ultrasonic wind anemometer. The simulated averaged wind direction is 11.3 ° and 198.2 ° before and after the passage of the hurricane eye. The observed averaged wind direction is -1.9 ° and 199 ° before and after the passage of the hurricane eye. The simulated wind direction is close to the observed wind direction.



(a) (b)

Figure 2. Time history of wind speed (a) and wind direction (b) at the height of 10 m.

Fig. 3 shows the normalized longitudinal, lateral, and vertical velocity spectra $nS_{uu}(n)/u_*^2$ as a function of reduced frequency nz/U. By comparison, we can find that the simulated wind spectra agree with the observed spectra in longitudinal and lateral directions. Comparing the hurricane wind spectrum with the Kaimal spectrum, one can find that the normalized power spectra of hurricane wind in longitudinal, lateral, and vertical directions have more energy at lower frequencies.

The reduced frequency of peak power shifts to lower frequencies than that in the Kaimal spectrum, which is consistent with Yu's observations (Yu et al., 2008).

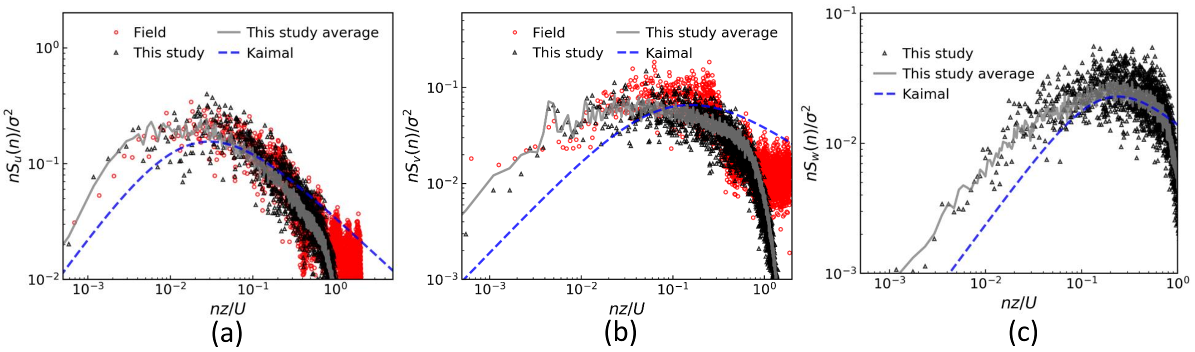


Figure 3. Power spectra densities of wind velocities during 26th 00:00 and 26th 01:00 in along-wind direction (a), cross-wind direction (b), and vertical direction (c).

4. CONCLUSION

An LES-based hurricane boundary layer model is developed to simulate extreme nonstationary hurricane winds. Using the proposed procedures, the hurricane winds at the Aranas Airport during the Hurricane Harvey passage are simulated and compared with the observations. The averaged wind speed and wind direction at 10 m elevation are consistent with the observed data. The model can predict turbulent wind and gust wind well. The simulated wind spectrum agrees well with the observed results. The standard Kaimal spectral model for neutral ABL underestimates the magnitude of the power spectral density in the HBL. The reduced frequency of peak power shifts to lower frequencies in HBL than the peaks of the Kaimal spectral model. The proposed nonstationary HBL model is validated and can be applied to model hurricane wind loading on civil infrastructure.

ACKNOWLEDGEMENTS

This work was supported by the Louisiana State University Economic Development Assistantship and the research was conducted using high-performance computing resources provided by Louisiana State University.

REFERENCES

Fernández-Cabán, P. L., Alford, A. A., Bell, M. J., Biggerstaff, M. I., Carrie, G. D., Hirth, B., Kosiba, K., Phillips, B. M., Schroeder, J. L., Waugh, S. M., et al., 2019. Observing Hurricane Harvey's eyewall at landfall. Bulletin of the American Meteorological Society 100, 759–775.

Ma, T. and Sun, C., 2021. Large eddy simulation of hurricane boundary layer turbulence and its application for power transmission system. Journal of Wind Engineering and Industrial Aerodynamics 210, 104520.

Worsnop, R. P., Bryan, G. H., Lundquist, J. K., and Zhang, J. A., 2017. Using large-eddy simulations to define spectral and coherence characteristics of the hurricane boundary layer for wind-energy applications. Boundary-Layer Meteorology 165, 55–86.

Xie, L., Bao, S., Pietrafesa, L. J., Foley, K., and Fuentes, M., 2006. A real-time hurricane surface wind forecasting model: Formulation and verification. Monthly Weather Review 134, 1355–1370.

Yu, B., Chowdhury, A. G., and Masters, F. J., 2008. Hurricane wind power spectra, cospectra, and integral length scales. Boundary-layer meteorology 129, 411–430.