105. AN IMPROVED METHODOLOGY FOR RISK ASSESSMENT OF TROPICAL CYCLONES UNDER CHANGING CLIMATE

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1. Introduction

Mitigation of losses due to tropical cyclones has become an increasing urgent and challenging issue in light of changing climate and continued escalation of coastal population density. This study proposed an improved methodology to effectively assess the climate change impacts on hurricane boundary-layer wind and rain fields. First, a physically-based intensity model was developed and compared to the state-of-the-art forecast model of DeMaria (2009). A newly-derived empirical formula of maximum potential intensity was also introduced in this study. Then, the gradient wind model was extended to integrate contributions of sea surface temperature (SST), tropopause temperature (T_0) and temperature at the top of boundary layer (T_{TBL}). This gradient wind model is used in conjunction with a height-resolving model recently developed by Snaiki and Wu (2017; 2018) to rapidly generate the boundary-layer wind and rain fields. The RCP 8.5 scenario was used for the risk assessment simulation, where a total of 10,000 years of tropical cyclone events have been generated. The comparison of the current and future climate scenario was conducted indicating a significant change of hurricane wind and rain under changing climate.

2. Proposed Risk Analysis Framework

There are several major components contributing to the risk assessment of tropical cyclones under changing climate, namely tracking model, intensity model and wind field model.

The tracking model (i.e., tropical cyclone translational velocity and heading angle) was revisited based on extensive statistical analysis with the HURDAT 6-hourly best track observations for each 5°x5° grids, where several plausible models were proposed and compared to select the most appropriate regression model for the hurricane risk simulation.

A physically-based intensity model was developed and compared to the state-of-the-art forecast model of DeMaria (2009) which was originally developed based on the logistic growth equation (LGE) commonly used to model population growth. Due to its good performance, DeMaria’s model is utilized by the National Hurricane Center (NHC) as one of the major forecast models for the tropical cyclone intensity prediction (Xu and Wang 2015) since it can capture the major physical and dynamical processes of the hurricane intensification (Xu et al. 2016). To determine the most important component of the risk analysis framework, namely the hurricane intensity, the v-momentum equation is written in the cylindrical coordinate system (r,θ,z) as:

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial r}+\frac{v}{r}\frac{\partial v}{\partial \theta}+w\frac{\partial v}{\partial z}+\frac{uv}{r}+fu=F_{friction} \quad (1)$$

where (u,v,w) = wind velocity components. Then, Eq. (1) is solved at $v_{\max}$ where the gradients are by definition equal to zero. Since the Coriolis force is negligible compared to the centrifugal force, it will be disregarded. The friction force is represented through the bulk aerodynamic representation in which the sea surface exchange coefficients for momentum is denoted as C_D. The latter is determined based on the theoretical formula of the maximum potential intensity V_{mpi} which has been derived by Emanuel (1986, 2003) as:

$$V_{mpi}^2=\frac{C_K}{C_D}\frac{T_s-T_0}{T_0}\left(k_0^*-k\right) \quad (2)$$

where C_K = sea surface exchange coefficients for enthalpy; T_s = sea surface temperature; T_0 = outflow temperature; and k_0^*, k are the enthalpies of the ocean surface and the atmosphere near the surface, respectively. Hence, the drag coefficient can be obtained as $C_D = \frac{C_K}{V_{mpi}^2}\frac{T_s - T_0}{T_0}\left(k_0^* - k\right)$. Accordingly, the hurricane intensity is given by:

$$\frac{\partial v_{\max}}{\partial t} = \left(-\frac{u_m}{r_m}\right)v_{\max} - \left[\frac{C_K\left(T_s - T_0\right)\left(k_0^* - k\right)}{T_0}\right]\frac{v_{\max}^2}{V_{mpi}^2} \tag{3}$$

where $r_m =$ radius of maximum winds. Setting $\kappa' = \left(-{u_m}/{r_m}\right)$ and $\beta' = \left[{C_K\left(T_s - T_0\right)\left(k_0^* - k\right)}/{T_0}\right]$, Eq. (3) reduces to:

$$\frac{\partial v_{\max}}{\partial t} = \kappa' v_{\max} - \beta' \frac{v_{\max}^2}{V_{mpi}^2} \tag{4}$$

