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Tropical Cyclone Wind Hazard Assessment for Southeast Part of Coastal Region of China

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A thesis submitted in partial fulfillment of the requirements for the degree in Doctor of Philosophy

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TROPICAL CYCLONE WIND HAZARD ASSESSMENT FOR SOUTHEAST PART OF COASTAL REGION OF CHINA

(Thesis format: Integrated Article)

by

Sihan Li

Graduate Program in Engineering Science
Civil and Environmental Engineering

A thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy

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Abstract

Tropical cyclone (TC) or typhoon wind hazard and risk are significant for China. The return period value of the maximum typhoon wind speed is used to characterize the typhoon wind hazard and assign wind load in building design code. Since the historical surface observations of typhoon wind speed are often scarce and of short period, the typhoon wind hazard assessment is often carried out using the wind field model and TC track model. For a few major cities in the coastal region of mainland China, simple or approximated wind field models and a circular subregion method (CSM) have been used to assess the typhoon wind hazard in different studies. However, there are differences among the values given by these studies and by the Chinese building design code. Moreover, there is a lack of a TC full track model simulating the TC from genesis to lysis developed for China. A TC full track model and a planetary wind field model (PBL) have been applied to assess the hurricane wind hazard for the U.S. and used to update the U.S. design code. This study finds this PBL wind field model is approximated and the effect of such approximation on the estimated hurricane wind hazards needs to be investigated. By using the best track dataset given by HURDAT, the TC full track model and a simplified version are developed for the U.S. The performance of the simplified TC full track model is verified and found to be comparable with the full version. For assessing the typhoon wind hazard for China, the best track dataset released from China Meteorological Administration (CMA) is used. The PBL wind field model is used with the CSM to assess a few coastal cities of mainland China. The practice is extended to cover the whole region of the southeast part of mainland China to develop the contour maps of the typhoon wind hazards. By using the CMA best track dataset, a full track model is developed for the western North Pacific basin. This full track model is combined again with the PBL wind field model to assess the typhoon wind hazard for mainland China. The results obtained by using the full track model are compared to those estimated by using CSM, by using long term ground observations and tabulated in the Chinese building code.

Keywords

typhoon, tropical cyclone, wind hazard, simulation, wind field model, track model.
Co-Authorship Statement

The material presented in Chapter 2, 3, 4 and 5 of this thesis have been published or submitted for potential publication in peer-reviewed journals.

A version of Chapter 2 is published in the Journal of Structural Engineering coauthored by S.H. Li and H.P. Hong.

A version of Chapter 3 is published in the Natural Hazards coauthored by S.H. Li and H.P. Hong.

A version of Chapter 4 co-authored by H.P. Hong, S.H. Li and Z.D. Duan is submitted for potential publication.

A version of Chapter 5 co-authored by S.H. Li and H.P. Hong is submitted for potential publication.
Dedication

To Mei, Edwin, Larry,

my parents and my parents in-law
Acknowledgments

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## Nomenclature

### Chapter 1

- **P**: the pressure field
- **ρ**: the air density
- **Φ₀**: geopotential
- **f**: Coriolis parameter
- **ψ**: latitude
- **Ω**: the rotation of the Earth
- **r**: the radius from the center of the storm
- **vₜ**: gradient wind speed
- **Vₜₘₐₓ**: maximum gradient wind speed
- **K**: empirical constant
- **Δp**: central pressure difference
- **Rₘₐₓ**: radius of the maximum wind speed
- **V**: mean wind speed
- **uₖ**: translation velocity of storm
- **Vᵣ**: *T* year return period wind speed
- **B**: Holland *B* parameter
- **Pᵥ**: central pressure
\(c\) translation velocity of the storm

\(\alpha\) angle from translation direction of the storm

\(\kappa\) non-dimensional constant (Von Karman constant)

\(z_{10}\) 10 m height above the mean height of roughness length

\(d\) zero-plane displacement

\(z_0\) roughness length

\(C_D\) surface drag coefficient

**Chapter 2**

\(\vec{u}_s\) wind velocity vector relative to the moving center of the vortex

\(\vec{u}_c\) storm translation velocity vector

\(\vec{u}_g\) wind velocity vector resulting from the large-scale pressure field

\(v_T\) \(T\) year return period wind speed

\(f\) Coriolis parameter

\(\psi\) latitude

\(\Omega\) rotation of the Earth

\(\hat{k}\) unit vector in the vertical direction

\(\rho\) density of air

\(p_c\) axisymmetric pressure field

\(K_H\) horizontal eddy viscosity coefficient
$C_D$  surface drag coefficient

$h$  depth of the planetary boundary layer

$p$  pressure field

$p_g$  large-scale pressure field

$u$  component of $\bar{u}$ in the $x$-direction

$v$  component of $\bar{u}$ in the $y$-direction

$V_T$  $T$ year return period wind speed

$A_u$  component of advection term in the $x$-direction

$A_v$  component of advection term in the $y$-direction

$F_u$  component of Coriolis term in the $x$-direction

$F_v$  component of Coriolis term in the $y$-direction

$P_u$  component of pressure gradient term in the $x$-direction

$P_v$  component of pressure gradient term in the $y$-direction

$E_u$  component of viscous force term in the $x$-direction

$E_v$  component of viscous force term in the $y$-direction

$D_u$  component of drag term in the $x$-direction

$D_v$  component of drag term in the $y$-direction

$\Delta x$  grid point spacing and

$\kappa$  non-dimensional constant (Von Karman constant)
$C_{D\text{max}}$  maximum value of the surface drag coefficient

$V_{10}$  mean wind speed at 10 m height

$a_i$  coefficient of the regression model regarding to storm translation velocity

$b_i$  coefficient of the regression model regarding to the storm heading

$d_i$  coefficient of the regression model regarding to the relative intensity

$\psi$  latitude

$\lambda$  longitude

$c_i$  translation velocity of the storm at $i$th step

$\theta_i$  storm heading at $i$th step

$I_i$  relative intensity at $i$th step

$T_s$  sea surface temperature

$\epsilon_c$  zero mean random error terms for regression model regarding to translation velocity

$\epsilon_{\theta}$  zero mean random error terms for regression model regarding to storm heading

$\epsilon_I$  zero mean random error terms for regression model regarding to relative intensity

$p_{da}$  ambient pressure

$p_{dc}$  minimum sustainable central dry partial pressures

$e_s$  saturation vapour pressure

VII
Chapter 3

$\mu$ mean of random variable

$\sigma$ standard deviation of random variable

$a_i$ probabilistic model parameter

$\mu_i$ probabilistic model parameter

$\sigma_i$ probabilistic model parameter

$k$ probabilistic model parameter

$\Delta p$ central pressure difference

$D_{\text{min}}$ minimum approaching distance

$\vec{u}_s$ wind velocity vector relative to the moving center of the vortex

$\vec{u}_c$ storm translation velocity vector

$\vec{u}_g$ wind velocity vector resulting from the large-scale pressure field

$f$ Coriolis parameter

$\psi$ latitude

$\Omega$ rotation of the Earth

$\hat{k}$ unit vector in the vertical direction

$\rho$ density of air

$p_c$ axisymmetric pressure field
$K_H$ horizontal eddy viscosity coefficient

$C_D$ surface drag coefficient

$h$ depth of the planetary boundary layer

$p$ pressure field

$c_0$ model coefficient

$c_1$ model coefficient

$\varepsilon_{\ln R_{\text{max}}}$ error term of the $\ln R_{\text{max}}$ model

$d_0$ model coefficient

$d_1$ model coefficient

$\varepsilon_{\ln B}$ zero mean normal variate

$R_{\text{max}}$ radius of the maximum wind speed

$B$ Holland parameter $B$

$\Delta p_0$ central pressure difference at landfall

$a$ filling rate

$a_0$ coefficient for filling rate model

$a_1$ coefficient for filling rate model

$\varepsilon_a$ error term of the filling rate model

$V_A$ annual maximum 10-min mean wind speed at 10 m height caused by typhoons

$v_T$ $T$ year return period wind speed
Chapter 4

$\bar{u}_s$  wind velocity vector relative to the moving center of the vortex

$\bar{u}_c$  storm translation velocity vector

$\bar{u}_g$  wind velocity vector resulting from the large-scale pressure field

$v_T$  $T$ year return period wind speed

$f$  Coriolis parameter

$\psi$  latitude

$\Omega$  rotation of the Earth

$\hat{k}$  unit vector in the vertical direction

$\rho$  density of air

$p_c$  axisymmetric pressure field

$K_H$  horizontal eddy viscosity coefficient

$C_D$  surface drag coefficient

$h$  depth of the planetary boundary layer

$p$  pressure field

$p_g$  large-scale pressure field

$R_{\text{max}}$  radius of the maximum wind speed

$B$  Holland parameter $B$

$\Delta p_0$  central pressure difference at the time of landfall
\( a \) filling rate

\( a_0 \) coefficient of filling rate model

\( a_1 \) coefficient of filling rate model

\( \varepsilon_a \) error term of the filling rate model

\( \sigma_{ea} \) standard deviation of the filling rate model

\( \Delta p(t_1 + \tau) \) central pressure difference at time \( t_1 \) since making landfall

\( \Delta p_L(t_1) \) central pressure difference at time \( t_1 \) since the intersection with the circle for the storm that has already made landfall

\( \Delta p_{L0} \) central pressure difference at the time of intersection

\( b_0 \) coefficient for filling rate model

\( b_1 \) coefficient for filling rate model

\( \varepsilon_b \) error term of the filling rate model

\( \sigma_{eb} \) standard deviation of the filling rate model

\( \Delta p \) central pressure difference

\( \varepsilon_B \) error term of the \( B \) model

\( \sigma_B \) standard deviation of the \( B \) model

**Chapter 5**

\( a_i \) coefficient of the regression model regarding to translation velocity of the storm

\( b_i \) coefficient of the regression model regarding to the storm heading
\( d_i \) coefficient of the regression model regarding to the relative intensity

\( \psi \) latitude

\( \lambda \) longitude

\( c_i \) translation velocity of the storm at \( i \)th step

\( \theta_i \) storm heading at \( i \)th step

\( I_i \) relative intensity at \( i \)th step

\( T_s \) sea surface temperature

\( \varepsilon_c \) zero mean random error terms for regression model regarding to translation velocity

\( \varepsilon_\theta \) zero mean random error terms for regression model regarding to storm heading

\( \varepsilon_I \) zero mean random error terms for regression model regarding to relative intensity

\( p_{da} \) ambient pressure

\( p_{dc} \) minimum sustainable central dry partial pressures

\( e_s \) saturation vapour pressure

\( \Delta p(t) \) central pressure difference at time \( t \) since the TC making landfall

\( \Delta p_0 \) central pressure difference at the time of landfall

\( v_T \) \( T \) year return period wind speed

\( a \) filling rate
\( a_0 \) coefficient of filling rate model

\( a_1 \) coefficient of filling rate model

\( \varepsilon_{\text{ua}} \) error term of the filling rate model

\( \sigma_{\text{ua}} \) standard deviation of the filling rate model
Chapter 1

1 Introduction

According to the World Meteorological Organization (WMO) Disaster Risk Reduction Programme, various natural disasters caused loss of 1.94 million lives and 2.4 trillion US dollars of property damage (http://www.wmo.int/pages/prog/drr/index_en.html accessed on April, 2015). Among these disasters, storm and floods contributed 79% of the disasters and caused 55% fatalities and 86% of economic losses. Tropical cyclones (TCs) can cause strong winds, heavy rainfalls and storm surges. For Northern Hemisphere, a strong TC affecting the US is known as hurricane; it is known as typhoon in several Asian countries.

Many regions in Asia are exposed to the threat of the typhoon wind hazard and typhoon induced hazards, such as storm surge, flood due to the heavy rainfall and typhoon rainfall-induced landslides. Countries that face typhoon hazard suffer huge economic losses. For example, Typhoon Haiyan occurred in 2013 that is recognized as one of the most devastating typhoons ever recorded. Its highest recorded gust wind speed was about 315 km/h (Daniell et al. 2013). It caused more than 6000 deaths, 28689 injuries and 1061 missing persons in Philippine, where the economic loss caused by Haiyan was about $13 billion US dollars. The highest storm surge reached about 11 m (Mas et al. 2015). Storm surge induced by Typhoon Haiyan prompted organizations, including the WMO, to develop and update the hazard and risk map due to storm surge. To develop the storm surge hazard and risk map, typhoon wind hazard modeling is the first and essential step. While the intensity of Typhoon Haiyan decayed as it approached to Hainan province of China, it remained in the typhoon category and caused damage to power transmission line system and to agriculture. Around 2 million people were affected by this event and the economic loss was about 4.6 billion Chinese Yuan (i.e., RMB).

Besides of this recent devastating typhoon event, historically, on average, the annual economic loss due to TCs is about 28.7 billion RMB and casualties between year of 1983 and 2006 are about 472 (Zhang et al. 2009). Most of the losses and casualties are
distributed in provinces located in coastal regions of southeast part of China due to the higher wind hazards in this area.

A tropical cyclone system is a low pressure system that has a warm-core and originates over tropical or subtropical oceans. The minimum required sea surface temperature (SST) to form a tropical cyclone system is 26.5°C (Reynolds et al. 2007). However, once formed, it can sustain over lower SST. A tropical cyclone system has a well-defined center, around which the deep convection is organized and a closed surface wind circulation is developed. The horizontal wind circulation is counter-clockwise in North Hemisphere and clockwise in South Hemisphere. The center of the tropical cyclone known as the eye is characterized by light winds and clear sky. The eye is surrounded by the eye wall, which is a ring of dense cloud having the heaviest rain and strongest wind. A tropical cyclone extracts the heat energy from the ocean having high temperature and dissipates over land or colder oceans.

1.1 An overview of TC wind hazard assessment approach for engineering applications

Typically, the wind hazard can be estimated by using the surface wind observations at meteorology stations if the recorded wind is deemed sufficiently for statistical analysis. Often such records are lacking and reliable extreme value analysis of the annual maximum wind speed cannot be carried out. To overcome this, numerical simulation procedure and hurricane wind hazard models were developed for the assessment of the TC wind hazard. These models basically require two components: a hurricane wind field model and a hurricane track model, which will be discussed in more detail in the following sections.

Some earlier studies focused on the hurricane wind hazard evaluation can be found in Russell (1968, 1971). These studies used the gradient wind field model and statistics of the hurricane tracks that intersect with a segment of coastline near the site of interest. Probabilistic distributions are assigned to model the key parameters of the TC tracks near the site including the central pressure, translation velocity, heading and radius of the
maximum wind speed ($R_{\text{max}}$). The assignment is based on statistics of the historical tracks. Instead of considering segment of tracks that cross the coastline, Georgiou et al. (1983) and Georgiou (1985) considered the segment of tracks that are within a circular centered at the site. In addition, to estimate the wind speed near the surface, these studies used the solution of the gradient wind field model (at gradient height) but scaled the solution by a factor to estimate surface wind speed and to develop the hurricane wind hazard contour maps for the US. The scaling factor is evaluated based on the comparison of the gradient wind field and an approximate solution of a planetary boundary layer slab wind field model (Chow 1971; Shapiro 1983). The approach given by Georgiou (1985) is followed by others (Vickery and Twisdale, 1995a, 1995b) but with an updated filling rate model. Simulating the track segments within a circular sub-region is referred to as the circular sub-region method (CSM).

The use of simulated tracks from genesis to lysis (i.e., full track approach) was considered by Vickery et al. (2000b) to estimate the hurricane wind hazard. In such a case, the regressive model used to simulate the full tracks was developed based on historical best track dataset known as HURDAT (Jarvinen et al. 1984); the model with geographically varying coefficients predicts three key hurricane track parameters: the TC translation velocity, heading and relative intensity. The prediction of the relative intensity for the TCs after making landfall requires the application of a filling-rate model – a model describes the decay of the TC after the storm making landfall. In addition, Vickery and Wadhera (2008) and Vickery et al. (2009a) developed model parameters to define the boundary layer wind profile model and the model parameters such as Holland B (Holland 1980) and radius of the maximum wind speed ($R_{\text{max}}$) needed to define the wind field. The development of these model parameters were facilitated by the measurements from dropsonde, aircraft reconnaissance and reconstructed surface wind field based on observations.

There are other models and approaches considered by different researchers to estimate hurricane wind hazard for engineering applications. The general approaches adopted by these studies are similar. However, details in track and the wind field modeling differ. For
example, hurricane track models are also developed by Powell et al. (2005), James and Mason (2005), Emanuel et al. (2006), Hall and Jewson (2007). The TC track is modeled as a Markov process in Powell et al. (2005); the changes in the motions and intensity of TC are sampled using their probability distribution functions assessed based on historical best track dataset. In James and Mason (2005), an auto-regressive model was adopted to predict the change of the TC location and of the central pressure. One of the models proposed in Emanuel et al. (2006) is based on Markov chain whose probability of vector displacement change depends on position, season, and the previous 6-hour vector displacement. The model presented in Hall and Jewson (2007) assumes that the TCs in a location of the Atlantic tend to move in a similar manner; the motions of a hurricane over a 6 hour interval and along the latitude and longitude depend only on its present position; and that the probability distributions of the motion can be assessed using historical tracks. The mentioned full track models are developed to assess TC hazards for US, and it seems that the full track model applicable to western North Pacific basin, in particular, to assess TCs wind hazard for coastal region of China, is unavailable in the open literature.

Several studies focused on the estimation of TC wind hazard at sites located in coastal region of China (Ou et al. 2002; Xiao et al. 2011; Zhao et al. 2005). These studies used the CSM to estimate the TC wind hazard. However, different wind field models are used in these studies. In Ou et al. (2002) the gradient wind field model was used. Xiao et al. (2011) adopted the wind field model described in Cardone et al. (1992) and Thompson and Cardone (1996). Moreover, there are appreciable differences of the estimated return period values of the annual maximum TC wind speed among these studies. This is even the case when the estimated return period TC wind speeds are compared to those recommended in Chinese design code (GB-50009 2012). As the TC wind hazard is important for making the design code, it is critical to investigate reasons behind the observed discrepancy. In addition, it is noted that while the full track model is adopted for TC wind hazard assessment and updating the national building design code of the U.S. in ASCE-07 (ASCE 2010; Vickery et al.2009b, 2009c, 2010), this model has not been accessible in public domain.
1.2 Review of the wind field model used in the TC induced wind hazard assessment

Whether the CSM or the full track approach is employed for the TC wind hazard assessment, a wind field model is needed. The accuracy of the wind field model affects the adequacy of the estimated TC wind hazard. In general, the wind field model employed for engineering applications can be classified as gradient wind field model and planetary boundary layer (PBL) wind field model.

The governing equation of the gradient wind field model can be expressed by (Holton 2004)

\[ \frac{1}{\rho} \frac{\partial P}{\partial r} = \frac{\partial \Phi_0}{\partial r} = \frac{v_g^2}{r} + \frac{f v_g}{r} \]  

(1.1)

where \( v_g \) m/s is the gradient wind speed, \( P \) Pa is the pressure field, \( \rho \) kg/m\(^3\) is the air density, \( \Phi_0 \) m\(^2\)/s\(^2\) is the geopotential, \( f \) rad/s is Coriolis parameter equal to \( 2\Omega \sin \psi \) at latitude \( \psi \) (\(^\circ\)) in which \( \Omega \) rad/s represents the rotation of the Earth with magnitude \( 2\pi \) day and \( r \) m is the radius from the center of the storm.

Instead of directly solving the governing equation, an empirical equation was given in Russell (1968), Schwerdt et al. (1979) and Batts et al. (1980) and can be expressed as,

\[ V_{g_{\text{max}}} = K \sqrt{0.01\Delta p - 0.5 \times 10^{-3} f R_{\text{max}}} \]  

(1.2)

where \( K \) is an empirical constant varying between 6.93 to 6.97, \( \Delta p \) Pa is the central pressure difference and \( R_{\text{max}} \) m is the radius of the maximum wind speed ranging from 8,000 m to 100,000 m. Furthermore, an empirical relation is used to convert the modeled gradient maximum wind speed to surface maximum wind speed by using an empirical relation,

\[ V(z = 10, R_{\text{max}}) = 0.865 V_{g_{\text{max}}} + 0.5 u_c \]  

(1.3)
where \( u_c \) m/s is the translation velocity of the storm. This model is an axisymmetric model that cannot capture the asymmetric characteristics of the observed TC wind field. Moreover, the scaling factor (0.865) is a constant value and is higher than the mean value of the scaling factor calculated from the dropsonde data (Vickery et al. 2009b). Also, this model only uses the central pressure difference, and the horizontal pressure profile in a TC is not considered.

To improve the gradient wind field, a modified pressure profile was introduced by Holland (1980),

\[
P(r) = P_c + \Delta p \times \exp \left(- \left( \frac{R_{\text{max}}}{r} \right)^B \right)
\]  

where \( B \) in Eq. (1.3) is commonly referred to as Holland \( B \) parameter and is considered to range from 1 and 2.5, \( P(r) \) is the pressure field, \( P_c \) Pa is the central pressure, \( \Delta p \) Pa is the central pressure difference, and \( R_{\text{max}} \) and \( r \) are defined previously. Considering the pressure profile defined in Eq. (1.4), solution of the gradient wind field governed by Eq. (1.1) can be expressed as,

\[
V_g(r) = \left[ \left( \frac{R_{\text{max}}}{r} \right)^B \frac{B \Delta p}{\rho} \times \exp \left( - \left( \frac{R_{\text{max}}}{r} \right)^B \right) \left( \frac{rf}{2} \right)^{\frac{1}{2}} \right] - \frac{rf}{2}
\]  

By considering the curvature effect, an adapted gradient wind field model was given by Georgiou et al. (1983), which is also used in Lee and Rosowsky (2007). The model can be expressed by,

\[
V_g(r) = \left[ \left( \frac{R_{\text{max}}}{r} \right)^B \frac{B \Delta p}{\rho} \times \exp \left( - \left( \frac{R_{\text{max}}}{r} \right)^B \right) \left( \frac{c \sin \alpha - rf}{2} \right)^{\frac{1}{2}} \right] - \frac{c \sin \alpha - rf}{2}
\]  

where \( c \) m/s is the translation velocity of the storm and \( \alpha \) is angle from translation direction, which is defined to be clockwise positive. Although the gradient wind field has
an analytical solution and can be easily integrated into the wind hazard assessment, the neglecting of the surface friction, a key merit of the TC boundary layer, makes this model less adequate in describing the physical process of the wind field within the boundary layer and inadequate in modeling the asymmetry feature of the real observed wind field.

To consider the surface friction effect, a planetary boundary layer (PBL) wind field model was introduced by Chow (1971), which represents a vertically averaged TC wind field. The governing equation and detailed discussion on the solving process are to be presented in Chapter 2. The pressure profile used in Chow’s study is same as that defined by Eq. (1.4) but with Holland parameter $B$ being equal to unity; the turbulence flux are considered by including a drag force term and viscous term in the momentum equation. The drag coefficient $C_D$ used in Chow (1971) is linearly increasing with the wind speed and is given by,

$$C_D = \left(0.5 + 0.06 |V|\right) \times 10^{-3}$$  \hspace{1cm} (1.7)

where $V$ m/s is the wind speed at slab height relative to the fixed coordinate.

The boundary depth is assumed to be 1000 m. A finite difference solution scheme was also given and used to solve the moment equation, including the effect of the translation of the TC. Chow’s study is only focused on the wind field at slab height.

Although Shapiro (1983) does not directly follow Chow’s work, the same governing equation is used but expressed in cylindrical coordinate. The pressure profile is assumed to be in gradient balance and governed by Eq.(1.1). The drag coefficient used in their study is different than that used by Chow (1971), which can be written as,

$$C_D = \left(1.1 + 0.04 |V|\right) \times 10^{-3}$$  \hspace{1cm} (1.8)

The boundary depth is also assumed to be 1000 m. To improve the numerical efficiency, Shapiro (1983) considered that the solution of the wind field can be expressed in terms of Fourier series, and that the consideration of first two terms in the series can be adequate.
This study is again focused on the wind field at slab height. This wind field model was adopted by Vickery and Twisdale (1995a, b); a scaling factor of 0.8 is introduced to convert the modeled wind field at slab height to the surface level (i.e., 10 m height) and a halved drag coefficient given in Eq. (1.8) was used. The truncated spectral analysis used in Shapiro (1983) was found to be less adequate in describing the wind field structural feature as compared to the full nonlinear solution of the equation of the motion (Vickery et al. 2000a).

