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A physics-based tropical cyclone model for Western North Pacific Basin

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SUMMARY:
A physics-based tropical cyclone model consisting of a Poisson regression genesis model, a Beta and Advection Model (BAM) stochastic track model, and a fast intensity simulator is established in this paper. It performs well at representing the temporal and spatial distributions of the geneses, the moving patterns of the tracks, and the development of the intensity of the tropical cyclones across the Western North Pacific basin. Compared to traditional pure statistical models, this model is driven by a group of thermodynamical and climatological variables, enabling it to improve the reliability of the risk analysis results under climate change scenarios. This model can also be integrated with other flood or rainfall models for regional hazard hindcast or projection analysis.

Keywords: Tropical cyclones, Physics-based model, Natural hazards

1. INTRODUCTION

Tropical Cyclones (TCs) are one of the most devastating natural hazards all around the world, resulting in significant death tolls and substantial economic losses every year. The Western North Pacific (WNP) basin is most frequently attacked by TCs during the past decades. Therefore, it is imperative to build a reliable numerical tropical cyclone model for basin-specific risk assessment. Traditionally, the tropical cyclone models are established using pure-statistical methods based on limited historical records to enlarge the cyclones data repository. However, these models can only generate synthetic storms with the same temporal and spatial probability distributions as historical ones. With global warming, the statistical models will be deficient if new climatology appears in the future. This work aims to find a physics-based tropical cyclone model capable of simulating the whole process of TCs while being adaptive to climate change.

2. DATA SOURCE

The best track dataset used in this study was provided by Hong Kong Observatory (HKO). To ensure data accuracy, only track data after the 1970s, i.e., post-satellite era, are used in this work. All climate and weather data are extracted from ERA5, the fifth generation European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis datasets with a resolution of 0.25°×0.25°. The ocean depth is computed from the bathymetry dataset provide by General Bathymetric Chart of the Oceans (GEBCO).

3. PHYSICS-BASED MODEL AND VALIDATION

The physics-based TC model comprises three parts, which are introduced in detail below. The spatial resolution of the mesh grid is defined as 2°×2°, which is tested with enough accuracy and computational efficiency.

3.1. Genesis

An effective way to estimate the temporal and spatial distributions of the genesis points is to resort a Poisson regression model based on several key environmental elements (Gray, 1977, Tippett et al., 2011). The expected monthly mean number of the genesis points in each grid cell μ is estimated by:

$$ln\mu = w_{\eta}x_{\eta} + w_{sst}x_{sst} + w_h x_h + w_s x_s + w_f x_f + b = \boldsymbol{w}^T\boldsymbol{x} + b \quad (1)$$

where x_{η}, x_{sst}, x_h, x_s are the monthly mean of the relative vorticity at 850 hPa, the sea surface temperature, the relative humidity at 600 hPa, and the vertical shear of 850-250 hPa respectively, f is the Coriolis parameter, w_x is the weight of the corresponding variable x, b is the intercept term.

The spatial distribution density of the genesis points of historical data and the genesis model are shown in Fig. 1 and Fig. 2, respectively. Overall, the Poisson regression genesis model reproduces the two kernels of the spatial distribution of the genesis points over the 50-year period while underestimating the maximum number of the geneses near the kernels. Based on the expected number of genesis points, 100 realizations are conducted to initialize the synthetic storms. The seasonal distributions of the historical and simulated geneses of the TCs are presented in Fig. 3. Basically, the historical means fall into the range of the estimated number of the genesis points.