The obtained equation highlights important physical principles governing the tropical cyclone intensity. It is noted that the evolvement of the tropical cyclone intensity is controlled by two key mechanisms: the inward advection of the angular momentum (first term) and a decay mechanism through the frictional forces (second term) that limits the intensity to an upper limit. These were also the arguments upon which DeMaria (2009) founded his statistical model by using the logistic growth equation (LGE) since it contains similarly a growth term and a decay one. It is interesting to note that the proposed physically-based model is similar to the LGE model of DeMaria (2009) $\left[\frac{\partial v_{\max}}{\partial t} = \kappa v_{\max} - \beta v_{\max}\frac{v_{\max}^n}{V_{mpi}^n}\right]$. The derived exponent of ${v_{\max}}/{V_{mpi}}$ is 2 in the proposed model, while the empirically determined value n in DeMaria's model is 2.6. The second term of DeMaria's model explicitly contains the $v_{\max}$, which is implicitly considered in the proposed model with the sea surface exchange coefficients for enthalpy C_K that can be linearly related to $v_{\max}$ (e.g., Donelan et al. 2004; Bell et al. 2012). The growth rate parameter κ in DeMaria (2009) was empirically related to environmental factors such as the environmental wind shear that can substantially contributes to the tropical cyclone size. This approach has been justified by the observation in this study that the κ' is inversely proportional to the hurricane size r_m. Therefore, the empirical relationship proposed by DeMaria (2009) for the growth rate will be utilized here.

Miller (1958) was the first one to introduce the concept of the maximum potential intensity (MPI) that is required for the widely-used intensity models. Emanuel (1988) and Holland (1997) proposed theoretical formulas to characterize MPI. On the other hand, empirical formulas have also been developed for V_{mpi} over the North Atlantic as a function of the SST. Among them, the formula of $V_{mpi} = A' + B' e^{C'\left(SST - T_0'\right)}$ has been widely used (e.g., DeMaria and Kaplan 1994; Zeng et al. 2007; Xu et al. 2016) with different values of the fitting constants $\left(A', B', C'\right)$ estimated using the least squares. Several examples with different constant values are illustrated in Fig. 1. As pointed out by DeMaria and Kaplan (1994), the abovementioned exponential function does not allow for a reduced slope that is clear above SST=28°C. This flattening phenomenon has been attributed to variations in the tropopause temperature (DeMaria and Kaplan 1994). Hence, a new empirical formula is proposed here to consider the flattening process:

$$V_{mpi} = A' + B' \exp\left[-C'\left(\frac{T_0'}{SST}\right)^{D'}\right] \tag{5}$$

where the constants A', B', C', and D' are determined using the least squares based on the HURDAT database. The obtained results with the proposed formula ($A' = 34.5770\, m/s$; $B' = 80.4092\, m/s$; $C' = 0.7102$; $D' = 5.0868$; and $T_0' = 28°C$) are illustrated in Fig. 1.

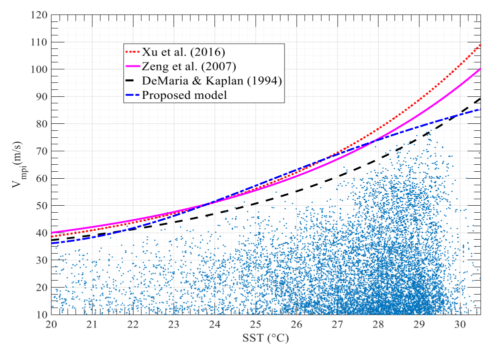

Fig. 1. V_{mpi} as a function of SST based on all tropical cyclones in the North Atlantic basin

The wind field model is another important component in the risk analysis framework. In this study, a height-resolving analytical model is utilized to rapidly simulate the wind field inside the hurricane boundary layer. The height-dependent analytical wind model was obtained based on the decomposition method where the wind speed is decomposed into a gradient and frictional wind components. While the frictional wind were obtained using the boundary layer model of Snaiki and Wu (2017a, b), the gradient wind model was enhanced in this study to integrate the effects of changing climate on the wind field.

