Journal of Wind Engineering & Industrial Aerodynamics 172 (2018) 325–340

Contents lists available at ScienceDirect

Journal of Wind Engineering & Industrial Aerodynamics

journal homepage: www.elsevier.com/locate/jweia

A statistical dynamics track model of tropical cyclones for assessing typhoon wind hazard in the coast of southeast China

Yu Chen, Zhongdong Duan *

Department of Civil and Environmental Engineering, Harbin Institute of Technology, Shenzhen Graduate School, Shenzhen, China

ARTICLE INFO

Keywords:
Track model
Statistical dynamics
Typhoon wind hazard
Monte Carlo method

ABSTRACT

An improved full track model for tropical cyclones (TCs) based on statistical dynamics method is developed to estimate typhoon wind hazard in the coast of southeast China. The track model includes genesis model, movement model, and intensity model. The genesis model is established based upon an improved kernel probability density function with the biased cross-validation bandwidth. The movement model is developed based on the Beta and Advection Model (BAM). The intensity model consists of an auto-regression ocean intensity model and an inland decay model using the nearest neighbor method. Using the historical environment data, 1000 years TC tracks are simulated by the improved model and compared with features of the historical tracks in the western North Pacific (WNP) basin, the results verify that the developed model performs well. Moreover, typhoon wind hazard in the coastal areas of southeast China is estimated by the improved track model combined with a parametric wind field model. Compared with the current Chinese design code, the relative differences between estimated return period velocities and those recommended in design code are less than 13.4%. The developed model enables analyzing typhoon hazard in the context of climate change, which is our future task.

1. Introduction

Tropical cyclone (TC) is a devastating natural disaster which produces strong wind, storm surge, and heavy rainfall. It accounts for the majority of natural catastrophic losses in the developed world and, next to floods, is the leading cause of death and injury among natural disasters affecting developing countries (Emanuel et al., 2008). The western North Pacific (WNP) basin is the area most affected by TCs, thus the wind resistance design and regional insurance industry need to assess the risk of TCs in order to reduce the losses caused by TCs. Nevertheless, the historical TC records are limited and the quality of historical records cannot be guaranteed due to the loss of records and inaccuracy of observation apparatuses. Consequently, it's of interest to develop a method for extending TC data.

A traditional method of expanding TC dataset is the single site probabilistic model proposed by Russell (1971), followed by the development of Tryggvason et al. (1976), Batts et al. (1980), Georgiou (1985), Vickery and Twisdale (1995). The basic idea of this method is to form a region by expanding a defined radius from a single site (radius is generally 200–300 km), and then analyzes the statistical characteristics of historical TCs which pass through this region. According to the statistical features, a large number of TCs can be synthesized through the Monte Carlo method to expand typhoon regional dataset for wind hazard analyses. This method is mature to the small areas while cumbersome to perform for hazard analyses in large areas, such as coastal multi-cities, railways, and power grid systems. Moreover, the single site model is deficient in the high latitude regions with insufficient historical records.

To estimate the risk of TCs in a larger area, an empirical full track model utilizing statistical characteristics of historical track records directly is proposed to synthesize a large number of full tracks over the whole ocean (Vickery et al., 2000; James and Mason, 2005; Hall and Jewson, 2007). The empirical track model can be divided into three parts: genesis model, movement model, and intensity model. As the synthetic track model segments the life of TCs and the physical significance of each segment is clear, it is possible to assess TC hazard in a wider area. Likewise, this empirical track model relies too much on historical track data, thus it performs well in TC-rich areas, but underperforms in regions where historical records are rare. Recently, a track model based on statistical dynamics method has been proposed to overcome this shortcoming (Emanuel et al., 2006; Vickery et al., 2010). Unlike the empirical track model, the statistical dynamics relationship of TC motion is developed rather than simply statistical characteristics of historical tracks, and then combined with the environment data which cover the whole world for synthesizing full tracks. Therefore the synthetic full track

* Corresponding author.
E-mail address: duanzd@hit.edu.cn (Z. Duan).

https://doi.org/10.1016/j.jweia.2017.11.014
Received 13 May 2017; Received in revised form 15 November 2017; Accepted 15 November 2017

model can be applied to historical records scarce areas where we have an interest in assessing TC risk. In addition, since the statistical dynamics relationship of each part in the model is well defined, the statistical dynamics track model can be combined with variable climatic environmental data to assess TC activities under the context of climate change (Colbert et al., 2013; Emanuel, 2013).

This paper further improves the genesis and movement model and establishes a new intensity regression model for estimating typhoon wind hazard in the coast of southeast China. For the genesis positions, the genesis model is improved based upon a revised kernel probability density function with the biased cross-validation best bandwidth to avoid the genesis probability for lands. For the movements, the 6-h translational velocity is divided into steering velocity and beta-drift velocity; the former is defined as annulus pressure-weighted mean wind velocity and the latter is estimated by regional mean beta-drift velocity. Moreover, a lag-two autoregressive method based on maximum wind speed is used to establish the ocean intensity model with new regression variables selected by stepwise regression method. The inland decay model is fitted as a decreasing function through selecting the k nearest landing positions. A large number of full tracks are simulated using the historical environment data and compared with features of the historical tracks in the WNP basin. Finally, the improved statistical dynamics track model combined with a parametric wind field model is given to estimate typhoon wind risk in the coastal areas of the southeast China.