3.2. Track

After initialized by the genesis model, the TCs will then move along a track integrated from a Beta and Advection Model (BAM) (Emanuel et al., 2006, Hong and Li 2021). The track velocity can be written as the vector summation of the steering flow and the beta drift:

$$\boldsymbol{U}_{track} = \boldsymbol{U}_{str} + \boldsymbol{U}_{\beta} = [\alpha\boldsymbol{U}_{850} + (1-\alpha)\boldsymbol{U}_{250}] + \boldsymbol{U}_{\beta} \quad (2)$$

where $\boldsymbol{U}_{track}$ is the track velocity, $\boldsymbol{U}_{str}$ is the steering flow, $\boldsymbol{U}_{\beta}$ is the beta drift, $\boldsymbol{U}_{850}$ is the monthly mean wind speed at 850 hPa level, $\boldsymbol{U}_{250}$ is the monthly mean wind speed at 250 hPa level, α is the coefficient of the corresponding wind speed component.

The components of $\boldsymbol{U}_{850}$ and $\boldsymbol{U}_{250}$ are the function of the time and space of the track, and thus can be decomposed into two parts with one representing the mean and the other representing the covariance of the wind. We randomly select 50 tracks from the historical dataset and another 50 from the simulated dataset, as shown in Figs. 4 and 5. Generally, the BAM reproduces the motion patterns of the historical records that the tracks first move towards northwest and then turn northeast at high latitudes. However, the tracks generated by the BAM show more randomness than the historical ones.

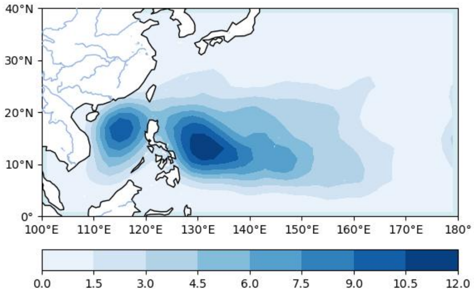

Figure 1. Historical spatial density of genesis points

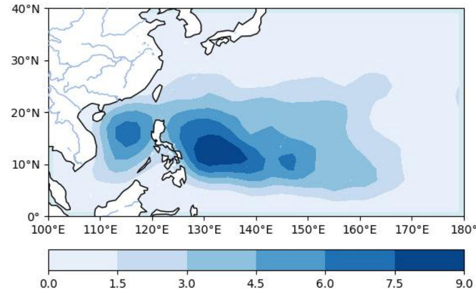

Figure 2. Predicted spatial density of genesis points

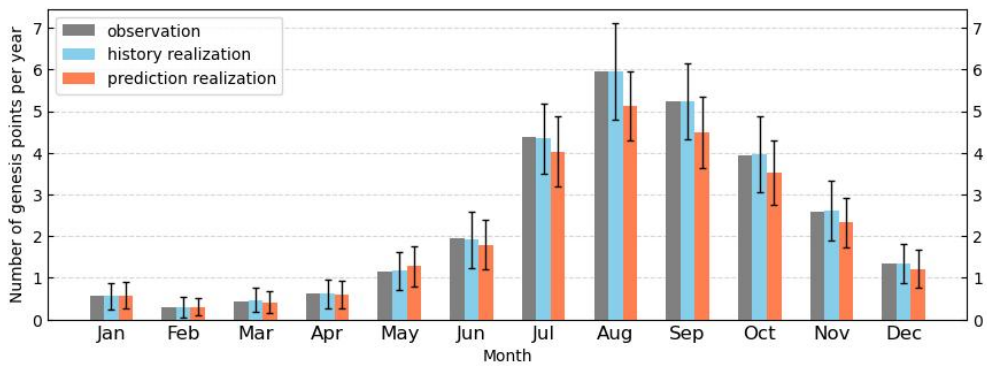

Figure 3. Seasonality of the number of genesis points

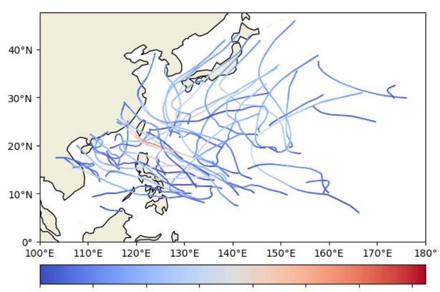

Figure 4. Fifty historical tracks and intensity (kt)