The pioneering work of Emanuel (1986) suggests that the moist entropy s_m and the angular momentum M are related through the following relationship:

$$-r^2 \frac{\partial s_m}{\partial r} \Delta T = \frac{1}{2} \frac{\partial M^2}{\partial r} \tag{6}$$

where r = radius from the storm center; $\Delta T = T_{TBL} - T_0$; T_{TBL} = temperature at the top of the boundary layer; and T_0 = outflow temperature. Furthermore, the radial variation of the moist entropy proposed by Wang et al. (2015) is employed in this study leading to the following expression:

$$s_m(r) = \Delta s_m \exp\left({-r^2}/{2\lambda^2} \right) + s_{env} \tag{7}$$

where s_{env} = moist entropy in the ambient air; Δs_m = moist entropy deficit; and λ = horizontal width of the moist entropy. Combining Eqs. (6) and (7) leads to (Wang et al. 2015):

$$M(r) = \mu \sqrt{2\lambda^2 (1-\varepsilon) - r^2 \varepsilon} \tag{8}$$

where $\mu = \sqrt{2\Delta T \Delta s_m}$; and $\varepsilon = \exp\left(-r^2 / 2\lambda^2 \right)$. On the other hand, the angular momentum is given by definition as $M(r) = rV + \frac{1}{2} fr^2$ in which V is the tangential wind component, leading to:

$$V = \frac{\mu}{r} \sqrt{2\lambda^2 (1-\varepsilon) - r^2 \varepsilon} - \frac{fr}{2} \tag{9}$$

Furthermore, the moist entropy deficit can be obtained based on Emanuel's theory in which the tropical cyclone can be regarded as a Carnot heat engine:

$$\Delta s_m = -\frac{R \ln\left(p_c / p_0 \right)}{\varepsilon_{effi}} \tag{10}$$

where R = ideal gas constant; p_c = hurricane central pressure; p_0 = environmental pressure; and ε_{effi} = thermodynamic efficiency of the Carnot cycle expressed as $\varepsilon_{effi} = \frac{T_s - T_0}{T_s}$ where T_s is the sea surface temperature. Hence the parameter μ can be expressed as $\mu = \sqrt{2\Delta TR \ln\left(p_0 / p_c \right) / \varepsilon_{effi}}$. As a result, the gradient wind is given as:

$$V_{gr} = \sqrt{2\left(2\lambda^2 \left[1-\varepsilon \right] - r^2 \varepsilon \right) \Delta TR \ln\left(p_0 / p_c \right) / \left(r^2 \varepsilon_{effi} \right)} - \frac{fr}{2} \tag{11}$$

In order to determine the gradient wind speed, the horizontal width of the moist entropy λ need to be specified. To this end, the derivative of the gradient wind with respect to radial coordinate at the radius of maximum winds r_{m} is set to zero, leading to the following expression:

$$\lambda = \sqrt{\frac{-f}{4A} \frac{r_{\mathrm{m}}^3}{(1-\varepsilon_m)} \sqrt{\frac{2\lambda^2}{r_{\mathrm{m}}^2}(1-\varepsilon_m) - \varepsilon_m} + \frac{2\varepsilon_m r_{\mathrm{m}}^2}{4(1-\varepsilon_m)} + \frac{\varepsilon_m r_{\mathrm{m}}^4}{4\lambda^2 (1-\varepsilon_m)}} \tag{12}$$

where $\varepsilon_m = \exp\left[-r_{\mathrm{m}}^2 / 2\lambda^2 \right]$; and $A = \sqrt{2\Delta TR \ln\left(p_0 / p_c \right) / \varepsilon_{effi}}$. According to Eq. (12), λ need to be determined based on the iteration process.

3. Simulation Results

3.1. Hurricane Intensity and Frequency

In this study the RCP 8.5 scenario was used for the risk assessment simulation, where a total of 10,000 years of tropical cyclone events have been generated. The comparison of the current and future climate scenario was conducted and the results are illustrated in Fig. 2.

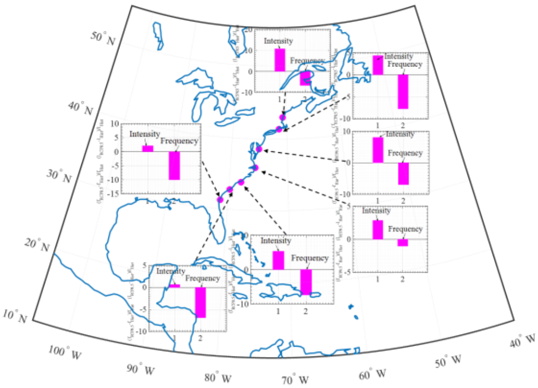

Fig. 2. Hurricane Intensity and Frequency

Seven locations along the US east coast, where a substantial increase in the sea surface temperature was noticed, were selected. As shown in the figure, an increase in the hurricane intensity was highlighted. This observation is expected since the SST will increase substantially based on RCP 8.5 scenario. On the other hand, a decrease in the hurricane frequency was noticed which can be attributed to the increase in the environmental wind shear following the RCP 8.5 simulation.