2. Data

The data used in this improved track model are shown as following. The Joint Typhoon Warning Center (JTWC) best-track dataset is used to represent the observed TC events, which include 1951 historical TCs for a total of 70 years from 1945 to 2014. The target area of JTWC is the WNP basin (including the South China Sea), the statistical data include every 6 h of center location, maximum sustained wind speed, central minimum pressure, maximum wind speed radius, and radius of specified wind intensity. It is noteworthy that JTWC started providing data to the last three parameters since 2001. It is assumed that inland cannot generate TCs, so all records whose initial positions locate in the inland are deleted from the dataset.

Atmospheric and oceanic environment parameters include monthly mean sea surface temperature, 4 times daily environmental wind velocity, monthly mean atmospheric ambient temperature, and monthly mean atmospheric ambient specific humidity. In these parameters, except that the sea surface temperature is obtained from the COBE-SST dataset which provides a resolution of 1° in both latitude and longitude (Ishii et al., 2005), the rest of the parameters are from the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis dataset which provides a resolution of 2.5° in both directions (Kalnay et al., 1996). The environmental wind velocity and atmospheric ambient temperature in the NCEP-NCAR reanalysis dataset have 17 vertical levels from 1000 hpa to 10 hpa while the specific humidity is only available for the lowest 8 levels. Therefore, the specific humidity of the rest levels is assumed to zero due to extremely small value. All environment parameters are interpolated into TC center locations and time in simulation process.

3. Statistical dynamics track model development

The basic simulation procedures for synthesizing full tracks are similar to Vickery et al. (2000). First of all, the genesis model generates annual occurrence numbers and initial positions (including latitude, longitude and time). Secondly, the movement model simulates the translational speeds to propagate TCs to the next positions along minimum arc between two positions on the earth in 6 h. The subsequent locations are then continually updated with similar procedures. Meanwhile, intensity model estimates the TC intensity at each position. Finally, the full track model is terminated when the simulated intensity is lower than tropical depression. Although the improved statistical dynamics model inherits the idea of synthetic full track, it distinguishes it from Vickery's empirical full track model. This model is improved in the genesis, track and intensity simulation of TCs based on a more solid meteorological basis. The following subsections focus on the improvements for full track model in detail.

3.1. Genesis model

Unlike the traditional method which extracts directly historical genesis positions and performs parameter estimation for annual genesis numbers (Vickery et al., 2000; Li and Hong, 2016), here, a nonparametric method is adopted to simulate annual genesis numbers and initial positions. The nonparametric method doesn't require a prior distribution hypothesis, relying entirely on the training data. Therefore, this method is simple and intuitive, and easy to understand. As a matter of fact, Terrell and Scott (1992) have rigorously demonstrated that almost all nonparametric methods are asymptotic kernel density methods. The kernel probability density basic functions are as follows.

$$f(\boldsymbol{x}) = \frac{1}{nh}\sum_{i=1}^{n} K\left(\frac{\boldsymbol{x}-\boldsymbol{x}_i}{h}\right) \tag{1}$$

where $\boldsymbol{x}$ is the vector to be estimated; $\boldsymbol{x}_i$ is the ith sample vector; h is the bandwidth; n is the sample size; $K(\bullet)$ is the kernel density estimator, and the Gaussian kernel density function is used in this paper. First, Eq. (1) is employed to estimate the probability density of annual occurrence number in the WNP basin. Choosing an appropriate bandwidth is a key to accurately estimate the kernel probability density, because too large or too small bandwidth will cause the estimated probability density too smooth or too rough respectively.

Here, a one-dimensional Gaussian kernel biased cross-validation method proposed by Scott (2012) is used to calculate the optimal bandwidth of the annual occurrence number probability density as shown below.

$$BCV(h) = \frac{1}{2nh\sqrt{\pi}} + \frac{1}{64n^2h\sqrt{n}}\sum_{i<j}\left(\Delta_{ij}^4 - 12\Delta_{ij}^2 + 12\right)\exp\left(-\Delta_{ij}^2/4\right) \tag{2}$$

where $\Delta_{ij}=(x_i\text{-}x_j)/h$, x_i and x_j represent the ith and jth annual sample number of TCs respectively. Using the JTWC 70-year best-track dataset, the optimal bandwidth h is obtained by minimizing Eq. (2). By substituting the optimal bandwidth into Eq. (3), the probability density of annual occurrence number can be estimated easily.

$$\hat{f}(x) = \frac{1}{70h}\sum_{i=1}^{70}\frac{1}{\sqrt{2\pi}}\exp\left(-\frac{(x-x_i)^2}{2h^2}\right) \tag{3}$$

Since the annual occurrence number of TCs is discrete, it is necessary to integrate the estimated probability density to obtain the discrete probability of the annual number. Finally, a large number of annual occurrence numbers of TCs are simulated by Monte Carlo method. In order to further inspect whether the distribution of simulated annual occurrence number is consistent with historical distribution, two nonparametric tests, Kolmogorov-Smirnov test and rank sum test, are used to verify the consistency of distribution with a significant level of 0.05. The results of both two nonparametric tests demonstrate the consistency of distribution.

Likewise a three-dimensional kernel density function is used to estimate the space-time probability density of TC genesis position. The space-time of TC genesis position is composed of three dimensions: latitude, longitude and time. Since the simulated TC generation positions are periodic in time dimension with a period 0–366 days, it is necessary to extend the historical generation positions to 3 times in the time dimension for considering the impact the last year and next year genesis