By following Chow’s solving scheme, the solution of the equation of motion is also given in Thompson and Cardone (1996) but considering that the boundary layer depth $h$ equals 500 m. The drag coefficient in their study differs from that used in Chow (1971) and Shapiro (1983). The drag coefficient in their study is estimated based on the similarity theory. This results in $C_D$ to be dependent on the similarity parameters and the wind speed. Consequently, the calculation procedure for the wind field is more complex as compared to the case where $C_D$ is given by Eqs. (1.7) or (1.8). The similarity parameters are also used as the basis to develop the boundary layer model.

Vickery et al. (2000a) adopts the wind field model given by Thompson and Cardone (1996) including their boundary layer model, but replaced the drag coefficient with the one given in Vickery and Twisdale (1995a) and setting the boundary layer depth $h$ equal to 1000 m. Vickery et al. (2000a) validated their model by comparing the estimated wind speeds to the surface wind observations. The model in Vickery et al. (2000a) is further updated by Vickery et al. (2009a) by including:

1. Newly developed empirical models for Holland $B$ and $R_{\text{max}}$ which are given in Vickery and Wadhera (2008); and
2. An empirical boundary layer model and an upper limit of the drag coefficient, which are developed based on dropsonde data and reconstructed surface wind field (Powell et al. 1998).

It is noted that the series studies by Vickery et al. mentioned earlier provided the basis for the wind hazard map in the ASCE-7 (2010). However, the application and assessment of the adequacy of the wind field model for estimating the typhoon wind hazard (in other...
regions in the world) caused by the TCs originating from western North Pacific basin are not discussed in the literature. This is important since the results of the model depend on the empirical models for Holland $B$ parameter and $R_{\text{max}}$, which are developed using US data.

Other wind field model used for engineering applications includes the one developed by Meng et al. (1995). Their model is adopted by Zhao et al. (2005) to assess the typhoon wind hazard for Shanghai. This model has similar governing equation as that for PBL wind field model, but assumes that the wind field of a storm within the boundary layer can be considered as a superposition of the gradient wind field and a wind field “induced” by surface friction. The gradient wind field component can be solved by assuming the gradient wind balance, while the friction wind field is solved iteratively. The parameters used to define this wind field model include the central pressure difference, translation velocity, storm heading and roughness length $z_0$. The drag coefficient is expressed in terms of the roughness length and is given by,

$$ C_D = \frac{\kappa^2}{\ln[(z_{10} + h - d)/z_0]^2} $$

(1.9)

where $\kappa$ is Von Karman constant equal to 0.4, $z_{10}$ is 10 m height above the mean height of roughness length, $d$ m is the zero-plane displacement and $z_0$ m is the roughness length. The value of $z_0$ used in the model is extremely important since the friction velocity plays a key role in this model. In fact, the model given by Meng et al. (1995) is a function of wind direction dependent $z_0$. As such a wind direction is unknown at priori, it must be determined iteratively by solving the wind field and adjusting the corresponding $z_0$ according to the coming wind direction. This could complicate the application of the model.

Meng et al. (1997) updated the model shown in Meng et al. (1995) by changing the constant viscosity coefficient used in Meng et al. (1995) to be a non-linear differential equation. This change further increases the complexity in applying the model.
An axisymmetric slab wind field model is also proposed in Smith (2003) and subsequently updated in Smith and Vogl (2008). To get this slab model, the equation of motion in 3D is integrated and averaged vertically. For terms maintain the vertical velocity in the 3D equation, as a result of integration, the vertical velocity at the boundary height is maintained in the averaged governing equation. To solve the governing equation of this slab model, it assumes that the simulated wind field is in steady state and axisymmetric, which are implemented by setting the time derivative and azimuthal derivative equal to zero correspondingly. This axisymmetric slab model is used to investigate the TC wind field structure diagnostically, such as supergradient wind (i.e., the wind speed around eyewall which is faster than the gradient wind speed). The axisymmetric feature of this model cannot capture the asymmetric characteristic of observed TC wind field.

A 3D wind field model was given in Kepert (2001) and Kepert and Wang (2001). The model given in Kepert (2001) is a linear height resolving 3D model, while its non-linear enhancement is given in Kepert and Wang (2001). It seems that these models have not been considered in any major engineering tropical cyclone wind hazard and risk assessments. The governing equation for this 3D model can be considered as a general form of the equation of motion under the assumption of neutral condition, which the acceleration of air at boundary equals zero. The slab model, including the PBL wind field model and axisymmetric slab model, can be derived from this governing equation through some simplifying assumptions. In fact, the governing equation for the PBL wind field model can be obtained by vertically averaging the governing equation for this 3D model and neglecting the vertical velocity. The governing equation for the axisymmetric slab wind field model can be derived by vertically averaging this 3D wind field model and neglecting the azimuthal and time derivatives. Difference between the 3D model and the slab model also exists in how to treat the turbulence flux, which is commonly parameterized by using the bulk aerodynamic formula that reflects the surface friction by employing a drag coefficient. For the slab model, the drag coefficient is calculated by using the wind speed at slab height (i.e., the mean boundary layer flow because the boundary layer flow is vertically averaged). However, the 3D model uses the surface
wind speed to calculate the drag coefficient. Kepert (2010a,b) argues that using the mean boundary layer flow to calculate the drag coefficient contributes to the difference of the simulated wind field by using slab model and that by using 3D height resolving model. Kepert (2010a,b) also indicate that the vertical average of the non-linear terms also contributes to the difference of modeled wind field. It is unavailable in Kepert (2010a,b) that a comparison of the wind field estimated from the 3D model to the observed tropical cyclone wind field.

1.3 Review of the TC track simulation methods

The track modeling is another essential component for the TC wind hazard assessment model. Methods used to simulate the trajectory of the TC can be generally categorized into two classes, which are local (or sub-region) model and basin wide TC track model. The basic idea behind these two kinds of track modeling techniques is the same except in the former statistical characteristics of the tracks near a site of interest (e.g., within 250 km) are considered while the latter considers the statistics of historical tracks from genesis to lysis. The parameters needed for the track modeling include the location of the TCs at given time interval, central pressure of TC, heading and translational velocity of TC.

The sub-region method was considered by several researchers including Russell (1968, 1971), Tryggvason et al. (1976), Batts et al. (1980), Georgiou et al. (1983), Neumann (1991), Vickery and Twisdale (1995a). In all cases, to sample the tracks near the site of interest, the approach needs to assign probabilistic models of the key TC parameters, including the central pressure difference, heading and translation velocity of TC, the radius of the maximum wind speed, and the minimum approaching distance or the coast crossing position. For the distribution assignment, the samples are extracted from the historical TC track observation available in the best track dataset within a specific region (e.g., a region defined by a circle centered at the site of concern or at the crossing section along the coastline). Monte Carlo approach is used to sample the key parameters from the assigned statistical distributions, which are used to mathematically represent a TC traveling along a straight line within the analysis domain. The intensity of the modeled
TC is assumed to be constant until it makes landfall, when the filling rate model (such as in Vickery, 2005) is activated to decay the modeled central pressure after making landfall. This approach is valid for a single site when sufficient data is available to assign the probabilistic models to the key parameters by using the site specific data obtained in the circle centered at the site of concern or from the intersection of the coastline segment. The procedure used in the application of such approach is similar in the studies mentioned previously. Differences among these studies mainly exist in the models accompanied physically, such as filling-rate models and the size of the region considered being valid for the TC climatology. Instead of modeling the central pressure of the TC, in Neumann (1991) it models the maximum surface wind speeds. The sub-region method is used to assess the hurricane wind hazards along the coastal line of U.S. in Battts et al. (1980), Geogiou et al. (1983) and Vickery and Twisdale (1995a&b).

The application of subregion method to estimate typhoon wind hazard in a few cities in China is also considered (Ou et al. 2000; Zhao et al. 2005; Xiao et al. 2011). A limitation of the subregion method is that the TC climatology in the defined subregion may not be statistically homogeneous and the data in the circle may be insufficient to define the probabilistic model for the key TC parameters.

To overcome these limitations in the subregion method, a TC track model from the genesis to lysis is developed in Vickery et al. (2000b) by using the best track data obtained from HURDAT. The model is used to generate synthetic TC tracks from genesis to lysis. Three regression equations are given to predict the change of the key TC parameters, including the heading and translation velocity of the TC and relative intensity (as defined in Darling (1991)). Samples extracted from the best track dataset in specific region, typically defined as a 5° × 5° square, are used to develop the coefficients of the regression equations. The developed track model is used to simulate the tracks from genesis to lysis. Moreover, a filling-rate model is needed to simulate the central pressure difference after the tracks making landfall.
The development of the TC track model was also considered by others (Powell et al., 2005; James and Mason, 2005; Emanuel et al., 2006; Lee and Rosowsky, 2007; Hall and Jewson, 2007). In James and Mason (2005), an auto regression model is developed to model the TC location and the central pressure. A non-linear term was added into the first order auto regression model in to model the tendency of the TC moving away from the equator in Coral Sea, Australia. The same attempt was made to include a non-linear term in the auto regression model for predicting the change of central pressure such that an increasing tendency can be obtained for positive $\Delta p$ when the central pressure close to the mean potential intensity. Instead of using the regression models to deal with the TC location and the relative intensity (defined by the central pressure), Emanuel et al. (2005) proposes to model the location of the tracks using Markov chains, and the intensity of the TC (defined by the sustained wind speed at surface level) by a deterministic model. Hall and Jewson (2007) also gives a TC track model, which predicts the displacement of a TC by using the geographical weighted average value of the displacement derived from the historical observation in a specific region centered at the current analysis location with compositing a uncertainty term modeled by a bi-normal distribution. In their model, no attempt was made to predict the TC intensity along the modeled track.

The main difference between the CSM and full track modeling is apparent. The former requires the homogeneity assumption within the considered region and potentially associated with statistical uncertainty due to lack of data. The latter considers the full track model parameters are spatially varying. The simulated trajectory by the CSM, within the concerned circle, is assumed to be a straight line defined by randomly sampled key parameters (TC heading, translation velocity and minimal approaching distance) from fitted statistical distributions. The trajectory simulated by the full track modeling varies over time. Both the CSM and the full track model are widely used to assess the hurricane wind hazard in the US. However, the consideration of the full track model to assess the typhoon wind hazard in China seems missing.

Besides the wind field models and trajectory models, there are also models needed to compute the parameters, such as Holland parameter B, radius of the maximum radius
(R_{\text{max}}), height scaling factor and filling rate that are required to evaluate the wind field and wind speed at 10 m height.

1.4 Data availability

The historical track information is the essential information for the tropical cyclone wind hazard assessment. The track information in the HURDAT (Jarvinen et al. 1984) records the tropical cyclone originating in North Atlantic basin. There are four institutions release their best track datasets for tropical cyclones originating from west North Pacific (WNP) basin (Ying et al. 2014). They are the China Meteorological Administration (CMA), the Hong Kong Observatory (HKO), Regional Specialized Meteorological Center (RSMC) in Tokyo, and the Joint Typhoon Warning Center (JTWC) of the US Navy. A comparative study by Ying et al. (2014) indicated that CMA datasets have higher quality and longer records for TCs near the coastline of China and after making landfall, which is important for the TC wind hazard assessment over the TC prone coastal region of China. Consequently, all available information from the TC best track dataset provided by the CMA is considered for the analysis regarding to the typhoon wind assessment for China in this study. Both of the HURDAT and the best track dataset from CMA are considered in this study.

1.5 Objectives of the Current Study

The main objectives of this study include:

1) To follow a series of studies given by Vickery et al. (from 1995 to 2010) and reconstruct the full track model. This is necessary since their track model coefficients are proprietary. The reconstruction of the track model and scrutinize the PBL model also allow a detailed examination of the developed hurricane wind hazard used to develop wind hazard maps for ASCE-7;

2) To estimate the typhoon wind hazard for selected cities using the CSM and the well-established PBL wind field model. Such a study is necessary to understand the typhoon
wind hazards for the considered cities since there are large discrepancies in the estimated return period value of typhoon wind speeds reported in the literature.

3) Apply the CSM and the well-established PBL wind field model to develop the typhoon wind hazard for the coastal region in China. It seems that the mapping of such hazard for the coastal region is not available. The challenges of such a mapping are the assignment of probabilistic models for the track model and the development of an adequate filling-rate model applicable for the region.

4) The final objective of this study is to develop the full track model. The developed full track model is used to assess typhoon wind hazard for the coastal region of the mainland China. A comparison of the mapped wind hazard estimated based on CSM and full track approach is presented.

1.6 Chapter organization

Chapter 2 explores the PBL wind field model and reconstructs the full track model given in Vickery et al. (2000b). An approximation in solving the PBL wind field model is identified in Thompson and Cardone (1996) and Vickery et al. (2000a). The influence of such approximation on the simulated wind field is studied. The adequacy of the simulated wind field is verified by comparing the simulated wind field to that provided by H*Wind (Powell 1998), where the observation is used to reconstruct the observed surface wind field. The TC full track model given in Vickery et al. (2000b) is reconstructed by using the HURDAT dataset up to 2011. A simplified version of this TC full track model is developed. The reconstructed full track model and the simplified track model are validated by comparing the statistics of the key TC parameters to those calculated from the HURDAT. Hurricane wind hazard for the US is mapped by using different combination of the PBL wind field model (full solution of the governing equation or approximated solution) and the full track model (full version of the full track model given in Vickery et al. (2000b) or its simplified version). Finally, these developed hurricane wind hazard maps are compared.
Chapter 3 assesses the typhoon wind hazard for 9 coastal cities in southeast part of mainland China by using the CSM combined with the PBL wind field model. Statistics of the key typhoon parameters are calculated within a circle centered at each of these concerned cities. Statistical distributions are assigned to the key typhoon parameters. The coefficients of the assigned distributions are fitted from the CMA best track dataset. The PBL wind field model is validated by comparing the simulated TC wind speed to those observed at meteorology stations. A filling rate model is developed for the southeast part of China. The typhoon wind hazards for these nine sites are assessed by using the CSM and the PBL wind field model. The estimated return period typhoon wind speeds are compared to those found in the publication and those tabulated in Chinese building code.

Chapter 4 maps the typhoon wind hazard for southeast part of China by using the CSM and the PBL wind field model. The statistics of the key typhoon parameters are calculated for the entire southeast part of the China to characterize their spatial trends. Filling rate model developed in Chapter 3 is updated to consider the effect of Taiwan Island on landfalling TCs. Typhoon wind hazards are mapped and compared based on different radii used in the CSM. The typhoon wind hazard assessed by using the filling rate model developed locally for each site is compared to that assessed by using the filling rate model developed for three regions covering the southeast part of mainland China.

Chapter 5 develops a full track model in WNP basin and maps the typhoon wind hazard for southeast part of mainland China by using this developed full track model. The coefficients of the full track model are developed by using the CMA best track dataset. The adequacy of the full track model is validated by comparing the statistics of the key TC parameters calculated from the simulated TC tracks to those in the best track dataset. The typhoon wind hazards at nine cities defined in Chapter 3 are assessed by using the full track model and compared to those calculated by using CSM. The assessed typhoon wind hazards at two cities are compared to those estimated by using the ground observations. The developed typhoon wind hazard contour maps by using full track model are compared to those developed by using CSM.
Finally, Chapter 6 summarizes the main conclusions drawn from previous chapters. Contributions of this work are also highlighted in this chapter. Recommendations are given for the future work.

**Reference**


Chapter 2

2 Observations on hurricane wind hazard model used to map extreme hurricane wind speed

2.1 Introduction

Tropical cyclones, known as hurricanes in the Atlantic and east Pacific Ocean and typhoons in the west Pacific, are associated with extreme winds, intense rain and storm surges. They often cause damage to structures and infrastructure, fatalities and economic losses. Hurricane wind hazard modeling and simulation are important for hurricane risk assessment. The modeling requires the use of historical wind speed and track records.

The models and the simulation of extreme hurricane wind speed focused on the US were discussed in Vickery et al. (2009a, b, c); a model focused on Mexico was developed by Sanchez-Sesma et al. (1988); and a model focused on southeast coastal regions of China was described by Xiao et al. (2011). Also, under Florida Commission on Hurricane Loss Project Methodology (http://www.sbafla.com/methodology), in 2011 AIR Worldwide Corporation, Applied Research Associates, Inc., EQECAT, Inc., Florida International University (International Hurricane Research Center), and Risk Management Solutions, Inc. independently submitted their hurricane hazard models for review. General description of these models and the corresponding references can be found in the submissions. In all cases, each of the hurricane hazard models basically consists of two parts: a hurricane wind field model and a hurricane track model. Detailed information is available on the modeling techniques used to develop the hurricane wind contour maps in ASCE 7-98 (Vickery and Twisdale, 1995a, b), ASCE 7-05 (Vickery et al., 2000a, b) and ASCE 7-10 (Vickery et al., 2009a, b; Vickery et al. 2010). The use of the hurricane wind hazard model for risk assessment, which is implemented in FEMA (2006), was presented in Vickery et al. (2006).

One of the early tropical cyclone wind field models, presented in Chow (1971), investigated the structure of a moving tropical cyclone having an asymmetric wind field
induced by surface drag. The model is a two-dimensional (2D) model focused on a single horizontal layer of a uniform height within the planetary boundary layer. The wind field is described using the fluid momentum equation (Holton 2004) and its solution is obtained by applying the finite-difference method with nested grid (Chow 1971). Shapiro (1983) also studied the wind field in the planetary boundary layer beneath a translating tropical cyclone. Although it was not directly in accordance with Chow (1971) solution procedure, it was based on the same governing equation given in Chow (1971) but expressed in cylindrical coordinate. It considered that the solution of the equation for the wind field consists of an axisymmetric component and azimuthally-varying components at the first two Fourier frequencies, allowing for asymmetries. Such a wind field, representing vertically-averaged values of wind velocity, retained sufficient accuracy in comparison with the observed wind field in tropical cyclones. The Shapiro (1983) approach, which does not provide the full solution to the momentum equation and details of wind field asymmetry as the hurricane translation velocity increases, was adopted by Georgiou (1985) and Vickery and Twisdale (1995a). Cardone et al. (1992) proposed a wind field model with the same equation used by Chow (1971), but with different surface drag coefficient and boundary layer models. The model was refined by Thompson and Cardone (1996) applying a more realistic pressure field given by Holland (1980). This approach was adopted by Vickery et al. (2000a): it took the equation described in Chow (1971) and the solution was obtained using the finite difference method, but considered the pressure field and boundary layer model from Thompson and Cardone (1996) and the surface drag coefficient from Vickery and Twisdale (1995b). Solutions to the wind field model were precomputed and fitted using Fourier series along circular paths concentric with the coordinate center; the fitted series were stored and used to estimate hurricane wind speeds by applying Monte Carlo technique.

The previous discussion indicates that the equation representing the wind field presented in Chow (1971) plays an essential role in the hurricane wind field modeling and hazard assessment. However, a term expressed as the product of the hurricane translation velocity and gradient of the wind velocity relative to the moving center of the vortex in the governing equation, which was used in Chow (1971), was neglected in several
publications (see next section for details). However, the effect of this approximation on the calculated wind field has not been elaborated and investigated. To investigate this effect on the calculated hurricane wind field and hurricane wind hazard, the Chow (1971) model and its approximation are elaborated in the next section.

The other major component for estimating hurricane wind hazard is the hurricane track modeling. For computational efficiency, early hurricane hazard assessment (Georgiou et al., 1983; Vickery and Twisdale, 1995b) was carried out by simulating the track segments within a specified radius of the site of interest. For the simulation, the historical track records were used to assign the probabilistic models of the characteristics of the tracks such as heading, intensity, and translational speed of the hurricane. A limitation with this approach is that there could be insufficient historical data for a particular location to adequately define the probabilistic models. To overcome this, Vickery et al. (2000b) pioneered the use of the hurricane track model developed based on the historical track records in the National Hurricane Center’s North Atlantic hurricane database (HURDAT) (Jarvinen et al. 1984); the model was used to generate synthetic tracks from genesis to lysis. For the development, it was considered that the geographic region of interest can be covered using regular rectangular cells, and the historical track segments within each cell can be used to develop the track model defined by regression equations for the storm translation velocity, heading, and relative intensity. The development and use of the track model for hazard assessment were considered and expanded by others (Powell et al. 2005; James and Mason 2005; Emanuel et al. 2006; Lee and Rosowsky 2007; Hall and Jewson 2007). James and Mason (2005) was focused on cyclones over the Coral Sea, Australia; their model assumed that the position of the track can be modeled using the autoregressive stochastic process. Emanuel et al. (2006) considered that the synthetic track can be generated using Markov chains, while Hall and Jewson (2007) considered that the track can be modeled based on the local mean and variances of the displacement of historical track. However, it appears there is no consensus on the best track modeling technique.

This Chapter describes two main observations on the hurricane wind hazard modeling.
First, two sets of the wind fields are developed, as follows: (1) defined by the governing equation given in Chow (1971), and (2) defined by the governing equation with the approximation mentioned previously. Also, a qualitative comparison of these simulated wind fields to a few snapshots of hurricane wind fields from the Hurricane Wind Analysis System (i.e., H*Wind) (Powell et al., 1998) is presented. Second, an investigation is carried out to potentially simplify the track model proposed in Vickery et al. (2000b).

Four hurricane hazard models are assembled by considering combinations of wind field and track modeling components. For the combination, one of the two sets of wind fields (mentioned previously in this paragraph) is combined with one of the two track models, as follows: (1) original track model given by Vickery et al. (2000b) but with newly estimated model coefficients using up to date track records, and (2) simplified track model developed in the research reported in chapter. The assembled hurricane hazard models are used to estimate the return period values of annual maximum hurricane wind speed and to investigate the sensitivity of the estimates (to the adopted wind field and track models).

2.2 Wind field model and its solution

The vortex model proposed by Chow (1971) is the basis for the models used by Cardone et al. (1992), Thompson and Cardone (1996), and Vickery et al. (2000a, 2009b). The model that is based on the equation of horizontal motion, vertically averaged through the depth of the planetary boundary layer, can be written in the earth-fixed coordinate system as,

$$\frac{\partial \hat{u}}{\partial t} + \hat{u} \cdot \nabla \hat{u} + \bar{u}_s \cdot \nabla \bar{u}_s = -f \hat{k} \times \left[ \bar{u}_s + \bar{u}_c - \bar{u}_g \right] - \frac{1}{\rho} \nabla p_e + \nabla \cdot \left[ K_H \nabla \bar{u}_s \right] - \frac{C_D}{h} \bar{u}_s \cdot \left[ \bar{u}_s + \bar{u}_c \right]$$

(2.1)

where $\hat{u}$ m/s = the wind velocity relative to the moving center of the vortex; $\bar{u}_c$ m/s = the storm translation velocity; $\bar{u}_g$ m/s = the wind velocity resulting from the large-scale pressure field; $f$ rad/s is Coriolis parameter equal to $2\Omega \sin \psi$ at latitude $\psi$ in degrees in which $\Omega$ rad/s represents the rotation of the Earth with magnitude $2\pi$/day; $\hat{k}$ is the unit
vector in the vertical direction; \( \rho \) kg/m\(^3\) = density of air; \( p_c \) Pa is an axisymmetric pressure field; \( K_H \) is the horizontal eddy viscosity coefficient; \( C_D \) is the surface drag coefficient; and \( h \) m = the depth of the planetary boundary layer. In writing Eq. (2.1), it is considered that the total pressure \( p = p_c + p_g \), where \( p_g \) represents the large-scale pressure field, and it is assumed that \( \nabla p_g = -\rho \mathbf{f} \times \mathbf{u}_g \).