3.2. Simulation of Hurricane Boundary Layer Wind and Rain

The hurricane size represented by R_{max} is an important factor in the risk analysis framework. Since it significantly affects the likelihood of a given site of experiencing strong winds (Vickery et al. 2009). Therefore, the joint annual exceedance probability of wind speed and hurricane size (in terms of R_{max}) was determined in this study. An example is illustrated in Fig. 3 for the point located at (33.27°N, -79.17°W).

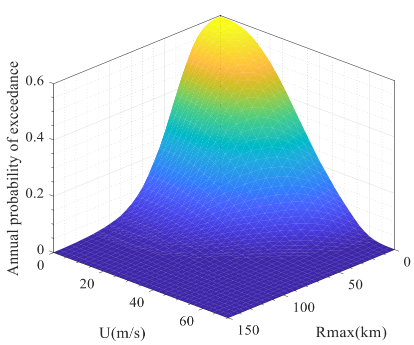

Fig. 3. Joint annual exceedance probability of wind speed and hurricane size

Similarly, the joint annual exceedance probability of wind speed and rain rate (Snaiki and Wu 2018) was determined for the same selected point. The results are illustrated in Fig. 4 which underline high values of the wind speeds and rain rates.

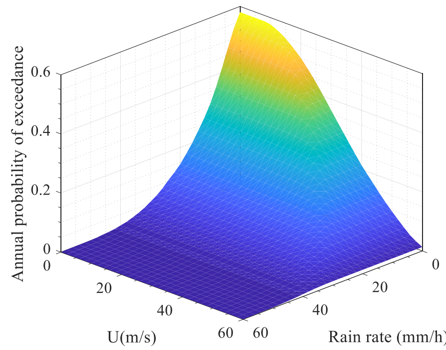

Fig. 4. Joint annual exceedance probability of wind speed and rain rate

Typically the hazard level is assessed based on the annual exceedance probability, then analyzed in terms of the mean recurrence interval (MRI) or the return period. Hence, the MRI was further evaluated. The MRI distribution of the wind speed at the selected point (33.27°N, -79.17°W) was constructed and is depicted in a logarithmic scale in Fig. 5.

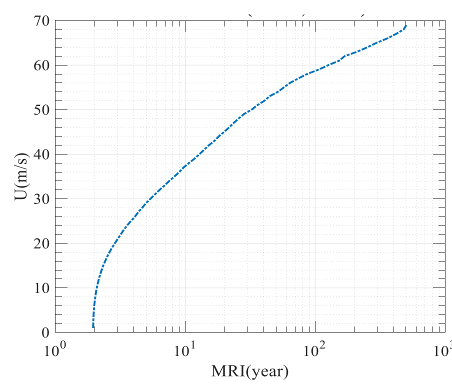

Fig. 5. MRI distribution of wind speed

Based on the obtained results, the difference between the simulated design wind speed based on the climate scenario RCP 8.5 and its corresponding one from ASCE 7 were compared. The increases in the design wind speed due to changing climate was noted for various MRIs. More specifically, an expected increase of 10.10 % for MRI=10, 14.92 % for MRI=25, 12.50 %

for MRI=50 and 11.00% for MRI=100 is obtained.

4. Concluding Remarks

An improved methodology for risk assessment of tropical cyclones under climate change was proposed in this study. First, a physically-based intensity model was developed which agrees with the general form of the state-of-the-art forecast model of DeMaria (2009). A newly-derived empirical formula of maximum potential intensity was also proposed to consider the flattening phenomenon of the maximum potential intensity in terms of SST. In addition, the gradient wind model was enhanced to integrate the contributions of several environmental factors. Based on the RCP 8.5 climate change scenario, a total of 10,000 years of tropical cyclone events have been generated. The simulations results indicate a significant increase in the wind speed and rain rate with a decrease in the tropical cyclone frequency.

5. Acknowledgements

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