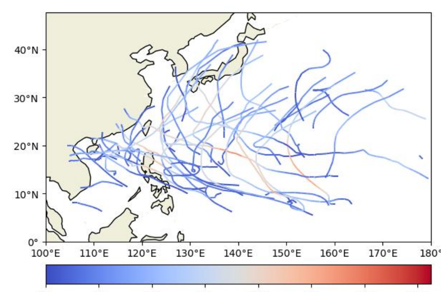

Figure 5. Fifty simulated tracks and intensity (kt)

3.3. Intensity

The fast intensity simulator takes into consideration the energy transition from wind shear and ocean to the TCs (Emanuel, 2017). It consists of two coupled ordinary differential equations:

$$\frac{dV}{dt} = \frac{1}{2}\frac{C_D}{h}\left[\alpha\beta V_p^2 m^3 - (1-\gamma m^3)V^2\right] \quad (3)$$

$$\frac{dm}{dt} = \frac{1}{2}\frac{C_D}{h}\left[(1-m)V - 2.2Sm\right] \quad (4)$$

where V is the cyclone intensity, m is the inner core saturation index, V_p is the potential intensity, S is the wind shear between 850 and 250 hPa levels, C_D is the surface drag coefficient, h is the boundary layer hight, α is the ocean interaction parameter, β and γ are coefficients of energy exchange.

Fig. 6 plots the trajectory of typhoon Mangkhut in 2018, and Fig.7 shows the historical and simulated intensity of this cyclone during its lifetime. The simulator successfully captures the increasing phase and the extreme value of the intensity, while the simulated intensity is little smaller than the recorded intensity during the decreasing phase. In the present simulation, there is a re-intensify phase after the track travels across the land and goes back on ocean again.

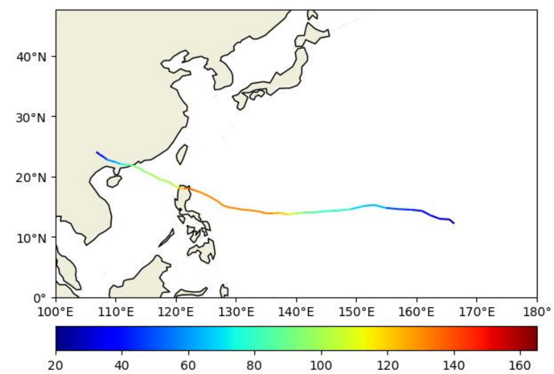

Figure 6. Track and intensity of typhoon Mangkhut

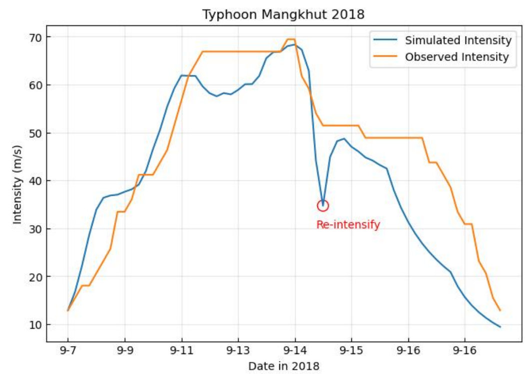

Figure 7. Historical and simulated intensity of typhoon Mangkhut

4. CONCLUSION AND DISCUSSION

A physics-based tropical cyclone model in the WNP basin was established, which consists of a Poisson regression genesis model, a BAM track model, and a fast intensity simulator. The results showed that this model performed well in reproducing the temporal and spatial distributions of the genesis points, the moving patterns of the tracks, and the evolutions of the intensity. The model was driven by a group of thermodynamical and climatological variables, enabling it to adapt the climate change scenarios with contrary to the traditional statistical models. It is also useful for the basin scale wind-induced risk analysis and assessments.

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