According to Chow (1971), \( \partial \mathbf{u}_s / \partial t \) in Eq. (2.1) represents the time change of \( \mathbf{u}_s \) (local) to the fixed coordinates (on earth), while \( \partial \mathbf{u}_s / \partial t + \mathbf{u}_c \cdot \nabla \mathbf{u}_s \) represents the time change of \( \mathbf{u}_s \) to the moving coordinates (i.e., center of the vortex). Chow (1971) used the notation \( \left( \partial / \partial t \right)_c \) to represent \( \left( \partial / \partial t \right) + \mathbf{u}_c \cdot \nabla \), and further expressed Eq. (2.1) in a moving Cartesian coordinate system \((x, y)\) with the origin always coinciding with the moving low pressure center as,

\[
\left( \frac{\partial}{\partial t} \right)_c u = -A_u + F_u - P_u + E_u - D_u \tag{2.2a}
\]

and,

\[
\left( \frac{\partial}{\partial t} \right)_c v = -A_v + F_v - P_v + E_v - D_v \tag{2.2b}
\]

where \( u \) (m/s) and \( v \) (m/s) are the components of \( \mathbf{u}_s \) in the \( x \)- and \( y \)-directions, respectively. The advection term \( A \), Coriolis term \( F \), the pressure gradient term \( P \), the viscous force term \( E \), and the surface drag term \( D \) are derived based on Eq. (2.1) and are defined explicitly in the subsequent text. The subscripts \( u \) and \( v \) (to \( A, F, P, E \) and \( D \)) represent that they are associated with the velocity components \( u \) and \( v \). The terms \( A, F, P, E \) and \( D \) are:

\[
A_u = u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} \tag{2.3a}
\]

\[
A_v = u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} \tag{2.3b}
\]
\[ F_v = f v \]  
\[ F_i = -fu \]  
\[ P_u = \frac{1}{\rho} \frac{\partial p_c}{\partial x} \]  
\[ P_v = \frac{1}{\rho} \frac{\partial p_c}{\partial y} \]  
\[ E_u = \frac{\partial}{\partial x} \left( K_H \frac{\partial u}{\partial x} + K_H \frac{\partial u}{\partial y} \right) \]  
\[ E_v = \frac{\partial}{\partial x} \left( K_H \frac{\partial v}{\partial x} + K_H \frac{\partial v}{\partial y} \right) \]  
\[ D_u = \frac{C_D}{h} \left( (u+u_c)^2 + (v+v_c)^2 \right)^{\frac{1}{2}} (u+u_c) \]  
\[ D_v = \frac{C_D}{h} \left( (u+u_c)^2 + (v+v_c)^2 \right)^{\frac{1}{2}} (v+v_c) \]  

By specifying \( K_H, C_D, h \) and the boundary condition of the wind field, Chow (1971) solved Eq. (2.2) using the finite difference method with a rectangular nested grid system consisting of five nests for \( \left( \frac{\partial}{\partial t} \right)_e \) equal to zero. Within each grid layer the grid point spacing is constant; the mesh size of the innermost nest is specified; and the mesh size is doubled as the nest grows outwards to the next layer. For the numerical analysis, the grid point spacing is 5×10^3, 10×10^3, 20×10^3, 40×10^3 and 80×10^3 m for the five nests; the entire grid domain covers about 1600 km². \( h \) in Eq. (2.7) is taken to be equal to 1000 m. This was also adopted by others (Shapiro 1983, Vickery et al. 2009b). The finite difference method was considered by Cardone et al. (1992), Thompson and Cardone (1996), and Vickery et al. (2000a) to solve Eq. (2.2). In all these studies, \( K_H \) is considered to be given by (Smagorinsky, 1963).
\[ K_H = 2\kappa^2 \left( \frac{\Delta x}{2} \right)^2 \left( \frac{\partial u}{\partial x} - \frac{\partial v}{\partial y} \right)^2 + \left( \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \right)^2 \right)^{1/2} \]  
\[ (2.8) \]

where \( \Delta x \) denotes grid point spacing and \( \kappa \) is a non-dimensional constant that takes a value of 0.4. \( \kappa \) plays a minor role in the model results (Chow, 1971). The pressure gradients \( \partial p_c / \partial x \) and \( \partial p_c / \partial y \) are obtained based on the radial pressure gradient expressed as:

\[ \frac{\partial p_c}{\partial r} = \Delta p B \left( \frac{R_{\text{max}}}{r} \right)^b \exp \left( -\left( \frac{R_{\text{max}}}{r} \right)^b \right) \]  
\[ (2.9) \]

where \( r \) m is the radial distance from the pressure center of the storm; \( B \) is Holland’s radial pressure model parameter (Holland, 1980) taken a value between 0.5 and 2.5 (Thompson and Cardone, 1996; Vickery et al., 2000a); \( \Delta p \ Pa = \) central pressure difference; and \( R_{\text{max}} \) m = radius of the maximum wind speed.

The term \( C_D \) was modeled as a linear function of wind velocity in Chow (1971) and Vickery et al. (2000a), while in Cardone (1992) and Thompson and Cardone (1996), it was modeled as a function of air-sea temperature difference resulting in \( C_D \) as a nonlinear function of wind velocity. More recently, Vickery et al. (2010), see also Large and Pond (1981) and Vickery et al. (2009b, c), considered that in the over land case \( C_D \) equals 0.0047, and in the over water case it is given by,

\[ C_D = \min \left[ \left( 0.49 + 0.065 V_{10} \right) \times 10^{-3}, C_{D\text{max}} \right], \]  
\[ (2.10a) \]

where,

\[ C_{D\text{max}} = \min \left\{ \max \left[ 0.0019, \left( 0.0881 \times 10^{-3} r_1 + 17.66 \right) \times 10^{-4} \right], 0.0025 \right\}, \]  
\[ (2.10b) \]

\( V_{10} \) m/s is the mean wind speed at 10 m height and \( r_1 = \max (r, R_{\text{max}}) \).

For simplification of reference, the wind field described by Eq. (2.2) is referred to as Model-E in the following. The term \( \left( \partial / \partial t \right)_c \) on the left hand side (LHS) of Eq. (2.2) deserves some discussions. It is presented in the formulation in Chow (1971) and Cardone et al. (1992). However, it appears that the computing code in Cardone et al.
(1992) neglected \( \vec{u}_c \cdot \nabla \vec{u}_s \). This observation is consistent with the fact that \( \left( \partial / \partial t \right)_c \) instead of \( \left( \partial / \partial t \right) \) is used in equations (8) and (9) in Thompson and Cardone (1996), and in equations (8a) and (8b) in Vickery et al. (2000a). Neglecting \( \vec{u}_c \cdot \nabla \vec{u}_s \) may be an adequate approximation. However, its effect on the calculated wind fields has not been investigated. The wind field described by Eq. (2.2), but with \( \vec{u}_c \cdot \nabla \vec{u}_s \) neglected [i.e., \( \left( \partial / \partial t \right)_c \) is replaced by \( \left( \partial / \partial t \right) \)], is referred to as Model-A in the subsequent text for simplicity.

To investigate the effect of neglecting \( \vec{u}_c \cdot \nabla \vec{u}_s \) on the predicted wind field, the solution procedure given in Chow (1971) is performed to solve Model E and Model A. The results are compared in Figure 2.1. It indicates the following:

1) The kidney shape isoline near the center is noticeably rotated clockwise as the storm translation velocity increases if Model E is used. However, if Model A is used, the rotation of the kidney shape versus the translation velocity is less significant; this is in agreement with the results in Vickery et al. (2000a). This shows that the shape of the predicted wind field is affected by neglecting \( \vec{u}_c \cdot \nabla \vec{u}_s \).

2) For small values of the storm translation velocity, the predicted wind fields obtained by using Model E and Model A are similar. This is expected since the magnitude of \( \vec{u}_c \cdot \nabla \vec{u}_s \) decreases as \( \vec{u}_c \) decreases.

3) The maximum wind speed estimated by Model A is about 3.5% less than that estimated by Model E. This difference is small considering all the uncertainties involved in assigning the needed coefficients for the wind field modeling. Additional analysis shows that the underestimation by neglecting \( \vec{u}_c \cdot \nabla \vec{u}_s \) could be increased to about 15% for hurricanes with the model parameters taking the values near the ends of their typical ranges (for example, with the central pressure difference equal to about 85 hPa).
Figure 2.1 Comparison of wind speeds in m/s at 10 m for overland condition. For the numerical analysis, $\Delta p = 6500$ Pa, $B = 1.05$ and $R_{\text{max}} = 45000$ m are considered. The storms translate vertically and upwards in the plan of the page; the conversion of the wind speed obtained from Eq. (2.2) to surface wind speed is explained in detail in the following section.

To further compare the effect of neglecting $\vec{u}_c \cdot \nabla \vec{u}_c$ on the wind field, the H*Wind snapshots (Powell et al. 1998) are considered. In particular, four such snapshots obtained from [http://www.aoml.noaa.gov/hrd/data_sub/wind.html](http://www.aoml.noaa.gov/hrd/data_sub/wind.html) (last access date July 1st, 2013) are shown in Figure 2.2. Several parameters [i.e., (1) the magnitude of translation velocity, $|\vec{u}_c|$, (2) storm heading (relative to the true north), (3) $R_{\text{max}}$, (4) central pressure $p_c$] are obtained or inferred from the snapshots and their associated information. The term $R_{\text{max}}$ and $p_c$ are directly given in the snapshots, and $|\vec{u}_c|$ and heading are estimated based on the wind field information (immediately before and after the snapshots shown in Figure 2.2). For the calculation, in accordance with Vickery et al. (2009c) and Powell and Uhlhorn (2009), Holland’s parameter $B$ is estimated. This is done by subtracting the
storm motion from the H*Wind, approximating the remaining wind field using an axisymmetric radial profile, scaling the approximate surface wind field to gradient wind, and finally calculating $B$ based on peak gradient wind velocity. The solutions of the wind fields with these parameters by using Model-E and Model-A are compared with the snapshots in Figure 2.2. The comparison of the shapes of the wind fields indicates that the solutions to Model E resemble those for the H*Wind and that this resemblance is reduced if Model A is used. The maximum wind speed caused by using Model E is at the right or right rear quadrant of the moving storm. This is a feature that is associated with three of the four H*Wind snapshots shown in Figure 2.2. However, the maximum wind speed caused by using Model A is located at the right front quadrant of the moving storm.

To further inspect the location of the maximum wind speed in the H*Wind snapshots, 489 snapshots for 45 hurricanes occurred from 2002-2013 are considered. For each snapshot, similar to the analysis carried out for the snapshots shown in Figure 2.2, the clockwise azimuth angle of the maximum wind speed with respect to the direction of storm heading is determined. The maximum wind speed for about 84% of snapshots is located on the right side of the storm motion; 42% and 58% of these snapshots are associated with maximum wind speed located at right front and right rear, respectively. For the snapshots with maximum wind speed located on the right side of the storm motion, the mean of the azimuth angle (with respect to the storm heading) is 97° and the mean of $\vec{u}_e$ is about 6m/s. This and the results shown in Figures 2.1 and 2.2 seem to support that Model E is preferred, although it must be noted that the H*Wind represents wind field from reanalysis results rather than actual measurements or observations.

In accordance with Vickery et al. (2000a), the numerical solution to Eq. (2.2) is fitted, stored, and used together with the hurricane track model to assess the hurricane wind hazard using the Monte Carlo technique in the subsequent sections. Moreover, for comparison purpose, database of wind fields defined by Model E and Model A is also established which will be used in the subsequent sections to estimate hurricane wind hazard.
Figure 2.2. Comparison of H*Wind snapshots to Model-E and Model-A. The value below the named hurricane refers to month, day, hour and minutes.

2.3 Empirical track models

2.3.1 Benchmark track model

The track model pioneered by Vickery et al. (2000b) was aimed at simulating the storm translation velocity, heading and relative intensity. The model is expressed in,
\[
\Delta \ln c = a_1 + a_2 \psi + a_3 \lambda + a_4 \ln c_i + a_5 \hat{\theta}_i + \varepsilon_i
\]  
(2.11)

\[
\Delta \theta = b_1 + b_2 \psi + b_3 \lambda + b_4 c_i + b_5 \hat{\theta}_i + b_6 \hat{\theta}_{i-1} + \varepsilon_0
\]  
(2.12)

\[
\ln(I_{i+1}) = d_1 + d_2 \ln(I_i) + d_3 \ln(I_{i-1}) + d_4 \ln(I_{i-2}) + d_5 T_s + d_6 \left(T_{s_{i+1}} - T_{s_i}\right) + \varepsilon_i
\]  
(2.13)

where \(a_i, b_i, \) and \(d_i\) are coefficients (or model parameters); \(\psi\) and \(\lambda\) = latitude and longitude, respectively; \(\Delta \ln c = \ln c_{i+1} - \ln c_i\), \(\Delta \theta = \theta_{i+1} - \theta_i\), \(c_i, \theta_i,\) and \(I_i = \) storm translation velocity, heading, relative intensity at the \(i\)th step, \(T_s = \) monthly averaged sea surface temperature; and \(\varepsilon_c, \varepsilon_\psi, \varepsilon_\lambda\) and \(\varepsilon_I = \) zero mean random error terms for Eqs. (2.11) - (2.13), respectively.

The relative intensity \(I_i\) without the subscript, \(I\), is defined as (Darling 1991),

\[
I = \left(p_{da} - (p_c - e_s)\right) / \left(p_{da} - p_{dc}\right)
\]  
(2.14)

where \(p_{da}\) and \(p_{dc}\) are the ambient and minimum sustainable central dry partial pressures, the saturation vapour pressure \(e_s = 6.112 \times \exp\left(17.67\times(T_s - 273) / (T_s - 29.5)\right)\), and \(T_s = \) the sea surface temperature in Kelvins. The time increment between \(i+1\) and \(i\) is 6 h. The coefficients are estimated for cells covering the geographic region of interest. The coefficients are spatially varying and take into account local hurricane climatology. Furthermore, two sets of coefficients [i.e., (1) for easterly headed storms, and (2) for westerly headed storms] are estimated; the coefficients for the cells with little or no historical data are assigned based on the nearest cells. Unlike the track model in Vickery et al. (2009a), Eqs. (2.11) - (2.13) do not include the ocean mixing effect. Although this could result in some differences in the estimated hurricane wind hazard, it does not change the spatial trends of the estimated hurricane hazard, and it does not affect the sensitivity analysis objectives which are the focus of this chapter.

In Vickery et al. (2000b), the coefficients for Eqs. (2.11) - (2.13) were estimated based on historical track records for each of the regular rectangular \(5^\circ \times 5^\circ\) cells, except for some
regions where smaller cells were used. The database containing their model coefficients are proprietary but not publically accessible. In this chapter, the coefficients considering the historical tracks up to year 2011 given in HURDAT are estimated. The coefficients obtained for Eq. (2.11) are illustrated in Figure 2.3, which shows that the variation of the coefficients is not smooth in some regions and that the spatial variation can be large.

![Figure 2.3. Illustration of some of the regression coefficients for Eq.(2.12) for the easterly and westerly headed storms.](image)

The relative differences are small and similar to those presented in Vickery et al. (2000b, 2009a), although the historical tracks used in the present study and in Vickery et al.(2000b,2009a) differ.
To see the adequacy of these estimated coefficients, tracks are simulated using the developed coefficients and the randomly selected hurricane genesis (i.e., location and date) from the historical events recorded in HURDAT. When a simulated track makes landfall, the filling-rate model (i.e., model for the decay of the central pressure difference after the storm making landfall due to the unavailability of oceanic heat source) given in Vickery (2005) was used. Using the simulated tracks, the mean and SD of four key parameters [i.e., (1) the annual occurrence rate, (2) storm heading, (3) storm translation velocity, and (4) central pressure difference] along the mileposts defined in Figure 2.4(a) are calculated.

![Figure 2.4. Mileposts along the Atlantic coastline (re-plotted from Vickery et al. (2000b)), and comparison of statistics from simulated and historical tracks at mileposts.](image)

For the estimation of the statistics, 100,000 years of hurricane activity are simulated; the values of $\Delta p$ used in the statistics are the largest observed within the area defined by a circle with a radius of 250 km centered at the milepost of interest and the values of other parameters are taken from the point on the track that is closest to the site. The comparison indicates that the direct use of the simulated tracks does not lead the statistics of the four key parameters comparable to those obtained from historical tracks in HURDAT. This is consistent with the observation made by Vickery et al. (2006, 2009a). To overcome this problem, the above analysis is repeated but taking into account their suggestions (see Page 303 in Vickery et al. 2009a) by adjusting the sea surface temperature in Gulf of
Mexico region and the relative humidity for the northeast coastal region, and by truncating the distribution of the track heading change.

In this case, the mean and SD of the four key parameters are calculated and compared in Figure 2.4(b) with those directly estimated from the track records in HURDAT. The comparison indicates that the statistics from the simulated tracks compare well with those obtained from historical tracks.

2.3.2 Simplified track model

There are many coefficients for the track model that need to be estimated for each cell. For a few cells, historical track data is scarce and it is unknown if the direct use of spatially interpolated coefficients is adequate.

In an attempt to improve the fit, the geographic weighted regression (GWR) method (Fotheringham et al. 2002) as implemented in ArcGIS is applied considering the track model shown in Eqs. (2.11)-(2.13). The method borrows track information from neighbouring cells or locations for the regression analysis. The analysis results indicate that the use of Eqs. (2.11)-(2.13) leads to collinearity problem, implying that the explanatory variables in the regression model should be reduced. This leads to the subsequent simplified track model,

\[
\Delta \ln c = a_i + a_2 \ln c_i + a_3 \Theta_i + \epsilon_c \\
\Delta \Theta = b_i + b_2 c_i + b_3 \Theta_i + \epsilon_\theta \\
\ln(I_{i+1}) = d_i + d_2 \ln(I_i) + d_3 \Theta_i + d_4 \left( T_{i+1} - T_i \right) + \epsilon_i
\]

(2.15)  
(2.16)  
(2.17)

The model parameters \(a_i, b_i \text{ and } c_i\) in Eqs. (2.15) to (2.17) depend on the geographical location. Unfortunately, the analysis carried out using the default setting in ArcGIS showed that the track model obtained by using coefficients developed from GWR alone does not lead to the statistics that match closely to those from historical tracks (Figure 2.4). Therefore, more detailed analysis with GWR, including potential adjustment for sea surface temperature and relative humidity, is not pursued in the subsequent text.
However, the regression analysis carried out for Eqs. (2.11) - (2.13) is repeated but considering Eqs. (2.15) - (2.17). Some of the obtained coefficients for Eq. (2.15) are illustrated in Figure 2.5. Again, spatial variation of the regression coefficients is observed in Figure 2.5 for Eq. (2.15); those for Eqs. (2.16) - (2.17) are not shown due to space limitations. The SD of the residuals shown in Figure 2.5 is comparable to that shown in Figure 2.3, indicating that the fit by the simplified track model, in terms of residuals, is comparable to those defined by Eqs. (2.11) - (2.13).

![Figure 2.5. Illustration of some of the regression coefficients for Eq. (2.15) for the easterly and westerly headed storms.](image)

To assess the adequacy of this simplified model, again, tracks for 100,000 years of hurricane activities are simulated. The statistics from the simulated tracks are shown in Figure 2.6. Comparison of the results shown in Figures 2.4 and 2.6 indicates that the performance of the simplified model, in terms of the mean and standard deviation, is comparable to that of the model defined by Eqs. (2.11)-(2.13).
Figure 2.6. Comparison of statistics from simulated and historical tracks at mileposts considering the simplified track model.

Figure 2.7. Samples of synthetic tracks: a) 60 tracks considering 60 geneses by using Eqs. (2.12) to (2.14); b) 60 tracks considering 60 geneses by using Eqs. (2.15) to (2.17); c) 100 tracks with the same genesis by using Eqs. (2.12) to (2.14); d) 100 tracks with the same genesis by using Eqs. (2.15) to (2.17).
Figure 2.7 further illustrates the tracks simulated by using Eqs. (2.11) - (2.13) and by using Eq. (2.15) - (2.17). Figure 2.7(a) shows 60 sampled tracks by using Eqs. (2.11) - (2.13); each track is associated with a genesis. Figure 2.7(b) is the same as Figure 2.7(a) except that the simulation is carried out using the model shown in Eqs. (2.15) - (2.17). Comparison of the results shown in Figs 2.7(a and b) indicates that the tracks simulated by the two track models exhibit similar statistical trend. Fig. 2.7 (c and d) present tracks sampled by using the models shown in Eqs. (2.11) - (2.13) and in Eqs. (2.15) - (2.17), respectively, but considering only a single genesis. The results illustrate the uncertainty in the track prediction and the similarity in the variability of the tracks predicted by the two models.

2.4 Comparison of the estimated extreme hurricane wind speed

First, characterization is carried out for the annual maximum hurricane (3-s gust) wind speed at a height of 10 m in open country terrain, $V$, by considering a hurricane wind hazard model (HWHM), in this case HWHM 1, in which the wind field is defined by Model A, and the track model is defined by Eqs. (2.11) - (2.13).

This is an attempt to mimic the ones given by Vickery et al. (2000b, 2009a). To estimate the $T$-year return period value of $V$ at a given site, denoted by $V_T$, 100,000 years of hurricane activity are simulated. The track and wind field models are combined to calculate the wind speed at the boundary layer height above the sites of interest. For the calculation, the position of the center of hurricane (i.e., low pressure center) is determined from the simulated track at 15-min interval (along the track). The wind field for each low pressure center is determined; the radius of the maximum wind speeds $R_{max}$ and $B$ required for solving the wind field model are calculated according to the information given in Table 2.1. The hurricane wind speed at the boundary layer height is adjusted to the gust wind speed at 10 m height using the boundary layer model and the gust factor model (Table 2.1). Samples of the annual maximum wind speed (considering the tracks fall within 250 km within the site of interest) are extracted from the calculated wind speeds from hurricanes at each site. The samples are then used to construct the empirical
probability distribution of $V$ and to estimate the needed $V_T$. To develop wind contour maps, this analysis process is carried out for grid points or sites in a rectangular pattern that are separated by 0.5° (in latitude or longitude) are used to cover the region of interest, except that the grid points separated by 0.1° for the Florida panhandle are used to achieve better resolution.

Table 2.1 Adopted models for $R_{\text{max}}$, $B$, boundary layer wind profile and gust factor.

<table>
<thead>
<tr>
<th>Model</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{\text{max}}$</td>
<td>$R_{\text{max}}$ is calculated based on the model given in Vickery and Wadhera (2008) (see also Eqs. (5) and (6) in Vickery et al. (2009a)). The model weights the $R_{\text{max}}$ from storms located at Atlantic region and Gulf of Mexico region based on the central pressure differences along the whole track. The models for the $R_{\text{max}}$ at the two regions are probabilistic models.</td>
</tr>
<tr>
<td>$B$</td>
<td>$B$ is calculated based on the equation given in Vickery and Wadhera (2008) (see also Eqs. (2) and (3) in Vickery et al. (2009a)). The calculation of $B$ requires several parameters, including $R_{\text{max}}$, the gas constant for dry air, sea surface temperature, central pressure of the tropical cyclone; difference between the $p_c$ and the far field pressure.</td>
</tr>
<tr>
<td>Boundary layer wind profile model</td>
<td>The wind speed variation along the height above the surface level is defined by the Boundary layer wind profile model. In this study, the model presented in Eq. (5) in Vickery et al. (2009b) is used. The boundary layer height parameter in the model is a function of inertial instability which is given by Kepert (2001).</td>
</tr>
<tr>
<td>Gust factor</td>
<td>The gust factor is a function of the peak factor and turbulence intensity. The model given in Eqs. (1) to (9) in Vickery and Skerlj (2005) is employed. In this model, the turbulence intensity for the marine condition and for the over land condition differ. The peak factor considers the differences between the standard deviations of the wind speed averaged over different durations.</td>
</tr>
</tbody>
</table>

The contour map for $V_T$ is shown in Figure 2.8(a) for $T = 50$ and 500 years. In general, the results shown in the figure are in agreement with those presented in Vickery et al. (2009a). However, there are differences that can be attributed to the differences in the track model. The fact that the track models used for estimating wind hazard maps were developed based on different periods of historical hurricane track records and that the final wind speed contour maps are relatively consistent demonstrated that the methodology developed by Vickery et al. (2000b, 2009a) is robust.
Figure 2.8. Maps for $V_T$ (m/s) for different hurricane wind hazard models: a) HWHM-1, b) HWHM-2, and c) HWHM-3, and d) HWHM-4.
Rather than developing the hurricane wind hazard maps using HWHM 1, the following alternatives are considered to investigate the influence of the wind field model and track model on the estimated hurricane hazard maps:

The HWHM 2: same as HWHM 1, except that Model E is used for the wind field;

The HWHM 3: same as HWHM 1, except that Eqs. (2.15) - (2.17) are used for the track model; and,

The HWHM 4: Model E is used for the wind field, and Eqs. (2.15) - (2.17) are used for the track model.

For HWHM 2-4, the wind speed contour maps for $V_{50}$ and $V_{500}$ are shown in Figs. 2.8(b-d). The comparison of $V_T$ obtained from the hurricane hazard models shown in the Figs. 2.8(b-d) indicates that they all exhibit similar trends.

The adopted wind field model mostly affects the estimated wind hazard for locations near the coastline; the influence increases as the return period increases from 50 to 500 years. For $T = 50$ years, HWHM 1 underestimates $V_T$ by about 2 to 4% as compared to that obtained using HWHM 2. Similarly, HWHM 3 underestimates $V_T$ by about 2 to 4% as compared to those obtained using HWHM 4. These values become 5 to 11% for $T = 500$ years. The increased difference for an increased $T$ can be explained by noting that $V_T$ for increased $T$ is mostly affected by rare and extreme hurricanes, and that the relative differences by neglecting $\vec{u}_c \cdot \nabla \vec{u}_p$ increases as the hurricane model parameters take the values near the ends of their typical ranges (see discussion in the previous sections).

To further inspect and to better appreciate the differences among the estimated extreme wind speed considering the four hurricane wind hazard models, the estimated $V_T$ along the mileposts is presented in Figure 2.9. The effect of the wind field alone on $V_T$ can be appreciated by comparing the results obtained by HWHM 1 and 2, and by comparing the results obtained by HWHM 3 and 4. The relative difference between the estimates obtained by using HWHM 1 and 2 is, on average, about 1% and the maximum relative difference is about 5% for $T = 50$ years. These values become 5% and 12% for $T = 500$
years, respectively. The largest difference was observed for $T = 500$ years and for sites near the milepost 1250 and 1350, which are located in southwest region of Florida. The comparison of the results obtained by using HWHM 3 and 4 leads to similar relative differences as those by using HWHM 1 and 2.

To assess the influence of the track model on $V_T$, the results obtained by using HWHM 1 and 3, as well as the results obtained by using HWHM 2 and 4. The comparison indicates that the relative difference in the estimates obtained by using HWHM 1 and 3 is, on average, about 3% and the maximum relative difference is about 10% for $T = 50$ years. These values become 4% and 10%, respectively, for $T = 500$ years. By considering HWHM 2 and 4, similar relative differences are observed.

![Figure 2.9. Comparison of $V_T$ (m/s) estimated based on four different hurricane hazard models: a) for $T = 50$ years, b) for $T = 500$ years.](image)

**2.5 Conclusions**

The effect of neglecting $\bar{u}_c \cdot \nabla \bar{u}_s$ on the wind field modeling is quantified; a potential simplification to the track model is explored. The differences in the estimated annual maximum hurricane wind speed based on four combinations of wind field and track models are presented. The conclusions that can be drawn from the numerical results are:

1) Neglecting $\bar{u}_c \cdot \nabla \bar{u}_s$ in the governing equation leads to different wind field shapes and to underestimation of the maximum wind speed. The difference increases as the translation speed of the hurricane, $\bar{u}_c$, increases. Although the underestimation in the maximum wind speed is less than 3.5% for typical key hurricane parameters such as
the central pressure difference ($\Delta p$), the underestimation could be increased if the hurricane model parameters are taking the values near the ends of their typical ranges. Also, a qualitative comparison of the calculated wind fields to the H*Wind, that are obtained from reanalysis results rather than actual observations, shows that the consideration $\mathbf{u}_e \cdot \nabla \mathbf{u}_i$ is preferable.

2) Analysis based on GWR method indicates that an existing track model could be simplified by reducing the number of explanatory variables because of the collinearity. Such a simplified hurricane track model is presented; its use results in the statistics of several important parameters [i.e., (1) annual occurrence rate, (2) storm heading, (3) storm translation velocity, and (4) central pressure difference] to be consistent with those from historical tracks at mileposts along the coastline. Although a more comprehensive analysis using the GWR and including environmental parameters, such as the sea surface temperature and relative humidity, is beyond the scope of this chapter, it does suggest that additional effort to investigate the track model could be beneficial.

3) The trends of the maps for the estimated annual maximum hurricane wind speed $V_T$ are similar for different combinations of wind field and track models. The relative difference in $V_T$ by considering different wind field model is small for a return period of 50 years, and can be in the order of 10% for a return period of 500 years. Similar observations can be made by using two different track models. Considering the uncertainties and assumptions involved in developing the hurricane hazard model, the observed consistency demonstrated that the methodology developed by Vickery and associates is robust.

References


23–34.


Chapter 3

3 Use of historical best track data to estimate typhoon wind hazard at selected sites in China

3.1 Introduction

China is severely affected by the tropical cyclones (TCs) (i.e., typhoons). The regions along the Chinese mainland coastline experience typhoon wind hazard; this is especially the case for the southeast coastal region of China. One of the typhoon wind hazard assessments was reported by Ou et al. (2002). Their assessment was focused on nine major cities in the region using an approach similar to that employed to assess the hurricane wind hazard by Georgiou (1985) and Vickery and Twisdale (1995a) for U.S. The approach referred to as circular subregion method (CSM) consists of four tasks. The first task in the CSM is to extract information from typhoon tracks that intersect and are within a circle centered at the site of a specified radius. The second task is to characterize the statistics of and to assign models for the main typhoon parameters: the annual occurrence rate, heading, translation velocity, the minimum approaching distance, and the central pressure difference. The third task is to adopt wind field model and pressure profile model, and/or to develop the wind field database (if it is needed for computational efficiency). The last task is to carry out extreme value analysis of the typhoon wind speed affecting the site of interest, which is obtained based on Monte Carlo technique. The results of Ou et al. (2002), which are obtained by adopting the wind field model given by Batts et al. (1980), indicate that the typhoon wind hazard is not negligible for the southeast coastal region of China. For example, they reported 50-year return period value of the (10-min mean) typhoon wind speed at 10 m height for Shanghai equals 33.85 or 36.24 m/s for site condition A, and 28.77 or 30.80 m/s for site condition B, where the site conditions A and B in Chinese code (GB-50009 2012) approximately relate to the over exposure and open country terrain, respectively. The first and second values for each case are obtained by adopting different distributions fitted to the simulated values. These
values are similar to those estimated by Tao et al. (2001) based on the surface wind observations.

The assessment of the typhoon hazard for Shanghai was also carried out by Zhao et al. (2005). Their study was focused on the evaluation of the reasonable range of some of the main typhoon parameters for Monte Carlo simulation and adopted the wind field model given by Meng et al. (1997). They consider that Holland pressure profile parameter, $B$, is uniformly distributed between 1.0 and 1.75. Their estimated 50-year return period value of 10-min mean wind speed at 10 m height for Shanghai by considering the roughness length $z_0$ equal to 0.08 is 39.7 m/s, which is about 32% higher than the code value of 30 m/s for $z_0 = 0.05$ (GB-50009, 2012). The assessment of $B$ applicable to Western North Pacific (WNP) and the Chinese mainland coastal region was given by Lin and Fan (2013). They concluded that for typhoons making landfall $B$ tends to be higher at lower latitude and decreases from south to north.

A more recent major study of the typhoon wind hazard for the southeast coastal region of China was reported by Xiao et al. (2011). In this case, the assessment is focused on 11 major cities in the mentioned region. Again, the analysis is carried out based on the CSM but using the wind field model originally developed by Chow (1971) and modified by Thompson and Cardone (1996). They indicated that the primary source of data used in their study is the best track dataset from China Meteorological Administration (CMA) for typhoon occurred from 1949 to 2008. Xiao et al. (2011) indicated that the data used contains standard typhoon information given at 6 hours interval and is gathered from several sources. The application of the CSM resulted in the return period values of the annual maximum typhoon wind speed for 11 cities considering a roughness length $z_0$ of 0.02 m. Their estimated 50-year return period value of the annual maximum 10-min mean wind speed at 10 m height caused by typhoons equals 43.24 m/s for Shanghai, which is greater than the code recommended value of 30 m/s (GB-50009 2012). This value is also greater than that reported in Ou et al. (2002) for the site condition B (defined in Chinese code); this is the case even after adjustment for the roughness length as well be discussed in the subsequent sections. Although the main factors causing this increase as well as the
preferred set of estimations are unknown, it must be noted that the wind field models in the two studies differ. Further comparison of the differences for additional sites will be discussed together with the results obtained in the present study.

It is noted that directly downloadable best track datasets are available at present from several websites. Ying et al. (2013) discussed the similarity of the available best track datasets, and the characteristics of the CMA TC best track dataset. The availability of the data is essential to validate the existing typhoon wind hazard and to develop new approaches for assessing typhoon wind hazard.

The present study is focused on the estimation of typhoon wind hazard for nine cities located within the coastal region of mainland China. For the analysis, the CSM is adopted. The best track dataset from the CMA is employed to develop probabilistic models for major parameters describing the typhoon activities within a specified region. The wind field solution procedure is the one discussed in Chapter 2, which is based on the wind field model developed and applied by Chow (1971), Thompson and Cardone (1996), and Vickery et al. (2000a, 2009). The return period values of the extreme typhoon wind speed for nine major cities are estimated and are compared to those reported by others and by Chinese design code.

It must be emphasized that the use of the TC track from genesis to lysis (Vickery et al. 2000a, b; Powell et al. 2005; James and Mason 2005; Emanuel et al. 2005; Hall and Jewson 2007; also in Chapter 2) is widely considered to estimate the hurricane wind hazard for coastal region in US. However, this approach is not considered in this study; this is because the hazard assessment is focused on selected sites rather than an extended region that could experience wind hazard due to the same TC events.

3.2 Database and characteristics of typhoon track alone the coastline

Tropical cyclone best track datasets for the WNP basin are provided by several organizations (Ying et al. 2013): the CMA, the Hong Kong Observatory (HKO), the Regional Specialized Meteorological Center (RSMC) in Tokyo, and the Joint Typhoon
Warning Center (JTWC) of the US Navy. The datasets are also included in the International Best Track Archive for Climate Stewardship (IBTrACCS) project (Knapp et al. 2010), which is an official World Meteorological Organization (WMO) global archiving and distribution resource for TC best track data. The IBTrACCS is an excellent resource, but it may be inhomogeneous in time and space, partly, because of the basin-to-basin variability. Even within the same basin, the TC best tracks data reported by different agencies are inconsistent. An overview of the TC best track dataset given by the CMA is presented by Ying et al. (2013). All available information from the TC best track dataset by the CMA is considered for the numerical analysis presented in the following.

The dataset (http://tcdata.typhoon.gov.cn/en/index.html, accessed January 2014) contains TC information since 1949, and includes two parts: the TC best track dataset and its supplementary data, and the TC-induced wind and precipitation observation dataset for the land area of China (which is not available at present). The TC best track dataset is focused on the TC occurring in the WNP basin and South China Sea region; the location and minimum sea level pressure are given every six hours for each track.

To appreciate the statistical characteristics of the typhoon activity from the dataset, the kilometer post (KP) are defined along the coastline of mainland China as shown in Fig. 3.1; the consideration of the islands of China is outside of the scope of this study. The distance between two adjacent KPs equals 100 km. For each of the KP, the main statistical characteristics of typhoon track parameters are evaluated: the annual occurrence rate, heading, translation velocity of typhoon, central pressure difference and the minimum approaching distance, denoted by $\lambda$, $\theta$, $u_c$, $\Delta p$ and $D_{\text{min}}$, respectively. The heading $\theta$ represents the angle between the direction of translation and the true north and is positive for the clockwise angle; $D_{\text{min}}$ is defined as positive if the site of interest is located on the right side of the typhoon’s translation direction. The results of this evaluation are used as a guide to judge the adequacy of the radius adopted for the CSM to assess the typhoon wind hazard for selected sites.
For the estimation of the statistics at a given KP, it is considered that a circle is centered at the KP with a radius $R$. The segments of the typhoon tracks that intersect and are within the circle are extracted from the dataset. The mean and standard deviation of the mentioned track parameters are evaluated. For $R$ equal to 250 km, the obtained statistics of the tracks ($\lambda_a$, $\theta$, $u_c$, $\Delta p$ and $D_{mn}$) are shown in Fig. 3.2. The observations are:

1) The annual occurrence rate is spatially varying along the coastline. This rate represents the annual average number of typhoons intersect the circle centered at the considered KP (with $R = 250$ km). The highest rate is slightly $> 4$.

![Diagram](image)

**Figure 3.1.** Definition of kilometer post (KP) for evaluating the statistical characteristics of typhoon along the coastline of mainland China and two islands.

2) The mean heading of the typhoons ranges from $-54^\circ$ to $30^\circ$. The standard deviation of the heading is relatively consistent as compared to the mean. Further inspection of the histogram of $\theta$ shows that it often exhibits bimodal characteristic, which will be discussed shortly for selected sites.
3) Both the mean and standard deviation of \( u_c \) tend to increase as the location of KP moves towards northeast. This indicates that typhoons that make landfall in the southern China are, on average, moving slower and with less variability.

4) There are steeper changes in the mean and standard deviation of \( \Delta p \) for region with latitude within about 28° N to 32° N as compared to the region outside of this latitude interval. The intensity of typhoon increases as \( \Delta p \) increases. Since the mean of \( \Delta p \) for region with latitude north of 32°N is smaller than that for region with latitude south of 28° N, the typhoon wind hazard for the former is likely to be smaller than that for the latter.

5) The spatial variation of mean and standard deviation of \( D_{\text{min}} \) is more pronounced as compared to those for \( \lambda_a \). The mean of \( D_{\text{min}} \) is close to zero, indicating that the typhoon tracks almost equally likely to pass from left or right sides of the some locations.

To investigate whether the above-listed conclusions are sensitive to the value of \( R \) used in extracting the typhoon information, the analysis carried out for \( R = 250 \) km is repeated for \( R \) equal to 150, 200, 300 and 350 km. The estimated statistics are also shown and compared with those obtained for \( R = 250 \) km in Fig. 3.2. The results indicate that the observations drawn from the results for \( R = 250 \) km are equally applicable to the range of \( R \) values considered. Moreover, it is somewhat surprising that the mean and standard deviation of \( \theta \), \( u_c \) and \( \Delta p \) and the mean of \( D_{\text{min}} \), are not sensitive to \( R \). The standard deviation of \( D_{\text{min}} \) increases as \( R \) increases as shown in Fig. 3.2. This is expected since an increase in \( R \) leads to include typhoon tracks with increased \( D_{\text{min}} \). The change in the magnitude of \( \lambda_a \) is expected since the number of the segments of typhoon tracks that intersect (or are within) a circle depends on \( R \); an increased \( R \) leads to an increased \( \lambda_a \). The ratio of \( \lambda_a \) for a given \( R \) to that for \( R = 250 \) km, denoted as \( r_{\lambda_a}(R) \), is shown in Fig. 3.3. Note that \( r_{\lambda_a}(500) \) is also calculated and shown in the Fig.3.3 for comparison purpose, since \( R = 500 \) km was employed by Xiao et al. (2011). The value of \( r_{\lambda_a}(500) \) ranges approximately within 2 to 3 (Fig.3.3). The average of this range is greater than the
ratio of the radii (i.e., 500/250=2) and is less than the ratio of the areas of the considered circles.

Figure 3.2. Statistics of several typhoon track parameters (symbols for b) to e) are the same as those shown in a)): a) Annual occurrence rate; b) Storm heading; c) Translation speed; d) Central pressure difference; e) Minimum approaching distance. Lines in plots b) to e) represent the same cases as those in plot a).

Based on the results show in Fig. 3.2 and 3.3, it is reasonable to use $R$ ranging from 200 to 300 km, with a typical value of 250 km, to estimate the typhoon wind hazard for selected sites in the following sections. The consideration of such a range is consistent with the values used by others (Vickery et al. 1995a, 1995b, Ou et al. 2002). Moreover, the selection of a typical $R$ of 250 km is also justified since the radius to the maximum 2-minute mean wind speed of 25.7 m/s for the tropical storms in the southeast coastal
region of China is mostly within 250 km (Yuan et al. 2007), and that the 50-year return period value of annual maximum 10-min typhoon mean wind speed is likely to be greater than about 30 m/s for coastal cities (GB-50009 2012).

![Graph showing estimated ratio of annual occurrence rate, r(R).](image)

### 3.3 Statistical characteristics of typhoon track around selected cities in the coastal region

The typhoon wind hazard analysis is carried out for nine selected major cities located in the southeast coastal region of China. The names of the nine cities as well as their geographic locations are shown in Fig. 3.4.

![Map showing locations of nine cities](image)

#### Table: Locations of nine cities considered in this study

<table>
<thead>
<tr>
<th>Name of City</th>
<th>Latitude (degree)</th>
<th>Longitude (degree)</th>
<th>$\lambda_w$ for $R=250$ km</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shanghai</td>
<td>31.2333</td>
<td>121.4833</td>
<td>1.36</td>
</tr>
<tr>
<td>Ningbo</td>
<td>29.8667</td>
<td>121.5167</td>
<td>1.63</td>
</tr>
<tr>
<td>Wenzhou</td>
<td>28.0167</td>
<td>120.65</td>
<td>1.97</td>
</tr>
<tr>
<td>Fuzhou</td>
<td>26.0833</td>
<td>119.3</td>
<td>2.78</td>
</tr>
<tr>
<td>Xiamen</td>
<td>24.4833</td>
<td>118.1</td>
<td>2.98</td>
</tr>
<tr>
<td>Guangzhou</td>
<td>23</td>
<td>113.2167</td>
<td>2.94</td>
</tr>
<tr>
<td>Shenzhen</td>
<td>22.55</td>
<td>114.1167</td>
<td>3.25</td>
</tr>
<tr>
<td>Hong Kong</td>
<td>22.3</td>
<td>114.1667</td>
<td>3.48</td>
</tr>
<tr>
<td>Zhanjiang</td>
<td>21.2713</td>
<td>110.3608</td>
<td>3.89</td>
</tr>
</tbody>
</table>

![Figure 3.4. Locations of nine cities considered in this study](image)
For the analysis, consider the location representing Shanghai. By extracting the information for the typhoon track segments that intersect with and fall within the circle centered at the site of interest with diameter of 250 km, samples of $\theta$, $u_c$, $\Delta p$ and $D_{\text{min}}$ are obtained and shown in Fig. 3.5 in the form of histogram, and the annual occurrence rate within the considered circle, $\lambda_{s_{\text{a}}}$, is calculated and listed in Fig. 3.4. The mean and standard deviation of ($\theta$, $u_c$, $\Delta p$, $D_{\text{min}}$) are calculated and also included in Fig. 3.5(a-d), respectively. An inspection of the results shows that the estimated $\lambda_{s_{\text{a}}} = 1.36$ for Shanghai shown in Fig. 3.4 is comparable to that presented in Fig. 3.2 for the coastline near Shanghai. This rate is smaller than that reported by Xiao et al. (2011), which equals 2.74 for $R = 500$ km, as expected. The ratio of the latter to the former equals 2.01, which is slightly smaller than $r_{\lambda_{s_{\text{a}}}} (500)$ shown in Fig. 3.3 for the location near Shanghai.

The histograms depicted in Fig. 3.5 indicate that $u_c$ and $\Delta p$ are positively skewed, $\theta$ appears to be bimodal, and $D_{\text{min}}$ may not necessarily be uniformly distributed. These observed shapes of the histograms are consistent with those reported in Ou et al. (2002) and Xiao et al. (2011). However, the statistics of the parameters differ from those reported by these references. For example, the mean value of $\Delta p$ derived from its probability distribution given by Ou et al. (2002) for Shanghai equals 31 hPa. Distribution fitting using the models listed in Table 3.1 and samples associated with Fig. 3.5 is carried out by using the maximum likelihood method. The best-fit distributions judged based on the Akaike information criterion (AIC) (Akaike 1974) for $\Delta p$ and $D_{\text{min}}$ are obtained. The Weibull distribution or the lognormal distribution can be the preferred model for $\Delta p$ depending on the considered site, and for all sites the trapezoidal distribution is preferable than the quadratic distribution and uniform distribution for $D_{\text{min}}$. The model parameters for the best-fit distributions for Shanghai are shown in Table 3.2, and the fitted distributions are presented in Fig. 3.6, showing that the fits by using the referred distributions are adequate.
Figure 3.5. Histograms of several typhoon track parameters for Shanghai.

To see the effect of $R$ on the probability distribution model parameters, the analysis carried out for $R = 250$ km is repeated but for $R = 200$ and 300 km. The results obtained are also included in Table 3.2 and Fig. 3.6. Comparison of the results shown in Fig. 3.6 indicates that in all cases the adequacy of the fit is similar. The changes in best fit distribution parameters are not very large, except those for $D_{\text{min}}$ because of the dependency of standard deviation of $D_{\text{min}}$ to $R$. Analysis similar to that carried out for Shanghai is performed for the remaining eight cities depicted in Figure 3.4. An illustration of the preferred fitted distribution is shown in Fig. 3.7 for $R = 250$ km. The conclusions drawn from the fitting results for the other eight cities are similar to those drawn from the results for Shanghai. However, it is noted that the preferred model for $\Delta p$ is not always Weibull. For $\Delta p$, the Weibull distribution is preferred model for only five out of the nine considered sites, while the lognormal distribution is the preferred model for the remaining four sites. The effect of using one or the other model for $\Delta p$ on the typhoon wind hazard will be assessed in the next section.
Table 3.1 Distribution models considered for the parameters of typhoon track.

<table>
<thead>
<tr>
<th>Distribution type</th>
<th>Mathematical equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lognormal</td>
<td>( f(x) = \frac{1}{x\sqrt{2\pi}\sigma} \exp \left( -\frac{1}{2} \left( \frac{\ln x - \mu}{\sigma} \right)^2 \right) )</td>
</tr>
<tr>
<td></td>
<td>where ( \mu ) and ( \sigma ) are mean and standard deviation of ( \ln x ), respectively.</td>
</tr>
<tr>
<td>Binormal</td>
<td>( f(x) = a \frac{1}{\sqrt{2\pi}\sigma_1} \exp \left( -\frac{1}{2} \left( \frac{x - \mu_1}{\sigma_1} \right)^2 \right) + (1-a) \frac{1}{\sqrt{2\pi}\sigma_2} \exp \left( -\frac{1}{2} \left( \frac{x - \mu_2}{\sigma_2} \right)^2 \right) )</td>
</tr>
<tr>
<td></td>
<td>where ( a ), ( \mu_i ), and ( \sigma_i ), ( i=1 ) and 2 are the model parameters.</td>
</tr>
<tr>
<td>Weibull</td>
<td>( f(x) = \frac{k}{a} \left( \frac{x}{a} \right)^{k-1} e^{-\left( \frac{x}{a} \right)^k} ) ( x \geq 0 ),</td>
</tr>
<tr>
<td></td>
<td>where ( a ) and ( k ) are model parameters.</td>
</tr>
<tr>
<td>Uniform, trapezoidal, and quadratic</td>
<td>( f(x) = \begin{cases} \frac{1}{b-a} &amp; x \in [b,a] \ 0 &amp; \text{others} \end{cases} ), ( f(y) = \begin{cases} 2ay + (1-a) &amp; \frac{x+R}{2R} \in [0,1] \ 0 &amp; \text{others} \end{cases} ),</td>
</tr>
<tr>
<td></td>
<td>( f(y) = \begin{cases} 3ay^2 + 2by + (1-a - b) &amp; \frac{x+R}{2R} \in [0,1] \ 0 &amp; \text{others} \end{cases} ),</td>
</tr>
<tr>
<td></td>
<td>where ( a ) and ( b ) are model parameters for the adopted model.</td>
</tr>
</tbody>
</table>

Table 3.2. Distribution parameters for Shanghai by considering different R values.

<table>
<thead>
<tr>
<th>Variable and distribution type</th>
<th>Distribution parameter</th>
<th>( R ) (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>250</td>
</tr>
<tr>
<td>( \theta ), Bi-normal</td>
<td>( a_1 )</td>
<td>0.23</td>
</tr>
<tr>
<td></td>
<td>( \mu_1 )</td>
<td>-62.39</td>
</tr>
<tr>
<td></td>
<td>( \sigma_1 )</td>
<td>25.17</td>
</tr>
<tr>
<td></td>
<td>( \mu_2 )</td>
<td>20.50</td>
</tr>
<tr>
<td></td>
<td>( \sigma_2 )</td>
<td>27.38</td>
</tr>
<tr>
<td>( u_c ), Log-normal</td>
<td>( \mu )</td>
<td>1.76</td>
</tr>
<tr>
<td></td>
<td>( \sigma )</td>
<td>0.52</td>
</tr>
<tr>
<td>( \Delta P ), Log-normal</td>
<td>( \mu )</td>
<td>2.86</td>
</tr>
<tr>
<td></td>
<td>( \sigma )</td>
<td>0.61</td>
</tr>
<tr>
<td>( D_{min} ), Trapezoidal</td>
<td>( a )</td>
<td>-0.10</td>
</tr>
</tbody>
</table>
Figure 3.6. Empirical and fitted cumulative distributions for $\theta$, $u_c$, $\Delta p$, and $D_{\text{min}}$ considering the site representing Shanghai with $R = 250$ km (first row), $R = 200$ km (second row) and $R = 300$ km (last row)
Figure 3.7. Empirical and fitted cumulative distributions (preferred) for $\theta$, $u_c$, $\Delta p$, and $D_{\text{min}}$ considering several sites with $R = 250$ km.
Figure 3.7. Empirical and fitted cumulative distributions (preferred) for $\theta$, $u_c$, $\Delta p$, and $D_{\text{min}}$ considering several sites with $R = 250$ km. (continued)
Figure 3.7. Empirical and fitted cumulative distributions (preferred) for $\theta$, $u_c$, $\Delta p$, and $D_{\min}$ considering several sites with $R = 250$ km. (continued)
3.4 Estimated typhoon wind hazard at selected sites

3.4.1 Wind field model

Besides of the typhoon track modeling, a wind field model is needed to estimate the typhoon wind hazard. The model adopted in this study is the one originated from Chow (1971), and subsequently, modified and/or enhanced by Cardone et al. (1992), Thompson and Cardone (1996), Vickery et al. (2000a, 2009), and in Chapter 2. The wind field model is governed by,

\[
\frac{\partial \vec{u}_s}{\partial t} + \vec{u}_c \cdot \nabla \vec{u}_s + \vec{u}_s \cdot \nabla \vec{u}_s = -f \hat{k} \times [\vec{u}_s + \vec{u}_c - \vec{u}_g] - \frac{1}{\rho} \nabla p_c + \nabla \cdot [K_H \nabla \vec{u}_s] - \frac{C_D}{h} \vec{u}_s + \vec{u}_c \left[ \vec{u}_s + \vec{u}_c \right]
\]

(3.1)

where \( \vec{u}_s \) m/s is the wind velocity relative to the moving center of the vortex, \( \vec{u}_c \) m/s is the storm translation velocity, \( \vec{u}_g \) m/s is the wind velocity resulting from the large-scale pressure field, \( f \) rad/s is the Coriolis parameter equal to \( 2\Omega \sin \psi \) at latitude \( \psi \) in degrees in which \( \Omega \) rad/s represents the rotation of the Earth with magnitude \( 2\pi / \text{day} \), \( \hat{k} \) is the unit vector in the vertical direction, \( \rho \) kg/m\(^3\) is the density of air, \( p_c \) Pa is an axisymmetric pressure field, \( K_H \) is the horizontal eddy viscosity coefficient, \( C_D \) is the surface drag coefficient and \( h \) m is the depth of the planetary boundary layer. In writing Eq. (3.1), it is considered that the total pressure \( p = p_c + p_g \), where \( p_g \) represents the large-scale pressure field, and it is assumed that,

\[
\nabla p_g = -\rho f \hat{k} \times \vec{u}_g.
\]

(3.2)

For the numerical solution of Eq. (3.1) by the finite difference method, it was noticed that the term \( \vec{u}_c \cdot \nabla \vec{u}_s \) in Eq. (3.1) was neglected in Thompson and Cardone (1996), and in Vickery et al. (2000a). The study in Chapter 2 showed that neglecting \( \vec{u}_c \cdot \nabla \vec{u}_s \) could affect the estimated wind speed and the position of the maximum wind speed with respect to the translation direction of tropical cyclones.
To use the wind field model for typhoon hazard assessment, additional models including the boundary layer wind profile, the models for estimating the radius of maximum winds $R_{\text{max}}$ and Holland pressure profile parameter $B$ to define the pressure profile, and the filling-rate model need to be developed and employed. In this study, the assembled wind field model parameters and the solution procedure described in Chapter 2, except those discussed in the following, are adopted. Note that the boundary layer wind profile model given in Eq. (3.5) in Vickery et al. (2009) with the boundary layer height parameter given in Kepert (2001) is employed; and the ratio of the 10-min mean wind speed to hourly-mean wind speed equal to 1.06 is applied. This adopted boundary layer wind profile model considers the sea to land transition effect.

It is noted that Xiao et al. (2011) developed models for $R_{\text{max}}$ and $B$ based on typhoon affecting mainland China and some available empirical information given in Chinese literature. These models are:

$$\ln R_{\text{max}} = c_0 + c_1 \Delta p + \varepsilon_{\ln R_{\text{max}}} \quad (3.3)$$

and

$$\ln B = d_0 + d_1 \ln R_{\text{max}} + \varepsilon_{\ln B} \quad (3.4)$$

where $c_0$ and $c_1$ are model coefficients; $\varepsilon_{\ln R_{\text{max}}}$ is a zero mean normal variate; $d_0$ and $d_1$ are model parameters and $\varepsilon_{\ln B}$ is a zero mean normal variate. Values of these parameters and the standard deviations of $\varepsilon_{\ln R_{\text{max}}}$ and $\varepsilon_{\ln B}$ can be found in Xiao et al. (2011). These models differ from those given in Vickery and Wadhera (2008). In particular, two of their models for $R_{\text{max}}$ (km) and $B$ are:

$$\ln R_{\text{max}} = 3.015 - 6.291 \times 10^{-5} \Delta p^2 + 0.0337 \psi + \varepsilon_{\ln R_{\text{max}}} \quad (3.5)$$

where $\Delta p$ is in hPa, the standard deviation of $\varepsilon_{\ln R_{\text{max}}}$, $\sigma_{\ln R_{\text{max}}}$ equals 0.448 for $\Delta p \leq 87$ hPa, $1.137 - 0.00792 \Delta p$ for $87$ hPa $< \Delta p \leq 120$ hPa, and 0.186 for $\Delta p > 120$ hPa; and,

$$B = 1.833 - 0.326 \sqrt{1000 f_c R_{\text{max}}} + \varepsilon_B \quad (3.6)$$
where the standard deviation of $e_B$, $\sigma_B$, equals 0.221.

For the site representing Hong Kong, a comparison of the models for $R_{\text{max}}$ shown in Eqs. (3.3) and (3.5) is plotted in Fig. 3.8(a); and a comparison of $B$ values calculated by using Eqs. (3.4) and (3.6) is presented in Fig. 3.8(b).

![Figure 3.8](image)

Figure 3.8. Comparison of the estimated $R_{\text{max}}$ and $B$: a) the estimated $R_{\text{max}}$ values by Eqs. (3.3) and (3.5); and b) estimated $B$ values by Eqs. (3.4) and (3.6).

The mean value and standard deviation of $R_{\text{max}}$ predicted by Eq. (3.3), for $\Delta p$ less than about 60 hPa, are larger than those predicted by Eq. (3.5) as seen in Fig. 3.8(a). The mean value of $R_{\text{max}}$ predicted by Eq. (3.3) for relatively small $\Delta p$ is much greater than the range of 25 to 50 km observed from aircraft reconnaissance for Western North Pacific for typical mature typhoons (Weatherford and Gray 1988). A further inspection of the results given in Xiao et al. (2011) indicates that it is unclear which of the functional forms shown in Eqs. (3.3) and (3.5) for their data are preferable. The results shown in Fig. 3.8(b) indicate that the mean of $B$ estimated by using Eq. (3.4) is much greater than that predicted by Eq. (3.6). Although the range of $B$ values is within that suggested by Holland (1980), Vickery et al. (2000b) and Willoughby and Rahn (2004), the differences between the predicted $B$ values depicted in Fig. 3.8(b) are large. Moreover, the results of Lin and Fang (2013) suggest that the mean of $B$ for typhoons that make landfall in China ranges from 1.01 to 1.33; they also indicated that the model given by Vickery and Wadhera (2008) is preferred. The range of $B$ for Shanghai in Zhao et al. (2005) is also smaller than that predicted by Eq. (3.4). Therefore, in the remaining part of this study only Eqs. (3.5) and (3.6) are considered, and the range of $B$ values within 0.8 to 2.5
recommended in Xiao et al. (2011) is considered.

The functional form for the filling-rate model used in Vickery and Twisdale (1995b) and in Vickery (2005) is given by,

$$\Delta p(t) = \Delta p_0 \times \exp(-at)$$  \hspace{1cm} (3.7)

where $\Delta p(t)$ is the central pressure difference at time $t$ since the storm making landfall; $\Delta p_0$ is the central pressure difference at the time of landfall; $a = a_0 + a_1 \Delta p_0 + \varepsilon_a$; $a_0$ and $a_1$ are model coefficients; and $\varepsilon_a$ is a zero mean normal variate.

By following the procedure employed to estimate the parameters for the filling-rate model in Vickery (2005), analysis for the filling-rate model is carried out using the best track dataset from CMA. In an attempt to take into account the effect of Taiwan Island on the typhoons that make landfall in mainland China, the entire coastal region of the mainland China is subdivided into three regions: a region with latitude that is north of 25.3° N, a region with latitude within 22° N and 25.3° N and a region with latitude that is south of 22° N. The latitude values for dividing the subregions correspond approximately to those associated with the northern and southern ends of Taiwan. The coefficients of the filling-rate model obtained for the three regions are listed in Table 3.3.

<table>
<thead>
<tr>
<th>Subregion</th>
<th>$a_0$</th>
<th>$a_1$</th>
<th>$\varepsilon_a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>North of 25.3°N</td>
<td>0.0084</td>
<td>0.00086</td>
<td>0.0261</td>
</tr>
<tr>
<td>Within 22°N and 25.3°N</td>
<td>0.0323</td>
<td>0.00061</td>
<td>0.0358</td>
</tr>
<tr>
<td>South of 22°N</td>
<td>0.0341</td>
<td>0.00048</td>
<td>0.0409</td>
</tr>
</tbody>
</table>

Similar to Vickery et al. (2000a), the numerical solution to Eq. (3.1) is fitted and stored in wind field database to be used with the track information to assess the typhoon wind hazard. For illustration purpose, five calculated wind field for selected sets of parameters are illustrated in Fig. 3.9. The results show that the maximum wind speed increases as $B$ or $\Delta p$ increases; $u_c$ influences the degree of asymmetry of the wind field; and $R_{\text{max}}$ affects the wind profile along the radial axis.
3.4.2 Simulation procedure for assessing typhoon wind hazard

The last task of the CSM is to estimate extreme value of the typhoon wind speed affecting the site of interest that is obtained based on Monte Carlo technique. The simulation for the circle centered at the site of interest with radius \( R \) is carried out for each year by:

1) Sample the number of typhoons in each year that is modeled as a Poisson process with the annual occurrence rate \( \lambda_y \).

2) For each track, calculate the maximum typhoon wind speed for the site by:

2.1) Sample \( D_{\min}, \theta, u_c \) and \( \Delta p \), according to their assigned probability distributions;
2.2) Determine the intersection points of the track with the considered circle, and find the locations of the typhoon center along the track starting from the first intersection point and with 15 minutes increment;

2.3) Apply the developed filling-rate model to determine $\Delta p$ at each location inland determined in Step 2.2). Evaluate $R_{\text{max}}$ and $B$ using Eqs. (3.5) to (3.6) that are needed to define the radial pressure profile. Extract the wind field from the wind field database according to the track information at each point determined in Step 2.2); and

2.4) Evaluate the wind speed at the site of interest by considering the boundary layer model.

3) Collect the maximum typhoon wind speed at the site due to each track and extract the annual maximum typhoon wind speed to form the time series of the annual maximum 10-min mean wind speed at 10 m height caused by typhoons, $V_A$. Use the empirical probability distribution of the annual maximum time series to find the return period value of $V_A$.

3.5 Return period value of the annual maximum typhoon wind speed

3.5.1 Effect of the modeling of the central pressure differences and comparison with existing results

For the base case, this study considers that $R = 250$ km, $D_{\text{min}}$ is distributed according to the trapezoidal distribution and $\Delta p$ is Weibull distributed. Furthermore, it is considered that $z_0 = 0.05$ m is representative for the standard site condition B suggested by the Chinese code (GB-50009 2012).

To obtain adequate number of samples, the simulation for each considered site is carried out for 10,000 years. The empirical distributions for the considered sites are shown in Fig. 3.10 in Gumbel probability paper. No attempt is made in fitting a probability
distribution to the samples shown in the figure. This is to avoid any potential error caused by selecting an inadequate distribution model to estimate the return period values of $V_A$, $v_T$, where $T$ denote the return period. However, a visual inspection of the plots indicates that the Gumbel model may not be adequate for $V_A$ if $\Delta p$ is modeled as a Weibull variate.

The identified $v_T$ from the empirical distribution functions shown in Fig. 3.10 is summarized in Table 3.4 for $T = 50$ and 100 years.

Table 3.4. Typhoon wind hazard for return period of 50 and 100 years.

<table>
<thead>
<tr>
<th>City</th>
<th>Design Codes</th>
<th>50 year</th>
<th>100 year</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Xiao et al. (2011) for $z_0$ (m)</td>
<td>This study. $\Delta p$ is modeled using</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.02</td>
<td>0.05</td>
</tr>
<tr>
<td>Shanghai</td>
<td>30</td>
<td>29/31</td>
<td>43</td>
</tr>
<tr>
<td>Ningbo</td>
<td>28</td>
<td>29</td>
<td>42</td>
</tr>
<tr>
<td>Wenzhou</td>
<td>31</td>
<td>31</td>
<td>44</td>
</tr>
<tr>
<td>Fuzhou</td>
<td>33</td>
<td>30</td>
<td>44</td>
</tr>
<tr>
<td>Xiamen</td>
<td>36</td>
<td>30</td>
<td>42</td>
</tr>
<tr>
<td>Guangzhou</td>
<td>28</td>
<td>30</td>
<td>38</td>
</tr>
<tr>
<td>Shenzhen</td>
<td>35</td>
<td>--</td>
<td>40</td>
</tr>
<tr>
<td>Hong Kong</td>
<td>38/39</td>
<td>30/36</td>
<td>41</td>
</tr>
<tr>
<td>Zhanjiang</td>
<td>36</td>
<td>--</td>
<td>39</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>City</th>
<th>Design Codes</th>
<th>100 year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shanghai</td>
<td>31</td>
<td>33/35</td>
</tr>
<tr>
<td>Ningbo</td>
<td>31</td>
<td>34</td>
</tr>
<tr>
<td>Wenzhou</td>
<td>33</td>
<td>36</td>
</tr>
<tr>
<td>Fuzhou</td>
<td>37</td>
<td>34</td>
</tr>
<tr>
<td>Xiamen</td>
<td>39</td>
<td>35</td>
</tr>
<tr>
<td>Guangzhou</td>
<td>31</td>
<td>34</td>
</tr>
<tr>
<td>Shenzhen</td>
<td>38</td>
<td>--</td>
</tr>
<tr>
<td>Hong Kong</td>
<td>39</td>
<td>34/41</td>
</tr>
<tr>
<td>Zhanjiang</td>
<td>39</td>
<td>--</td>
</tr>
</tbody>
</table>

Note: Unless otherwise indicated, the wind speed shown in the table represents 10-minute mean wind speed at 10 m height for $z_0 = 0.05$ m. The values in bold from this study represent those obtained using the preferred distribution for $\Delta p$; they are considered as preferred estimates. The first and second value showing in the column denoted as Design Code is from GB-50009 (2012) for open terrain condition and from HKBD (2004) for open sea terrain condition, respectively. In some cases, Ou et al. (2002) provided two values for a site; the first one is obtained by adopting Weibull distribution for $V_A$, and the second one by adopting Gumbel distribution for $V_A$. 


Before carrying out the comparison of the results with those found in the literature, it is noted that the lognormal is preferred for $\Delta p$ for four out of nine locations. Therefore, it is desirable to repeat the analysis carried out for the base case but considering $\Delta p$ as a lognormal variate to investigate the sensitivity of $v_T$ to probabilistic model for $\Delta p$. The obtained empirical distributions of the annual maximum wind speed for the considered locations are also shown in Fig. 3.10 and Table 3.4.

The results show that the empirical distribution of the annual maximum typhoon wind speed follows approximately the Gumbel distribution if $\Delta p$ is modeled as a lognormal variate. The comparison shown in Fig. 3.10 and Table 3.4 indicates that $v_T$ estimated based on lognormally distributed $\Delta p$ is greater than that based on Weibull distributed $\Delta p$. The relative differences are up to 8% for $T = 50$ years, and up to 12% for $T = 100$ years. The relative differences increase as $T$ increases. These differences can be important for structural design under wind load and need to be scrutinized using different best track datasets in a future study.

To verify the adequacy of the estimated $v_T$, it is noted that Holmes et al. (2009) showed that the estimated 50-year return period value of the hourly-mean wind speed (caused by Typhoons) for open terrain condition at 200 m height equals 47.5 m/s, which is less than the code value (HKBD 2004). Their estimate is obtained based on historical surface wind observations. By adopting power law wind profile with the exponent of 0.11 and the ratio of 10-min mean to hourly-mean wind speed equal to 1.06, the estimated 10-min mean wind speed at 10m height equals 36.2 m/s. The estimated $v_T$ in this study shown in Table 3.4 (which equals 36 m/s if the preferred model for $\Delta p$ is used) compares favourably to this value. Moreover, it is noted that $v_T$ reported by Tao et al. (2001) based on the historical surface wind observations and distribution fitting equals 31.3, 32.2 and 28.3 m/s for $T = 50$ years, and 33.3, 35.0, and 29.4 m/s for $T = 100$ years, if the Pearson type III, Gumbel and Weibull distributions are adopted for the distribution fitting, respectively. Unfortunately, there is neither detail on the comparison of adequacy of the fit nor original historical data made available. The estimated $v_T$ in this study shown in
Table 3.4 which equals 29 m/s for $T = 50$ years and 31 m/s for $T = 100$ years are within those given by Tao et al. (2001).

The above comparison with those based on surface observations for Shanghai and Hong Kong validates the values estimated and the procedure employed in this study. To identify the differences between the results of this study and those in the literature, this study included the estimated return period values given in Ou et al. (2002), Xiao et al. (2011), Chinese code (GB50009 2012) and HKBD (2014) in Table 3.4. The values reported by Chinese code (GB50009 2012) and Ou et al. (2002) are for site condition B that is considered to correspond to $z_0 = 0.05$ m. Since the value given by Xiao et al. (2011) is for $z_0 = 0.02$ m, for consistency, these values are converted to those for $z_0 = 0.05$ m using logarithmic wind profile (Dyrbye and Hansen 1996).

The results shown in Table 3.4 indicate that:

1. The preferred estimate of $v_{50}$ in this study is greater than or equal to that recommended in codes for all considered sites, except for Shanghai and Shenzhen where the difference is about 1 m/s for $T = 50$ years, and for Hong Kong where the value is equal to that reported by Holmes et al. (2009). For the sites where the code values are lower than the preferred estimates, the differences are up to 6.8% for $T = 50$ and 7.8% for $T = 100$ years. The largest differences are for Ningbo and Wenzhou.

2. The estimated $v_{50}$ in this study is consistently greater than or equal to those reported in Ou et al. (2002), except for Shanghai and Guangzhou.

3. The estimated $v_T$ is comparable to that reported by Xiao et al. (2011) for cities located in the south of Xiamen. However, for cities located in the north of Xiamen the values given by Xiao et al. (2011) are much greater than those obtained in this study or recommended by Chinese code. Part of this difference is likely due to the observed differences in the models for $B$ shown in Fig. 3.8.
The above observations could be important for updating the typhoon wind hazard in design codes since detailed information on the analysis leading to the recommended wind speed values for the coastal region is unavailable in the open literature and the historical surface wind observations for typhoon wind speeds is short.

3.5.2 Effect of the subregion size and distribution model for $D_{\text{min}}$

The estimation carried out for $R = 250$ km in the previous section is repeated by considering $R = 200$ and 300 km. In all cases, the difference in $v_T$ estimated by using different $R = 200$ or 300 km to the corresponding value estimated by using $R = 250$ km is within 5%.

Similarly, this study maintains the same condition as those used to estimate the values shown in Table 3.4, except the probability distribution of $D_{\text{min}}$ is replaced by the uniform distribution. Again, in all cases, the differences in estimated $v_T$ values by using the trapezoidal distribution and by using the uniform distribution are < 2%.

3.6 Conclusions

An assessment of typhoon wind hazard for nine major cities located in the coastal region of mainland China is carried out. The assessment is based on the CSM and uses typhoon wind field and track models. The adopted wind field model is the well-accepted model used to assess hurricane hazard implemented in ASCE code. The probabilistic characterizations of typhoon tracks for a subregion with radius $R$ around the site of interest are carried out using the best track data from CMA. Statistical analysis shows that the mean and standard deviation of the storm heading, translation velocity, and the central pressure difference are insensitive to $R$. Similarly, the mean of the minimum approaching distance, $D_{\text{min}}$, is insensitive to $R$; the standard deviation of $D_{\text{min}}$ and the annual occurrence rate of typhoon within the considered circle increase as $R$ increase, which is expected. The distribution fitting indicates that the preferred model for $\Delta p$ is the
Weibull distribution for five out of the nine considered sites, while the lognormal distribution is the preferred model for the remaining sites.

The results show that the estimated wind hazard is relatively insensitive to the size of the subregion considered, but it is affected by the adopted probability distribution model for $\Delta p$ as the return period increases. The estimated wind hazard for Shanghai and Hong Kong is comparable to those based on surface wind observations found in the literature, which validate the values estimated and the procedure employed in this study. The results also shown that the code recommended return period values for several cities are lower than those obtained in this study by up to 8%. The largest differences are for Ningbo and Wenzhou.
Figure 3.9. Empirical distribution of annual maximum typhoon wind speed based on simulated samples.
References


Cardone VJ, Greenwood CV, Greenwood JA. (1992). Unified program for the specification of hurricane boundary layer winds over surfaces of specified roughness. *Coastal Engineering Research Center US Army Engineer Waterways Experiment Station*.


Vickery PJ, Wadhera D, Powell MD, Chen Y. (2009). A hurricane boundary layer and


Chapter 4

4 Typhoon wind hazard estimation for coastal region in mainland China

4.1 Introduction

Tropical cyclones (TCs) affect the coastal region of mainland China. The direct economic loss due to TCs in China is about 25 billion yuan (i.e., RMB = Ren Min Bi) per year from 1983 to 2008 and is increasing (Zhang et al. 2009, Xiao and Xiao 2010). Strong tropical cyclones are known as typhoons in China (GB/T19201-2006 2006). Typhoon hazards are often characterized in terms of extreme wind speed, storm surges and rainfall. Typhoon season is from May to November but occurs most frequently during July to September in the region. There are about eight or nine typhoons that make landfall per year. Chinese structural design code (GB 50009 2012) explicitly states that both the synoptic and typhoon winds are considered in specifying the design wind load. However, the estimation of the return period values of the typhoon wind speed is not elaborated in the code. The estimation is not straightforward due to the unavailability of sufficient temporal and spatial surface observations of extreme typhoon wind speeds. Moreover, the direct use of the maximum sustained wind speed reported in the best track dataset (Ying et al. 2014) to estimate the return period value of the annual maximum typhoon wind speed can be too conservative since this maximum wind speed of a TC applies only to a small area within the wind field of the TC.

A literature review indicates that the TC wind hazard analysis for a few cities located in the coastal region of mainland China was carried out by Ou et al. (2002), Zhao et al. (2005), Xiao et al. (2011) and study in Chapter 3. These studies use the circular subregion method (CSM), which is similar to that used to assess the tropical cyclone (i.e., Hurricane) wind hazard by Georgiou (1985) and by Vickery and Twisdale (1995a, b) for the United States. The approach requires the statistical characterization of segment of historical typhoon tracks within the circle, the use of an adopted wind field model, and the estimation of the annual maximum typhoon wind speed using Monte Carlo technique.
Since the parameters controlling the typhoon occurrence rate, the intensity of the wind field and the track characteristics directly influence the estimated typhoon wind hazard, it is essential that the typhoon wind hazard assessment to be carried out based on a well-documented best track dataset. Besides of the CSM, the full track approach could also be used to assess the TC wind hazard. For example, Vickery et al. (2000, 2009b), Powell et al. (2005), James and Mason (2005), Emanuel et al. (2005), Hall and Jewson (2007), and study in Chapter 2 used the full track approach to estimate hurricane wind hazard for the United States. The application of the full track approach is more involved since it requires the statistical characterization and modeling of tracks from genesis to lysis. The use of the full track approach is necessary if it is of interest that the wind hazard and risk assessment of portfolio of spatially distributed buildings or large infrastructure system due to scenario tropical cyclones. However, the estimated extreme wind speeds at a site due to tropical cyclones by the full track approach and the CMS should be consistent if the statistical characteristics of the track models in both methods match those of historical data for a subregion surrounding the site of interest. Since this study is focused on the estimation of typhoon wind hazard due to all possible TC, rather than typhoon wind hazard at multiple sites due to the same TC, no further consideration of full track approach is made.

The available best track datasets that are applicable to the coastal region of mainland China are discussed in Ying et al. (2011, 2014). Ying et al. (2011) compared three best track datasets covering the western North Pacific (WNP) and South China Sea from: the Japan Meteorological Agency Regional Specialized Meteorological Center in Tokyo, the Joint Typhoon Warning Center of the US Navy, and the Shanghai Typhoon Institute of China Meteorological Administration (CMA). The comparison is focused on annual cycle of TC activity and data homogeneity, and shows that the basic statistical characteristics of the annual cycle are different among the three datasets. Ying et al. (2014) also discussed the three best track datasets but mainly focused on the characteristics of the best track dataset from the CMA (see http://tcdata.typhoon.gov.cn/). They described the reliability of the data from the CMA in terms of the completeness and the accuracy of the recorded data by using different techniques, including the satellite
image and/or aircraft renaissance results. They also explained the timeline when the change of sources of raw data and other important events occurred for the TC dataset since 1949. Most importantly, they indicated that the TC tracks from the CMA are longer for the TC near the coastline and after making landfall. This is important for the typhoon wind hazard assessment. Although the application of this TC best track dataset to estimate the typhoon wind hazard is carried out for nine cities and the estimations compare well with those from surface observations for Shanghai and Hong Kong (Chapter 3), the overall spatial trends of the typhoon wind hazard for the coast region is unclear and the TC wind hazard map for coastal region is unavailable in the literature.

The objectives of this study are to characterize the statistics of major parameters describing the typhoon track characteristics for the coastal region of mainland China, to assess the spatial variability and inhomogeneity of these parameters, and to estimate the return period values of annual maximum typhoon wind speed. For the analysis, the TC best track dataset from the CMA is considered; and an assessment is carried out for the characteristics of the annual occurrence rate, heading, translation velocity of typhoon, and central pressure difference and the minimum approaching distance. Using the developed track characteristics, the typhoon wind hazard estimation is carried out based on the CSM mentioned earlier with the wind field model and solution procedure elaborated in Chow (1971), Thompson and Cardone (1996), Vickery et al. (2000a, 2009b) and study in Chapter 2. The estimated return period values of the annual maximum typhoon wind speed is compared to those recommended in Chinese design code. The comparison could allow us to answer the question on whether the design wind pressure recommended in Chinese design code for the coastal regions is adequate given there is no sufficient details on their assessment.

4.2 Characteristics inferred from best track dataset

4.2.1 Statistics based on best track dataset

The TC best track datasets for the WNP basin can be obtained from the CMA, the Hong Kong Observatory, the Regional Specialized Meteorological Center in Tokyo, and the
Joint Typhoon Warning Center of the US Navy. The TC best track dataset reported by different agencies are inconsistent. Ying et al. (2011) compared the characteristics of the datasets in terms of annual cycle of TC activity and data homogeneity. They indicated that the basic statistical characteristics of the annual cycle are different among the three datasets, and that the quality of the CMA best track data is higher for the TC near the coastline and after making landfall, which is important for the typhoon wind hazard assessment. Ying et al. (2014) concluded that the use of the TC best track dataset since 1949 from the CMA is preferred. Unfortunately, the dataset containing TC-induced wind and precipitation observation for the land area of China described in Ying et al. (2014) is not released at present.

Based on the above considerations, the TC best track dataset from the CMA (http://tcdata.typhoon.gov.cn/, accessed January 2014) is used in the following. The dataset records the location and minimum sea level pressure every six hours. Since the use of the CSM to estimate the typhoon wind hazard for the coastal region of mainland China is considered in the following, statistics of the tracks must be assessed using the TC best track. For a given site of interest, the CSM assumes that the statistics and probability models of the track parameters are applicable within a circle of radius $R$. The track parameters are the annual occurrence rate, heading, translation velocity of typhoon, and central pressure difference and the minimum approaching distance, denoted by $(\lambda_a, \theta, u_c, \Delta p, D_{\text{min}})$, respectively. The probability models of $(\lambda_a, \theta, u_c, \Delta p, D_{\text{min}})$ are used together with an adopted wind field model to estimate the typhoon wind hazard through Monte Carlo technique, as illustrated in Fig. 4.1. The occurrence of TC that intersects the circle is assumed to be a Poisson process with the rate equal to $\lambda_a$.

The numerical analysis is carried out for each of the grids defined in Fig. 4.2. A few grid points are labeled A to G and will be discussed latter. To estimate the statistics for a given grid shown in Fig. 4.2, it is considered a circle centered at the grid of interest with a radius $R$. The TC tracks that intersect and are within the circle are extracted from the best track dataset. The mean and/or standard deviation of $\lambda_a$, $\theta$, $u_c$, $\Delta p$ and $D_{\text{min}}$ are evaluated for the extracted tracks by considering the segments of the tracks within the circle with $R$
equal to 250 km. The obtained statistics are shown in Fig. 4.3. For the contour plots shown in Fig. 4.3, the ordinary kriging is employed. This is because the root mean square error from (leave-one-out) cross-validation statistical analysis for the ordinary kriging is smallest for several considered deterministic and geostatistical methods: the inverse distance weighting method, global/local polynomial interpolation method, radial basis functions method (also known as splines), ordinary kriging, simple kriging, and universal kriging (Cressie 1993; Johnston et al. 2003). Since the cross-validation statistical analysis carried out also indicates that the ordinary kriging is preferred for the remaining contour plots in this study, unless otherwise indicated this technique is employed below for spatial interpolation.

Figure 4.1. Illustration of the circular subregion method.
Figure 4.2. Sites considered for evaluating the statistical characteristics of typhoon along the coastal region of mainland China.

The results presented in Fig. 4.3(a) indicates that the annual occurrence rate, representing the annual average number of TCs intersect the circle (with $R = 250$ km) centered at the considered site, is spatially varying. The rate at inland sites decreases with increasing distance from coastline. This is expected since TC losses the energy source and is dissipated as it moves towards inland. As shown in Fig. 4.3(b), the mean of $\theta$ ranges from -83° to 10°; the standard deviation of the $\theta$ is relatively consistent as compared to the mean and with a typical value of about 56°. The mean of $\theta$ decreases from east to southwest, although this trend is not very marked. Both the mean and standard deviation of $u_c$ shown in Fig. 4.3(c) tend to increase as the TC moves towards northeast, indicating that the TCs that make landfall on the northeast coastlines of mainland China are, on average, moving faster. Moreover, the mean of $u_c$ at inland sites tends to increase with increasing distance from coastline. There are large spatial variations of the mean and standard deviation of $\Delta p$ as shown in Fig. 4.3(d). The higher mean of $\Delta p$ along the coastline for Zhejiang Province (Fig. 4.2) suggests that the return period value of the TC wind speed for this region may be comparable to that for the Southern provinces, even though $\lambda_p$ for Zhejiang Province is lower than that for the Southern provinces. The trend that the mean of $\Delta p$ decreases as the TCs move towards inland and away from the
coastline is expected because of energy dissipation and unavailability of oceanic heat source. As will be seen, this dissipation leads to decreased typhoon wind hazard for the inland locations away from the coastline since the intensity of TC depends on $\Delta p$. The spatial inhomogeneity of the mean and standard deviation of $D_{\text{min}}$ is shown in Fig. 4.3(e). For sites with the mean (and median) of $D_{\text{min}}$ less than zero, the TC is more likely to travel on the right of the side (Fig. 4.1 for definition of $D_{\text{min}}$).

To assign probability distribution models for $\theta$, $u_c$, $\Delta p$ and $D_{\text{min}}$, following Georgiou (1985), Ou et al. (2002), Xiao et al. (2011) and study in Chapter 3, it is considered that $\theta$ can be modeled by using the bi-normal, $u_c$ can be modeled as a lognormal variate, $\Delta p$ can be modeled as a Weibull or lognormal variate, and $D_{\text{min}}$ can be fitted using the uniform or trapezoidal distribution function or quadratic polynomial probability density function.

![Figure 4.3](image)

Figure 4.3. Statistics of several typhoon track parameters for $R = 250$ km: a) Annual occurrence rate; b) Storm heading; c) Translation speed; d) Central pressure difference; e) Minimum approaching distance. For figures with two plots, the upper one is the mean value and lower one is the standard deviation.
Although the distribution fitting is carried out for each site shown in Fig. 4.2, for illustration, this study only shows the fitted distributions only for seven selected sites labelled as A to G in Fig. 4.2. These sites are close to Datangpo, Wuzhou, Macau, Ruijin, Jiaobei, Ningde and Shanghai. The sites A, C, E and G are selected to represent the sites along the coastline, while the sites B, D and F are selected to represent the inland sites and about 200 km away from the coastline. By carrying out the distribution fitting using the maximum likelihood method and applying the Akaike information criterion (AIC) (Akaike 1974) to select the preferred distribution among the considered distribution models for each of the random variables, the preferred best fit distributions for the seven sites are shown in Fig. 4.4. In all cases, the fit is considered to be adequate based on visual inspection. As shown in Fig. 4.4, depending on the considered site, the Weibull distribution or the lognormal distribution could be the preferred model for $\Delta p$. 

![Distribution Fitting Diagrams](image)
Figure 4.4. Empirical and fitted cumulative distributions for $\theta$, $u_c$, $\Delta p$, and $D_{\text{min}}$ considering seven selected sites (Sites of A to G shown in Fig. 4.2 are plotted from top to bottom).

For $D_{\text{min}}$, the trapezoidal distribution is preferred for all selected sites based on AIC. To inspect the spatial variation of the preferred models, a plot of the preferred distribution type for $\Delta p$ is shown in Fig. 4.5. The results presented in the figure indicate that in most cases, the lognormal distribution is preferred. The Weibull distribution is preferred for regions in Guangzhou, Zhejiang, and Jiangxi Provinces and for regions away from coastline in Fujian Province. Although a physic-based explanation for such preferences cannot be provided, it may indicate that the change in the preferred distribution type along the coastline is caused by the effect of the Taiwan and Hainan islands.

Figure 4.5. Spatial variation of the preferred distributions for $\Delta p$. 
4.2.2 Sensitivity of statistics to the size of subregion

To explore the effect of $R$ on the statistics of or probability distribution models for $\lambda_a$, $\theta$, $u_c$, $\Delta p$, and $D_{\min}$, the analysis carried out in the previous section is repeated for $R = 150$ and 350 km. Since the mean and standard deviation of $\theta$, $u_c$, and $\Delta p$, and the mean of $D_{\min}$ obtained for $R = 150$ and 350 km are similar to those for $R = 250$ km, they are not shown. However, the spatial variation of $\lambda_a$ and the standard deviation of $D_{\min}$ are affected by the considered $R$. This is presented in Fig. 4.6 for $R = 150$ and 350 km.

![Figure 4.6](image)

Figure 4.6. Statistics of annual occurrence rate and $D_{\min}$. The plots for a) and b) are for $R = 150$ km, while the plots for c) and d) are for $R = 350$ km.

The results shown in Fig. 4.6 and Fig. 4.3 indicate that the value of $\lambda_a$ and the standard deviation of $D_{\min}$ increases as $R$ increases. This is expected since an increase in $R$ results in the inclusion of TC tracks with an increased $D_{\min}$ to the site, and a greater number of TCs that intersect with the circle. The ratio of $\lambda_a$ for a given $R$ to that for $R = 250$ km, ranges approximately within 0.4 to 2.5. On average, the ratio is about 0.6 for $R = 150$ km and 1.5 for $R = 350$ km. This implies that the average ratio is approximately equal to $R/250$, and $\lambda_a$ is approximately and linearly proportional to $R$. Also, the probability distribution fitting exercise is carried out for $\theta$, $u_c$, $\Delta p$ and $D_{\min}$ by considering the cases with $R = 150$ and 350 km. Since the conclusions drawn from the results obtained based
on $R = 250$ km are equally applicable to those obtained based on $R = 150$, and 350 km, plots of the fitted distributions are not presented.

4.3 Modeling of wind field model, filling-rate model and pressure profile

The analysis in the following uses the wind field model presented in Chow (1971), and subsequently, modified and enhanced by Cardone et al. (1992), Thompson and Cardone (1996), Vickery et al. (2000a, 2009b) and study in Chapter 2. The model is described by the following equation,

$$
\frac{\partial \vec{u}_s}{\partial t} + \vec{u}_c \cdot \nabla \vec{u}_s + \vec{u}_s \cdot \nabla \vec{u}_s = -\hat{k} \times [\vec{u}_s + \vec{u}_c - \vec{u}_g] - \frac{1}{\rho} \nabla p_c + \nabla \cdot [K_H \nabla \vec{u}_s] - \frac{C_D}{h} \vec{u}_s + \vec{u}_c [\vec{u}_s + \vec{u}_c]
$$

(4.1)

where $\vec{u}_s$ m/s is the wind velocity relative to the moving center of the vortex, $\vec{u}_c$ m/s is the storm translation velocity, $\vec{u}_g$ m/s is the wind velocity resulting from the large-scale pressure field, $f$ rad/s is Coriolis parameter equal to $2\Omega \sin \psi$ at latitude $\psi$ in degrees in which $\Omega$ rad/s represents the rotation of the Earth with magnitude $2\pi$/day, $\hat{k}$ is the unit vector in the vertical direction, $\rho$ kg/m$^3$ is the density of air, $p_c$ Pa is an axisymmetric pressure field, $K_H$ is the horizontal eddy viscosity coefficient, $C_D$ is the surface drag coefficient and $h$ m is the depth of the planetary boundary layer which is considered to be equal to 1000 m. In writing Eq. (4.1), it is considered that the total pressure $p = p_c + p_g$, where $p_g$ represents the large-scale pressure field, and it is assumed that $\nabla p_g = -\rho f \hat{k} \times \vec{u}_g$. For the numerical solution of Eq. (4.1), solving scheme given in Chapter 2 in followed, including the consideration of $\vec{u}_c \cdot \nabla \vec{u}_s$ and the adopted model parameters except the filling-rate model, radius to maximum winds $R_{\text{max}}$ and Holland pressure profile parameter $B$ to define the pressure profile that are discussed below. The solution to Eq. (4.1) needed to define the wind field is illustrated in Figure 4.1.

The filling-rate model describes the decay of the central pressure difference after the
storm making landfall because of the unavailability of oceanic heat source and energy dissipation. Some of the earlier models can be found in Batts et al. (1980), Georgiou et al. (1983), and Georgiou (1985). The filling-rate model in Batts et al. (1980) depends on the time since the storm making landfall, and the angle between the storm moving direction and coastal line; the model in Georgiou (1985) depends on the distance traveled inland after landfall. A model presented in Vickery (2005) has the following form,

\[ \Delta p(t) = \Delta p_0 \times \exp(-at) \]  

(4.2)

where \( \Delta p(t) \) is the central pressure difference at time \( t \) since the storm making landfall; \( \Delta p_0 \) is the central pressure difference at the time of landfall; \( a = a_0 + a_1 \Delta p_0 + \varepsilon_a \); \( a_0 \) and \( a_1 \) are model coefficients to be determined; and \( \varepsilon_a \) is a zero mean normal variate with standard deviation \( \sigma_{\varepsilon_a} \).

Since a segment of the typhoon track may already made landfall before intersecting with a circular subregion and the time of landfall and \( \Delta p_0 \) are unknown, there is insufficient information to apply Eq. (4.2). To overcome this, this study notes that for a typhoon that has already made landfall and intersected a circular subregion at time \( \tau \), with pressure \( \Delta p(\tau) \), Eq. (4.2) can be re-written as,

\[ \Delta p(t_1 + \tau) = \Delta p(\tau) \times \exp(-a t_1) = \Delta p(\tau) \times \exp\left(-\left(a_0 + a_1 \Delta p_0 + \varepsilon_a\right) t_1\right) \]  

(4.3)

where \( \Delta p(t_1 + \tau) \) is the central pressure difference at time \( t_1 \) since making landfall. Based on Eq. (4.3), one could adopt the following approximate filling-rate model,

\[ \Delta p(t_1 + \tau) \approx \Delta p(\tau) \times \exp\left(-\left(a_0 + a_1 \Delta p(\tau) + \varepsilon_a\right) t_1\right) \]  

(4.4)

Alternatively, the following empirical model for a circular subregion could be considered,

\[ \Delta p_L(t_1) = \Delta p_{L0} \times \exp\left(-\left(h_0 + h_1 \Delta p_{L0} + \varepsilon_h\right) t_1\right) \]  

(4.5)
where $\Delta p_L(t)$ is the central pressure difference at time $t$, since the intersection with the circle for the typhoon that has already made landfall, $\Delta p_{L0}$ is the central pressure difference at the time of intersection, $b_0$ and $b_1$ are model coefficients to be determined, and $\varepsilon_b$ is a zero mean normal variate with standard deviation $\sigma_{\varepsilon_b}$.

By using the TC best track dataset from the CMA and Eq. (4.2), Chapter 3 carried out regression analysis and suggested that $(a_0, a_1, \sigma_{\varepsilon_b})$ for three subregions: region north of 25.3°N; region south of 22°N, and region between 22°N and 25.3°N. The separation of three subregions is an attempt to take into account the effect of Taiwan Island on the typhoons that make landfall in mainland China. A more detailed inspection of the information on the best track dataset and some preliminary analysis results of typhoon wind hazard for the entire coastal region by using the filling-rate model developed in Chapter 2 suggest that there is a need for improvement. This is because many TCs that made landfall in Taiwan Island and subsequently made landfall in the mainland China, referred to as DL (double-landfall) TCs, affect a wider coastal region than from 22°N and 25.3°N as shown in Figure 4.7. For example, there are 80% of DL TCs making landfall within 23.5°N and 27°N.

![Figure 4.7. Tracks for TCs that made landfall in Taiwan island and subsequently made landfall in the mainland China.](image)

By considering three subregions: region north of 27°N; region south of 23.5°N, and region between 23.5°N and 27°N, and carrying out regression analysis, the obtained regression coefficients of the filling-rate model are listed in Table 4.1. The model shown
in Table 4.1 is an improvement over the one given Chapter 3 since the average of the $\sigma_{ea}$ values given in Chapter 3 is greater than the average of those shown in Table 4.1. It should be noted that since $\epsilon_a$ is normally distributed, the value of the filling rate, 
\[ a = a_0 + a_1 \Delta p_o + \epsilon_a, \]
could be negative, resulting in an increased intensity for the landfalling TCs which is uncommon. To overcome this problem, a lower limit on $a$ is imposed for its application. By considering Eq. (4.5) and carrying out the regression analysis, the spatially varying model parameters estimated are shown in Fig. 4.8. As can be observed from the figure, the model parameters are geographically varying. The variation of $b_0$ and $\sigma_{eb}$ are moderate and the spatial variation of $b_1$ for west of Guangxi and east of Fujian is much pronounced. The magnitude of $\sigma_{eb}$ is similar to that of $\sigma_{ea}$ for most part of Fujian, Guangdong and Guangxi provinces. It must be emphasized that Eq. (4.5) with the model parameters shown in Fig. 4.8 applies to the segments of typhoon tracks that are within the considered circular subregion for the site of interest and for TCs that made landfall prior to intersect with the considered circular subregion.

<table>
<thead>
<tr>
<th>Region</th>
<th>$a_0$</th>
<th>$a_1$</th>
<th>$\sigma_a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>North of 27 °N</td>
<td>0.0374</td>
<td>0.00025</td>
<td>0.0333</td>
</tr>
<tr>
<td>Within 23.5 °N and 27 °N</td>
<td>0.0066</td>
<td>0.0013</td>
<td>0.0307</td>
</tr>
<tr>
<td>South of 23.5 °N</td>
<td>0.0298</td>
<td>0.00068</td>
<td>0.0281</td>
</tr>
</tbody>
</table>

Figure 4.8. Spatially varying model parameters for Eq. (4.5).

Given the central pressure $\Delta p$, $R_{max}$ km and $B$ could be evaluated using (Vickery and Wadhera 2008),
\[ \ln R_{\text{max}} = 3.015 - 6.291 \times 10^{-5} \Delta p^2 + 0.0337 \psi + \varepsilon_{\ln R_{\text{max}}} \quad (4.6) \]

where \( \Delta p \) is in hPa, the standard deviation of \( \varepsilon_{\ln R_{\text{max}}} \), \( \sigma_{\ln R_{\text{max}}} \), equals 0.448 for \( \Delta p \leq 87 \text{hPa} \), 1.137-0.00792\( \Delta p \) for \( 87 \text{hPa} < \Delta p \leq 120 \text{hPa} \), and 0.186 for \( \Delta p > 120 \text{hPa} \); and,

\[ B = 1.833 - 0.326 \sqrt{1000 f_c R_{\text{max}}} + \varepsilon_B, \quad (4.7) \]

where the standard deviation of \( \varepsilon_B \), \( \sigma_B \), equals 0.221. Although an assessment of the accuracy of Eqs. (4.6) and (4.7) for the coastal region of mainland China is valuable, it cannot be carried out due to lack of available quality data. Eqs. (4.6) and (4.7) are adopted in the following, since their use results in the estimated typhoon wind hazard comparable to that estimated by using the surface wind observations for Shanghai and Hong Kong (Chapter 3).

Similar to Vickery et al. (2000a), for computational efficiency, numerical solutions to Eq. (4.1) are fitted, stored in wind field database to be used with the track information to assess the typhoon wind hazard. Moreover, to evaluate the wind speed at 10 m height, the boundary layer wind profile model given in Eq. (4.5) in Vickery et al. (2000b) with the boundary layer height parameter suggested by Kepert (2001) is employed, and the ratio of the maximum 10-min mean wind speed to hourly-mean wind speed equal to 1.06 is employed. For the model development it also considered the Engineering Science and Data Unit (ESDU; 1982) (sea to land) transition model but with the limiting fetch distance reduced to 20 km.

Before carrying out the typhoon wind hazard assessment for the considered region, an illustration of the wind field model for two simulated track segments is shown in Fig. 4.9. It indicates that the wind field and maximum wind speed are influenced by \( u_c \), \( \Delta p \), \( B \) and \( R_{\text{max}} \).
To provide additional indication of the adequacy of the wind field model, two historical typhoons are considered including typhoon York in 1998 and typhoon Hagupit in 2008. The ground observations of the wind speeds were considered by Pande et al. (2002) for typhoon York, and were considered by Xiao et al. (2011) and Xiao (2011) for typhoon Hagupit. For typhoon York, the wind speed and direction at the recording site are calculated by solving Eq. (4.1) using the same track information and wind field parameters that are used by Pande et al. (2002). The time histories of the wind speed and wind direction are shown in Fig. 4.10(a). Similarly, the analysis for typhoon Hagupit is carried out but using the track information and wind field parameters used in Xiao (2011), except $R_{\text{max}}$ is calculated by using Eq. (4.6) because it is not given in Xiao (2011). The results are shown in Fig. 4.10(b) and compared with the values estimated from the wind record. The comparison shown in Fig. 4.10 further indicates the adequacy of the considered wind field model.
Figure 4.10. Comparison of the modeled and observed typhoon wind direction and velocity time history for a) and b) typhoon York at Waglan Island and c) and d) typhoon Hagupit at Yangjiang.
4.4 Contour maps for typhoon wind hazard

4.4.1 Comparison with design code values

Before carrying out the simulation analysis, it is noted that in the Chinese design load code (GB 50009, 2012) the reference wind pressure is tabulated for many locations. This reference wind pressure is estimated using 50-year return period value of the annual maximum wind speed (representing 10-min mean wind speed at 10 m height for open country exposure). Moreover, a lower bound value of 0.30 kPa is imposed to specify the reference wind pressure (for 50-year return period value); and the tabulated wind pressure is rounded upward and to the nearest 0.05 kPa. The code also explicitly stated that both the synoptic and typhoon winds are treated in the same manner in the code, although the estimation of the typhoon wind hazard is not elaborated in detail in the code or commentaries. A map for the design pressure corresponding to the return period of 50 years, and the values of design pressure corresponding to the return periods of 10, 50 and 100 years are also provided in the code.

The contour map given in the code is digitized and presented in Fig.4.11(a). For comparison purpose, the tabulated wind pressure in the code is also used to calculate the 50-year return period value of the wind speed for the coastal region. These values are presented in Fig. 4.11(b). Comparison of the maps shown in Figs. 4.11 (a and b) indicates that there are differences. Unfortunately, the source of the differences is unknown as no information is given in the code on the procedure leading to the interpolated map or the tabulated value. Moreover, a preliminary analysis by using some available surface wind observations indicates that these 50-year or 100-year return period values for the sites in coastal region are most due to typhoon winds.
Figure 4.11. 50-year return period values of annual maximum wind speed for the coastal region inferred from the Chinese design code, a) digitalized from the map given in the code; b) calculated based on the table given in the code.

4.4.2 Base case

To estimate the typhoon wind hazard, settings and models are considered as: $R = 250$ km; the filling-rate model shown in Eqs. (4.2) and (4.4); and the preferred distribution models for $\theta$, $u_c$, $\Delta \rho$ and $D_{\text{min}}$ determined from statistical analysis described in the previous section. This is referred to as Base Case.

Let $V$ denote the annual maximum typhoon (10-min mean) wind speed at 10 m height for open country exposure. By carrying out the analysis as outlined in Fig. 4.1 considering a simulation cycle for 10,000 years, samples of $V$ for each location defined in Fig. 4.2 are obtained and the $T$-year return period value of $V$, $v_T$, are estimated from the empirical distribution for $T = 50$ and 100 years. The estimated values are used as the basis to develop the contour maps plotted in Fig. 4.12. Ordinary kriging is used to map Fig. 4.12(a and c) with setting nugget not equal to zero; but with nugget equal to zero for developing Fig. 4.12(b and d), so more detailed (or less smoothed) contours can be appreciated. As expected, the comparison of Fig. 4.12(a and c) to Fig. 4.12(b and d) indicates that the former leads to smoother contours but with less detail than the latter.
Figure 4.12. Estimated return period value of 10-min mean wind speed at 10 m height due to typhoon $v_T$: a) $v_T$ for $T = 100$ years using ordinary kriging with nugget not equal to zero and b) $v_T$ for $T = 50$ years using ordinary kriging with nugget equal to zero, c) $v_T$ for $T = 50$ years using ordinary kriging with nugget not equal to zero, d) $v_T$ for $T = 100$ years using ordinary kriging with nugget equal to zero.

Comparison of the contours presented in Fig. 4.12 (a and b) to the contours depicted in Fig. 4.11(a) indicates that the spatial trends in these figures are similar, and the contours depicted in Fig. 4.12(b) follow closely to the coastline. The comparison also shows that the locations of the developed contours with $v_T$ ranging from 31 to 38 m/s match closely.
to those given in the design code but with more details if the interpolation is carried out using nugget equal to zero. The locations of the contours for $v_T$ ranging from 22 to 28 m/s shown in Fig. 4.12(a and b) differ from those shown in Fig. 4.11(a), especially for the contour line with $v_T = 22$ and 25 m/s. In general, as the site moves away from the coastline, the typhoon wind hazard estimated in this study decreases slower than that inferred from the current design code.

4.4.3 Discussion on the effect of subregion size, and modeling in central pressure difference and filling-rate

The estimated typhoon wind hazard may be influenced by the considered size of the subregion (i.e., $R$), the probability distribution type for $\Delta p$, and the filling-rate model. A parametric investigation is presented in this section by considering Base Case but changing $R$, the distribution of $\Delta p$, or the filling-rate model, one at the time which is defined as Case 1 to Case 5 shown in Table 4.2. For each case listed in Table 4.2, the analysis similar to that for Fig. 4.12 is carried out. The results are shown in Fig. 4.13, where the contours are interpolated using the ordinary kriging with nugget not equal to zero. Those interpolated with nugget equal to zero, that exhibit similar trends as those shown in Fig. 4.12 (b and d), are not presented to save space.

<table>
<thead>
<tr>
<th>Case</th>
<th>Conditions same as those for the Base case, except</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$R=150$ km</td>
</tr>
<tr>
<td>2</td>
<td>$R=350$ km</td>
</tr>
<tr>
<td>3</td>
<td>$p$ is lognormally distributed for all sites</td>
</tr>
<tr>
<td>4</td>
<td>$p$ is Weibull distributed for all sites</td>
</tr>
<tr>
<td>5</td>
<td>Replacing Eq. (4.4) by Eq. (4.5) as an approximation</td>
</tr>
</tbody>
</table>

Some observations drawn from the comparison of the results shown in Figs. 4.12 (a and c) and those depicted in Fig. 4.13 are:

1) The decrease of $R$ from 250 km to 150 km (i.e., Case 1), leads to the contours shown in Figs. 4.13(a and b). These contours are similar to those presented in Figs. 4.12(a and c). A more detailed inspection of the results indicates that the contours are shifted towards coastline by about 10 to 20 km. If $R$ is increased from 250 km to 350 km (i.e.,
Case 2), the resulting contours are shown in Figs. 4.13(c and d). The trend on the shift is reversed as compared to Case 1. This is especially the case for the contours with $v_{50} = 22$ m/s or $v_{100} = 25$ m/s. By considering $T = 50$ and 100 years, on average, the estimated $v_T$ at a site is increased up to 4\% by varying $R$ from 150 km to 250 km, and 5.8\% by varying $R$ from 250 km to 350 km. Therefore, the use of $R = 250$ km for the typhoon wind hazard estimation is considered. Note that $R = 250$ km is also used by Georgiou (1985) and Vickery and Twisdale (1995a, b).

2) By considering that $\Delta p$ is lognormally distributed throughout the region (Case 3), rather than using the preferred distribution identified in Fig. 4.5, the estimated $v_T$ in the affect zones (i.e., zones with Weibull distributed $\Delta p$ replaced by lognormally distributed $\Delta p$) within Guangdong and Zhejiang provinces is increased up to 9\% for $T = 50$ years and 12\% for $T = 100$ years. The average increase for the mentioned zones is 1.7\% for $T = 50$ years and 2.3\% for $T = 100$ years. The increase reflects by the fact that the contours within these zones are shifted towards inland, and that the use of lognormal model instead of Weibull model for $\Delta p$ leads to an increased estimate of typhoon wind hazard. For the results shown in Fig. 4.13(g and h) – corresponding to Case 4 – the estimated $v_T$ is decreased by up to 1.7\% for $T = 50$ years and 2.5 \% for $T = 100$ years for the sites where the lognormal model is replaced by Weibull model for $\Delta p$ (Fig. 5). This again indicates that the use of lognormal distribution for $\Delta p$ results in a greater $v_T$ than that obtained by using the Weibull distribution for $\Delta p$.

3) The results for Case 5 are presented in Fig. 4.13(i and j). As the model coefficients for the filling-rate model shown in Fig. 4.8 is spatially varying, the trends on the differences between $v_T$ shown in Fig. 4.12(a and c) and those shown in Fig. 4.13(i and j) are spatially varying. The spatial trends on the differences are not entirely clear or systematic. However, in all cases, the relative differences range from -6\% to 6\%. The average value of the absolute relative difference is within 2\%. Among the considered grid points, there are only 4 sites with a relative difference greater than 5\% if $T = 50$ years is considered. The number of sites become 6 if $T = 100$ years is considered.
Figure 4.13. Estimated return period value of 10-min mean wind speed at 10 m height due to typhoon, $v_T$, considering cases 1 to 5 shown in Table 4.2. Plots a), c), e), g) and i) show $v_{50}$ for Cases 1 to 5, respectively; plots b), d), f), h) and j) show $v_{100}$ for Cases 1 to 5, respectively.
Figure 4.13 (Continued). Estimated return period value of 10-min mean wind speed at 10 m height due to typhoon, $v_T$, considering cases 1 to 5 shown in Table 2. Plots a), c), e), g) and i) show $v_{50}$ for Cases 1 to 5, respectively; plots b), d), f), h) and j) show $v_{100}$ for Cases 1 to 5, respectively.

4.5 Conclusions

The return period value of the annual maximum TC wind speed, $v_T$, is estimated in the present study for coastal region of mainland China. For the estimation, the circular subregion method is applied and the TC track model for a circular subregion centered at each point of interest is assessed using the best track dataset from the CMA.

The analysis results of the tracks indicate that the annual occurrence rate of TC track intersecting the circle, is spatially varying, and decreases as the circle moves away from the coastline and towards inland, which is expected. The mean of the heading varies
widely and decreases from east to southwest; the standard deviation of the heading is relatively consistent as compared to the mean. The landfall TCs on the northeast coastlines of mainland China are, on average, moving faster, and translation velocity tends to increase as the TC moves towards inland and away from the coast. By considering the lognormal and Weibull distributions, the analysis results show that there are clearly identified zones where the lognormal (or the Weibull) distribution is the preferred model for the central pressure difference. The estimated \( v_T \) are used to develop the contour maps for typhoon wind hazard. The locations of the developed contours with \( v_T \) ranging from 31 to 38 m/s match closely to those given in the design code; the locations of the developed contours for \( v_T \) ranging from 22 to 28 m/s moved further inland as compared to those given in the design code, implying that the code underestimates the typhoon wind hazard. Sensitivity analysis also shows that \( v_T \) is not very sensitive to the radius of the circular subregion. For a return period equal to 100 years, the consideration of spatially varying filling-rate model or the approximate model shown in Eq. (4.4) alters \( v_T \) by less than 6%; the use of lognormal or Weibull distribution to model \( \Delta p \) affect the estimated \( v_T \) by up to 12%.

References


Chapter 5

5 Typhoon Wind Hazard Estimation for China Using an Empirical Track Model

5.1 Introduction

China experiences severe tropical cyclone (TC) wind hazard and risk every year (Zhang et al. 2009; Xiao and Xiao 2010). A strong TC is known as typhoon in China (GB/T19201 2006); the typhoon wind hazard is explicitly considered in Chinese design code (GB 50009 2012). The extreme TC wind hazard can be estimated using surface wind observations if sufficient data are available. However, the observations are rare at a meteorological station and for a short number of years. To overcome the lack of sufficient data, the TC wind field and track models are often used to simulate and map the TC wind hazard. For example, the design wind speeds recommended in the ASCE 7-05 (2005) and ASCE 7-10 (2010) are developed based on the simulation results using the hurricane wind field and track models (Vickery et al. 2009c).

The wind field models used for engineering applications include the gradient wind field model (Batts et al. 1980; Georgiou 1985; Lee and Rosowsky 2007) and planetary boundary layer wind field model (PBL) (Chow 1971; Thompson and Cardone 1996; Vickery et al. 2009a; Chapter 2). The gradient wind field model is simple but cannot cope with the asymmetric characteristics of the observed TC wind field. The PBL wind field model is developed by considering the steady condition for the momentum equation being averaged through the depth of the boundary layer and neglecting the vertical velocity. The adequacy of this model has been assessed by Vickery et al. (2009a; 2009b) for the landfalling hurricane in the US. Its use for the landfalling TC events affecting China is also considered by Xiao et al. (2011), and study in Chapter 3. Other models that considered in the literature include those given by Meng et al. (1995), Kepert (2001) and Kepert and Wang (2001).
The modeling of the TC tracks can be classified as local track modeling and full track modeling. The local track modeling is based on the statistics of the key parameters of the TC tracks within a circle whose center is located at a site of interest, where the TC wind hazard is to be estimated (Georgiou 1985). This approach is referred to as the circular subregion method (CSM). The key parameters are the annual occurrence rate, heading, translation velocity, minimum distance from the site to the track and central pressure difference. The use of CSM to assess the hurricane wind hazard for US is considered by Georgiou (1985) and Vickery et al. (1995). It is used to estimate the typhoon or TC wind hazard for China by Ou et al. (2002), Zhao et al. (2005), Xiao et al. (2011), studies in Chapter 3 and Chapter 4. The terms typhoon wind hazard and TC wind hazard are used interchangeably throughout this study for winds caused by TC affecting China, even though the intensity of a TC may be less than that of the typhoon class defined in GB/T19201 (2006). The full track modeling is developed to describe the TC track from genesis to lysis; it can be used to estimate the TC wind hazard and risk for spatially distributed structures due to a single or multiple TC events; it can also be used as the basis to estimate the extreme TC wind hazard for a region. Different approaches are considered in the literature to develop full track models (Vickery et al. 2000b; Powell et al. 2005; James and Mason 2005; Emanuel et al. 2006; Hall and Jewson 2007). The model developed by Vickery et al. (2000b) considers that the hurricane track (position and relative intensity) can be modeled using the regression equations with spatially varying model coefficients. This model is adopted in Chapter 2, where it also showed that the model could be simplified; the use of the two models lead to comparable estimated TC wind hazard maps for the US. The TC track is represented as a Markov process in Powell et al. (2005); the changes in the motions and intensity of TC track are sampled using their probability distribution functions assessed based on historical best track dataset. In James and Mason (2005), an autoregressive model was considered to predict the changes in the TC location and the central pressure. One of the models proposed in Emanuel et al. (2006) is based on Markov chain; it considered that the probability of displacement change is conditioned on position, season, and the previous 6-hour vector displacement. The model presented in Hall and Jewson (2007) assumes that the TCs
within a location of the Atlantic basin tend to move in a similar manner but with uncertainty; the motions of a hurricane over a 6-hour interval and along the latitude and longitude depend only on its present position; and that the probability distributions of the motion can be assessed using historical tracks. The mentioned full track models are developed to assess TC hazards for the US. It seems that the full track model applicable to western North Pacific (WNP) basin, in particular, to assess typhoon wind hazard for coastal region of China, is unavailable in the literature.

The two main objectives of this study are to develop an empirical track model based on the historical track information, and to map the TC wind hazard in the coastal region of the mainland China. A simple mathematical functional form (Chapter 2), that was used to model the tracks from genesis to lysis for hurricane occurred in Atlantic basin, is adopted. The model coefficients in the present study are determined through regression analysis by using the information on the historical tracks available from the China Meteorological Administration (CMA) (Ying et al. 2014). The use of the best track dataset from the CMA is justified (Ying et al. 2011, 2014) since for the landfalling TCs in the mainland China it is preferable than the track datasets from the Joint Typhoon Warning Center of the US Navy, and from the Japan Meteorological Agency Regional Specialized Meteorological Center in Tokyo. The developed track model is validated by comparing the statistics of several key TC parameters along the coastline estimated from the simulated tracks and from historical tracks. For the mapping of TC wind hazard, a well-established planetary boundary layer wind field model, including the model parameters found in the literature (Vickery et al. 2000a, 2009b; Vickery and Wadhera 2008; Chapter 2), are adopted and the TC tracks simulated by using the developed track model are considered.

In the following sections, first, relevant statistics derived from the best track dataset considered are presented. This is followed by the development of the empirical track model, and the application of the developed track model to evaluate and map the TC wind hazard.
5.2 Statistics of the considered best track dataset

The best track dataset available from the CMA (Ying et al. 2014) covers the region north of the equator and west of 180°E, including the South China Sea (SCS) from 1949 to 2012 (http://tcdata.typhoon.gov.cn/, accessed 2013). The dataset contains the information on each TC track at every 6 hours including the time, location (latitude and longitude), intensity category, and the minimum pressure near the TC center. The intensity category (IC) of the TC given in the best track dataset is based on the following definition: tropical depression (Category 1), tropical storm (Category 2), severe tropical storm (Category 3), typhoon (Category 4), severe typhoon (Category 5), and super typhoon (Category 6). This classification system is recommended in GB/T19201 (2006). The wind speed interval is 10.8-17.1 m/s for IC = 1, 17.2-24.4 m/s for IC = 2, 24.5-32.6 m/s for IC = 3, 32.7-41.4 m/s for IC = 4, 41.5-50.9 m/s for IC = 5, and ≥51.0 m/s for IC = 6, where the wind speed represents the near surface maximum 2-min mean wind speed near the TC center.

The dataset also contains the sub-centers of TC - circulation centers associated with warm cores and induced by the parent TCs (Ying et al. 2014). The sub-center is a phenomenon only recorded in the CMA best-track dataset. The consideration of some of the sub-centers as independent TC events could be important. Criteria given in Ying et al. (2014) to classify the sub-centers are: C1) if a sub-center develops for a period while its parent TC quickly decays, it can be considered as an extension of its parent TC; C2) if a sub-center develops into or maintains at least an intensity of tropical storm category (i.e., IC = 3), while its parent TC persists for a significant period, it can be considered as an independent TC; and C3) if the sub-center is weak and quickly decays, it can be excluded in the analysis. They indicated that approximately 40 TCs generating sub-centers recorded in the dataset can be classified according to C1 to C3. An inspection of the best track dataset is also carried out in this study by adopting the suggested criteria. This resulted in a total of 51 sub-centers. The duration of the storm associated with the sub-center varies from 6 to 156 hours. The highest intensity of 38 out of the 51 storms is up to IC = 2; four of them fall within C1 which are listed in Table 5.1, and the other 35 which
fall within C3 are neglected. The remaining 13 out of 51 storms that are associated with the sub-centers have the highest IC equal to 3 or 4. Four of the 13 sub-centers are associated with fast decay and short duration; they fall within C3. In addition, one sub-center (starting on Aug. 11 at 00:00 from the named TC, Mary in 1974) among the 13 sub-centers could be neglected because its genesis is located within the inland of the mainland China and its intensity was low while translates within the concerned region. Inspection of the eight (out of 13) sub-centers indicates that two of them fall within C2, and six of them fall within C1. These eight sub-centers are also listed in Table 5.1. Note that nine of the twelve events shown in Table 5.1 were already identified in Ying et al. (2014).

**Table 5.1** Sub-centers shown in the CMA best track dataset classified according to Criteria C1 and C2.

<table>
<thead>
<tr>
<th>Year</th>
<th>Month</th>
<th>Day</th>
<th>Hour</th>
<th>Name of Parent TC</th>
<th>Criterion</th>
</tr>
</thead>
<tbody>
<tr>
<td>1952</td>
<td>8</td>
<td>7</td>
<td>0</td>
<td>Jeanne</td>
<td>C1</td>
</tr>
<tr>
<td>1959</td>
<td>9</td>
<td>7</td>
<td>18</td>
<td>Nora*</td>
<td>C1</td>
</tr>
<tr>
<td>1960</td>
<td>8</td>
<td>8</td>
<td>0</td>
<td>Trix*</td>
<td>C2</td>
</tr>
<tr>
<td>1963</td>
<td>7</td>
<td>18</td>
<td>18</td>
<td>Wendy*</td>
<td>C1</td>
</tr>
<tr>
<td>1963</td>
<td>7</td>
<td>19</td>
<td>18</td>
<td>Wendy*</td>
<td>C1</td>
</tr>
<tr>
<td>1971</td>
<td>10</td>
<td>10</td>
<td>12</td>
<td>Faye*</td>
<td>C2</td>
</tr>
<tr>
<td>1982</td>
<td>7</td>
<td>29</td>
<td>0</td>
<td>Andy*</td>
<td>C1</td>
</tr>
<tr>
<td>1984</td>
<td>7</td>
<td>3</td>
<td>6</td>
<td>Alex*</td>
<td>C1</td>
</tr>
<tr>
<td>1989</td>
<td>9</td>
<td>11</td>
<td>12</td>
<td>Sarah</td>
<td>C1</td>
</tr>
<tr>
<td>1990</td>
<td>9</td>
<td>7</td>
<td>12</td>
<td>Dot</td>
<td>C1</td>
</tr>
<tr>
<td>1992</td>
<td>8</td>
<td>31</td>
<td>18</td>
<td>Polly*</td>
<td>C1</td>
</tr>
<tr>
<td>1997</td>
<td>8</td>
<td>20</td>
<td>0</td>
<td>Winnie*</td>
<td>C1</td>
</tr>
</tbody>
</table>

Note: * represents the named storms having sub-centers that were identified in Ying et al. (2014). Wendy has two sub-centers.

By considering the best track dataset, including the identified sub-centers listed in Table 5.1, the spatial distribution of the geneses of the TCs in the WNP basin is illustrated in Fig. 5.1(a), showing that the location of the genesis is spatially distributed with concentrations within 5°N to 25°N. There are about 17% of the geneses located west of 120°E. The mean and the variance of number of TCs in each year, X, are 32 and 48,
which is fitted by using the negative binomial distribution (see Fig. 5.1(b)). The choice of this distribution is justified since such a model is considered in Vickery et al. (2000b) and Chapter 2 for hurricanes occurred in Atlantic basin, and the model is preferable than the Poisson model for cases where the mean of $X$ is smaller than its variance. The probability mass function of the negative binomial distribution, $p(x)$, is,

$$p(x) = \binom{x+r-1}{x} (1-p) p^x$$  

(5.1)

where $x$ is the value of $X$, and $r$ and $p$ are the distribution parameters. The mean and variance of $X$ are equal to $(1-p)r/p$ and $(1-p)r/p^2$. The fitted distribution is compared to the empirical distribution of $X$, indicating that the fit is adequate.

Figure 5.1 Distribution of the genesis based on the CMA best track dataset: a) Spatial distribution of genesis; b) Probability distribution of number of TCs per year.

To qualitatively appreciate the TC wind hazard, each data point (i.e., latitude, longitude and IC reported at 6-hour interval) for each TC track is extracted. The point is presented in Figs. 5.2(a) to 5.2(e) for IC = 2 to 6, respectively. Figure 5.2 shows that part of inland of the mainland China is affected by TCs with IC = 2 and 3, the coastal region experiences TCs with IC ranging from 2 to 6, but mostly only up to IC = 4, and the islands, including Taiwan, is impacted by TCs with IC greater than 4. To appreciate the statistical characteristics of the TC tracks, the mean and standard deviation of the key TC parameters including annual occurrence rate $\lambda$, heading $\theta$ (°), translation velocity $c$ (m/s) and central pressure difference $\Delta p$ (hPa) at kilometer posts (KPs) shown in Figure 5.3 are
estimated based on the CMA best track dataset. The heading $\theta$ represents the angle between the direction of translation and the true north and is positive for the clockwise angle. The KP0 is placed at the boundary between China and Vietnam and at the coastline; the distance between the adjacent KPs equals 100 km.

Figure 5.2. Spatial distribution of points on TC tracks that are extracted according to their intensity category: a) Intensity Category 2, b) Intensity Category 3; c) Intensity Category 4; d) Intensity Category 5; e) Intensity Category 6.
For the estimation of the statistics at a KP, $(\lambda, \theta, c, \Delta p)$ for the segments of TC tracks that intersect and are within a circle centered at the KP of interest with a radius $R = 250$ km are considered. The use of $R = 250$ km has been considered and justified by others (Vickery et al. 2009a; Chapter 2) through parametric investigation. The obtained statistics are presented in Figure 5.4.

![Figure 5.4](image)

Figure 5.3. Definition of the kilometer posts (KPs).

Figure 5.4(a) shows the value of $\lambda$, representing the average number of tracks per year that intersect the circle centered at the KP of interest with a radius $R = 250$ km. $\lambda$ attains its maximum value near KP300, $\lambda$ decreases from south to north starting from KP300, and $\lambda$ is less than unity north of KP2500. The mean of $\theta$ exhibits an increasing trend from south to north; it varies from $0^\circ$ and $30^\circ$ for regions north of KP2000. The variation of the standard deviations of $\theta$ along the coastline is much less than its mean value. The mean of $c$ shows an increasing trend from south to north. This may be due to that a slow moving TC over the cold water is likely to be dissipated. The spatial trend of the standard deviation of $c$ is similar to that of the mean of $c$; standard deviation of $c$ is about one-half of its mean. The mean and standard deviation of $\Delta p$ are presented in Fig. 5.4(d); $\Delta p$ is a critical parameter controlling the intensity of TC. It shows in Fig. 5.4(d) that values of the
statistics of $\Delta p$ for sites north of KP2500 are much lower than those for sites south of KP2500, indicating that the typhoon wind hazard for north of KP2500 is not very important as compared to that for the south of KP2500. Based on this observation, the typhoon wind hazard to be carried out in the following sections will mainly focused on the coastal region that is south of KP2500.

Figure 5.4. Statistics of the TC parameters at the KPs calculated from historical best track dataset.

### 5.3 Empirical TC track model

Several hurricane wind hazard models applicable to the US are developed; the models developed by Vickery et al. (2000b, 2009b) are used as the basis to map the hurricane wind hazard in ASCE 7-05 (2005) and ASCE 7-10 (2010). For the hurricane wind hazard estimation, a track model was employed. A comparison of the performance of their track model and a simplified version with less model parameters is given in Chapter 2, showing that the simplified track model is adequate in terms of the estimated statistics of the key parameters ($\theta, c, \Delta p$) and hurricane wind hazard. Therefore, the mathematical
form of this simplified model is considered in this study. The model estimates the (future) state at $i + 1$ of the TC track given the current state at $i$ is known, and is expressed as,

$$\Delta \ln c = a_1 + a_2 \ln c_i + a_3 \theta_i + \varepsilon_c$$  \hspace{1cm} (5.2)

$$\Delta \theta = b_1 + b_2 c_i + b_3 \theta_i + \varepsilon_\theta$$  \hspace{1cm} (5.3)

$$\ln(I_{i+1}) = d_1 + d_2 \ln(I_i) + d_3 T_s + d_4 (T_{s,i} - T_s) + \varepsilon_I$$  \hspace{1cm} (5.4)

where $a_i$, $b_i$ and $d_i$ in Eqs. (5.2) to (5.4) are the geographically dependent model parameters; $c$, $\theta$, $T_s$ and $I$ with subscripts are the translation velocity m/s, heading in degree, sea surface temperature (SST) °K, and relative intensity of the TC. The relative intensity is defined as $I = (p_{da} - p_c + e_s)/(p_{da} - p_{dc})$, where $p_c$ hPa = central pressure, $p_{da}$ hPa = ambient pressure, $p_{dc}$ hPa = minimum sustainable surface value of central pressure (of dry air), and $e_s = 6.112 \times \exp\left[17.67 \times \left(\frac{T_s - 273}{T_s - 29.5}\right)\right]$ is the saturation vapour pressure. In Eqs. (5.2) and (5.3), $\Delta \ln c = \ln c_{i+1} - \ln c_i$ and $\Delta \theta = \theta_{i+1} - \theta_i$.

To determine the model coefficients, the geographical region covering the map shown in Fig. 5.1(a) is subdivided into $5^\circ \times 5^\circ$ square cells; information is extracted from the historical best track dataset for each cell; regression analysis is carried out separately, for easterly and for westerly headed storms. For the analysis, since $T_s$ is unavailable in the best track dataset, the monthly averaged SST derived from the HadISST dataset from 1870 to 2011 (Rayner et al. 2003), which has a $1^\circ \times 1^\circ$ resolution (http://www.metoffice.gov.uk/hadobs/hadisst/data/download.html, accessed, 2012) is employed. The use of this SST and the $5^\circ \times 5^\circ$ square cells is similar to that in Chapter 2. For cells with little or no historical track information the coefficients are assigned based on adjacent cells. Moreover, regression analyses for $2^\circ \times 2^\circ$ and $1^\circ \times 1^\circ$ square cells for regions near coastline are also considered for a better spatial resolution of the model coefficients if the cell contains sufficient statistics of the TC tracks. The obtained coefficients for Eq. (5.2) are illustrated in Fig. 5.5, showing non-smooth spatial variation of the coefficients.
Figure 5.5. Illustration of obtained coefficients for Eq.(5.2) for easterly (left) and westerly (right) headed storms.

To generate synthetic TC track catalogue, including the track information from genesis to lysis, the number of TCs in each year is generated according to the negative binomial
distribution shown in Eq. (5.1) and the distribution parameters shown in Fig. 5.1(b). The genesis of each TC is randomly selected from the geneses of the historical TCs, and the track is simulated using the developed empirical track model given in Eqs. (5.2) to (5.4) and by considering $T_s$ equal to the monthly averaged SST derived from the HadISST dataset. However, a preliminary analysis carried out by using the simulated tracks indicates that the statistics of the key parameters estimated by using the simulated tracks for a few KPs differ from those obtained from the historical best track dataset shown in Fig. 5.4. This may be partly due to the use of the monthly average SST which may not capture the local and temporal variation of ocean current and eddies. There are two regions in the WNP having seasonal warm currents accompanied by warm eddies (Lin et al. 2005; Pun et al. 2011; Hu et al. 2000) affecting the TC intensification. One lies within 10°N to 26°N, 121°E to 170°E identified as southern eddy zone (Pun et al. 2011) and the other covers the SCS (Hu et al. 2000). A detailed investigation of the seasonal variability of the warm eddies and its effect on TCs is beyond the scope of this study. To overcome the inability of using monthly average SST in taking into account the effect of the warm eddies on the intensification of the TCs, an increased SST for some regions is considered. The practice of increasing the SST for some regions was also considered by Vickery et al. (2009c) to model hurricane wind hazard for the US. In this study, it was found by trial and error that for Southern Eddy zone in the WNP, an increase of the SST for the region from 15°N to 26°N, and from 121°E to 140°E and for the region from 15°N to 19°N and from 114°E to 118°E is considered for the empirical track model.

To show the adequacy of the simulated tracks with the above mentioned adjustment, the mean of $\lambda$, and the mean and standard deviation of $\theta$, $c$ and $\Delta p$, which equals 1010 - $p_c$ hPa with $p_c$ calculated using the simulated relative intensity $I$, are estimated for the KPs up to KP2400. For the estimation of statistics, 100,000 years of TC activities are simulated and used throughout this study. The estimated values are shown in Fig. 5.6 and compared with those obtained by using the historical best track dataset. It shows in Fig. 5.6 that the statistics of the key parameters of the simulated TCs match well with those
calculated using the best track dataset, especially considering that there is statistical uncertainty in the estimated statistics using the historical tracks.

Figure 5.6. Comparison of the statistics of the TC parameters at KPs calculated from simulated and historical best track dataset.

To further inspect the adequacy of the simulated tracks, the probability that a track intersects two circles of radius of $R = 250$ km, one centered at the KP$i$ and the other centered at the KP$k$, denoted as $P(KP_i \cap KP_k)$, is calculated using the simulated tracks. The estimated probability is shown in Fig. 5.7 and compared with that calculated using the best track dataset. The close agreement between the results obtained by using the simulated and historical tracks indicates that the developed track model is adequate, at least, in reproducing the spatial statistics of the tracks near the coastline.

As there are 64 years of historical tracks included in the considered best track dataset (from 1949 to 2012), samples of tracks for 64 years are simulated and compared to historical tracks in Fig. 5.8 to appreciate their overall spatial trends. As showing all the
simulated tracks in a single plot does not facilitate the comparison, tracks are presented in two groups to better appreciate the spatial trends of the tracks.

Figure 5.7. Comparison of the estimated joint probability $P(KP_i \cap KP_k)$ using the simulated and historical tracks.
Figure 5.8. Spatial trends of historical (Panels a and c) and simulated (Panels b and d) tracks.

More specifically, each track shown in Panels a) and b) in the figure has a segment falling within “south region” (Latitude within [15°, 25°] and Longitude within [105°, 118°]); each track shown in Panels c) and d) in the figure has a segment falling within “east region” (Latitude within (25°, 35°] and Longitude within (118°, 125°)). A visual inspection of the results shown in the Fig.5.8 indicates that the spatial trends of the simulated tracks follow those of the historical tracks. It also shows in Fig. 5.8 that, on average, tracks shown in Panels a) and b) tend to head towards west, whiles those shown in Panels c) and d) tend to head towards northeast.
5.4 Wind field model and filling-rate model

In addition to the track model, a TC wind field model is required to assess the TC wind hazard. Among several TC wind field model employed for engineering application, the wind field model originally proposed in Chow (1971) and subsequently extended and enhanced by others (Thompson and Cardone 1996; Vickery et al. 2000a, 2009a) has been considered. The model requires the solution of the momentum equation to obtain the PBL wind field. It was verified by comparing the modeled hurricane wind speeds to those observed at the meteorology stations (Vickery et al. 2009a). A systematic comparison of the modeled snapshots of the hurricane wind fields to the re-constructed surface hurricane wind fields obtained from the Hurricane Wind Analysis System (i.e., H*Wind) (Powell et al. 1998) is given in Chapter 2. The estimated typhoon wind speed time series is also compared to those observed at meteorology stations for Typhoon York and Typhoon Hagupit (Chapter 4).

It must be emphasized that the above mentioned verification and comparison involve the consideration of additional models: model for the radius to maximum winds $R_{\text{max}}$; model for Holland pressure profile parameter $B$; and boundary layer wind profile model. The values of $R_{\text{max}}$ and $B$ are needed to solve the momentum equations; the boundary layer wind profile model is used to estimate the wind speed at 10 m height above the surface using the wind speed obtained from the PBL wind field model. These models that are summarized in Table 5.2 are adopted in the present study.

Use of the assembled typhoon wind field model to estimate the wind field, time series of the wind speed and wind direction at a site and the wind hazard due to the passage of Typhoon York (see Fig. 5.9(a)) is illustrated. In estimating the wind field shown in the figure at given instances, the track information and wind field parameters given in Pande et al. (2002) are employed. The wind speed obtained from the calculated wind field is then converted to the hourly mean wind speed at 82 m height above the ground surface, where an anemometer is located. The predicted wind speed and wind direction at a particular site such as the Waglan Island site (22.18°N, 114.3°E) is then recorded for Typhoon York (occurred in 1999). The modeled wind field for two instances is illustrated
in Fig. 5.9(b); the modeled wind speed and direction time histories are compared to the observed values in Fig. 5.9(c), illustrating the adequacy of the assembled model. The wind hazard map shown in Fig. 5.9(a) represents the maximum wind speed experienced at the sites due to passage of Typhoon York. For the calculation, the grids with resolution of 0.2° are used.

Figure 5.9. Predicted wind hazard, wind field at selected instance, and time series of wind speed and wind direction for Typhoon York (the wind speed shown in the figure represent the hourly-mean wind speed at the anemometer height (i.e., 82 m above the ground surface). Besides of the models shown in Table 5.2, a filling-rate model describing the decay of the central pressure difference after the storm making landfall is required. The decay is due to the unavailability of oceanic heat source and energy dissipation. Some of the filling-rate models for hurricane making landfall in the US are given in Batts et al. (1980), Georgiou et al. (1983) and Vickery (2005).
Table 5.2. Summary of the adopted models to model the TC wind field.

<table>
<thead>
<tr>
<th>Model</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>PBL wind field model</td>
<td>The momentum equation described by Chow (1971) can also be found in Cardone et al. (1992), Thompson and Cardone (1996), Vickery et al. (2000a, 2009a), and Chapter 2. Details on the solution procedure given in Chapter 2 are adopted. It involves the use of finite difference method with five nested rectangular grids. Each grid has the same number of grid points, but the distance between adjacent points is halved with each successive grid. The distance between the adjacent points in the inner most grid is 10% of the ( R_{\text{max}} ). ( R_{\text{max}} ) is calculated using Eqs. (11) and (12) given in Vickery and Wadhera (2008) (see also Eq.(3.5) in Chapter 3). According to this model ( R_{\text{max}} ) is a function of ( \Delta p ) and latitude.</td>
</tr>
<tr>
<td>( R_{\text{max}} )</td>
<td></td>
</tr>
<tr>
<td>Holland pressure profile parameter ( B )</td>
<td>( B ) is calculated using Eq.(23) given in Vickery and Wadhera (2008) (see also Eq.(3.6) in Chapter 3). In this case, ( B ) is modeled as a function of the ( R_{\text{max}} ) and Coriolis parameter.</td>
</tr>
<tr>
<td>Boundary layer wind profile model</td>
<td>For wind speed variation along the height above the surface level, the model shown in Eq. (5) in Vickery et al. (2009b) is used. The model is a function of inertial stability discussed in Kepert (2001). A factor of 1.06 is used to scale hourly mean wind speed to maximum 10-min mean wind speed.</td>
</tr>
</tbody>
</table>

The model presented in Vickery (2005), which is considered in Chapter 3 and Chapter 4 for landfalling TCs in the mainland China, has the following functional form,

\[
\Delta p(t) = \Delta p_0 \times \exp\left(-at\right)
\]  \( \tag{5.5} \)

where \( \Delta p(t) \) is the central pressure difference at time \( t \) since the TC making landfall; \( \Delta p_0 \) is the central pressure difference at the time of landfall; \( a = a_0 + a_1 \Delta p_0 + \varepsilon_a; \) \( a_0 \) and \( a_1 \) are model coefficients to be determined; and \( \varepsilon_a \) is a zero mean normal variate with standard deviation \( \sigma_{\varepsilon_a} \). The model parameters suggested in Chapter 4 is considered in this study. The model parameters were developed for three subregions: region north of 27°N; region south of 23.5°N, and region between 23.5°N and 27°N. The consideration of three regions takes into account that many TCs made landfall in Taiwan Island and subsequently made landfall in the mainland China, and that there are about 80% of these tracks making landfall within 23.5°N and 27°N. Moreover, a lower limit on \( a \) is imposed for the
application of the model since an increased intensity for the landfalling TCs which is uncommon and, $\varepsilon_a$ is a zero mean normal variate that could results in a possible negative value of $a = a_0 + a_i\Delta P_0 + \varepsilon_a$. This setting is consistent with the practice to assess the TC wind hazard for the US (Vickery 2005).

5.5 Estimated typhoon wind hazard

5.5.1 Procedure to estimate TC wind hazard for a single simulated track

To estimate the annual maximum typhoon wind hazard at a site by using the adopted wind field model and the developed empirical TC track model, simple simulation procedure can be applied. The procedure basically involves four steps: randomly select the TC genesis from the historical geneses of TCs; sample the change of the TC track using Eqs. (5.2) to (5.4) for 6-hour interval; apply the filling-rate model for the landfalling segment of the track; and model the TC wind speed if the simulated TC track is within 250 km of the coastline and a specific distance to a site, where the TC wind hazard assessment is required. The steps are sketched in Fig. 5.10. To ensure that the maximum TC wind speed due to the passage of the TC is captured, in the following numerical analysis, the points on the simulated track with 6 hours increment are used as the basis to interpolate the points representing the track with 15 minutes increment; and the wind field is calculated by considering each point on the track with 15 minutes increment.

If the estimation or mapping of the TC wind hazard for a region is of interest, the above mentioned procedure can also be used. However, to improve computation efficiency, in the last step, one could model the TC wind field for each point on the track and assign the calculated TC wind speeds to the grids covering the region. The maximum TC wind speed observed at each grid represents the TC wind hazard for the simulated TC event.
5.5.2 Estimation of TC wind hazard at selected sites

Using the procedure described in the previous section, and considering 100,000 years of simulated TC activity, samples of TC wind hazard for nine cities shown in Table 5.3 are obtained. The samples are used to develop empirical probability distribution of the annual maximum TC wind speed $V$ (representing 10-minute mean wind speed at 10 m height for roughness length $z_0 = 0.05$ m), and to estimate $T$-year return period values of $V$, denoted as $v_T$, for $T$ equal to 50 and 100 years.

For comparison purpose, following Chapter 3 and Chapter 4, the CSM is also applied to estimate $v_{50}$ and $v_{100}$ for the listed sites in Table 5.3. For consistency, the model parameters for the filling-rate model developed in the Chapter 4 are considered for the estimation. Comparison of the $v_T$ values shown in Table 5.3 indicates that $v_T$ estimated based on full track approach is consistent with that estimated based on the CSM, especially if the Weibull distribution is used to model the central pressure difference in the CSM. The largest differences between $v_T$ estimated by using the CSM and the full track approach occur for Fuzhou and Zhanjiang.

Figure 5.10. Illustration of sampling the extreme TC wind speed at a site.
Table 5.3. Typhoon wind hazard at selected cities for return period of 50- and 100-year.

<table>
<thead>
<tr>
<th>City</th>
<th>Design Code</th>
<th>$V_{50}$</th>
<th>Using CSM; $\Delta p_I$ is modeled using Weak (WL.D.)</th>
<th>Using Full Track</th>
<th>$V_{100}$</th>
<th>Using CSM; $\Delta p_I$ is modeled using Weak (WL.D.)</th>
<th>Using Full Track</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Using CSM; $\Delta p_I$ modeled using Weak (WL.D.)</td>
<td>Using Full Track</td>
<td></td>
<td>Using CSM; $\Delta p_I$ modeled using Weak (WL.D.)</td>
<td>Using Full Track</td>
</tr>
<tr>
<td>Shanghai</td>
<td>29.7</td>
<td>28.7</td>
<td>29.2</td>
<td>28.9</td>
<td>31.0</td>
<td>31.6</td>
<td>32.2</td>
</tr>
<tr>
<td>Ningbo</td>
<td>28.3</td>
<td>30.4</td>
<td>32.3</td>
<td>30.0</td>
<td>31.0</td>
<td>33.3</td>
<td>36.2</td>
</tr>
<tr>
<td>Wenzhou</td>
<td>31.0</td>
<td>33.0</td>
<td>35.2</td>
<td>34.0</td>
<td>33.5</td>
<td>36.1</td>
<td>39.1</td>
</tr>
<tr>
<td>Fuzhou</td>
<td>33.5</td>
<td>32.2</td>
<td>34.1</td>
<td>32.5</td>
<td>36.9</td>
<td>34.8</td>
<td>37.8</td>
</tr>
<tr>
<td>Xiamen</td>
<td>35.8</td>
<td>33.9</td>
<td>35.9</td>
<td>36.4</td>
<td>39.0</td>
<td>36.4</td>
<td>39.1</td>
</tr>
<tr>
<td>Guangzhou</td>
<td>28.3</td>
<td>28.4</td>
<td>39.3</td>
<td>29.4</td>
<td>31.0</td>
<td>30.5</td>
<td>32.1</td>
</tr>
<tr>
<td>Shenzhen</td>
<td>34.6</td>
<td>33.9</td>
<td>36.5</td>
<td>34.7</td>
<td>37.9</td>
<td>36.4</td>
<td>40.2</td>
</tr>
<tr>
<td>Hong Kong</td>
<td>37.9</td>
<td>35.6</td>
<td>37.7</td>
<td>35.5</td>
<td>39.0</td>
<td>37.6</td>
<td>41.5</td>
</tr>
<tr>
<td>Zhanjiang</td>
<td>35.8</td>
<td>34.9</td>
<td>37.1</td>
<td>35.2</td>
<td>39.0</td>
<td>37.5</td>
<td>40.9</td>
</tr>
</tbody>
</table>

Note: The wind speed represents 10-minute mean wind speed at 10 m height for $z_0 = 0.05$ m. When the CSM is used, the needed central pressure difference $\Delta p_I$ at the point where the track intersects with the circle centred at the site of interest with a radius of 250 km, is considered to be Weibull distributed (denoted as WL.D.) or lognormally distributed (LN.D.). Justification of using these models was given in Chapter 3. The number in bold represents the estimated value with the preferred probability distribution of $\Delta p_I$ judged based on the Akaike information criterion.

To corroborate the models and methods used to assess the TC wind hazard, a comparison of the estimated $v_T$ values to those recommended in the Chinese design code (GB 50009, 2012) is included in Table 5.3. It shows that the difference between the estimated $v_{50}$ by using the full track approach to the code recommended value is within 1 m/s for four out of nine considered cities, and is within 1.5 m/s for six considered cities. The largest differences between the estimated and code recommended $v_{50}$ occurred at Wenzhou, where the code value underestimates $v_{50}$ by 8% as compared to that in this study. It is noteworthy that the estimated $v_T$ shown in Table 5.3 for Shanghai and Hong Kong are comparable to those assessed based on the surface wind observations reported by Tao et al. (2001) and Holmes et al. (2009) (see Chapter 3 for detail). In addition to this, a comparison of the empirical distribution of $V$ derived from surface wind observations and simulation results is shown in Fig. 5.11. For the surface wind observations, an exposure correction is carried out based on a gust factor approach proposed by Ashcroft (1994) and as applied in Mo et al. (2015). Fig. 5.11 shows that the empirical distributions obtained
based on the simulation results agree well with those obtained based on surface wind observations. This partially validates the models and procedure employed to estimate $v_T$, at least for the four locations.

![Graph showing wind speed data comparison](image)

Figure 5.11. Return period TC wind speeds estimated from observation and simulation at two selected cities.

### 5.5.3 Mapping TC wind hazard for the coastal region

To map the TC wind hazard, a grid system with resolution of 0.5° covering the coastal region is considered. For each grid point, $v_T$ is estimated based on the full track approach. The estimated $v_{50}$ and $v_{100}$ are used as the basis to map the TC wind hazard as shown in Fig. 5.12 (a and b). For the mapping, the ordinary kriging (Johnston et al. 2003) is used. Fig. 5.12 (a and b) shows that the shape of the contour lines are similar to the shape of the coastline, and that as the contour line moves inland its associated wind speed decreases, which is expected. For comparison purpose, the mapped TC wind hazard based on the CSM is also shown in Figs. 5.12(c) and 5.12(d). In all cases, the general spatial trends observed from Figs. 5.12(c) and 5.12(d) are similar to those that can be observed from Figs. 5.12(a) and 5.12(b). Differences in the mapped $v_T$ do exist, especially for small regions in the mainland China but near Hainan island or Taiwan island. For these regions, the use of the CSM overestimates the TC wind hazard by up to 2 m/s as compared to those obtained by using the full track approach. The differences can be considered to be small and acceptable considering the uncertainty involved in the models.
Figure 5.12. Contour maps of $v_T$: a) Estimated $v_{50}$ using the full track approach; b) Estimated $v_{100}$ using the full track approach; c) Estimated $v_{50}$ using the CSM; d) Estimated $v_{100}$ using the CSM.

5.6 Conclusions

An empirical model is developed to probabilistically predict the TC tracks from the genesis to lysis for western North Pacific basin. The development is based on historical
best track dataset, and the spatially varying model coefficients are determined through regression analysis.

Statistics of the annual occurrence rate, storm translation velocity, storm heading and central pressure difference are estimated using the simulated tracks at sites along the coastline. The statistics compare favorably to those obtained using the historical best track dataset, indicating the adequacy of the developed track model. Also, the spatial trends of the simulated tracks are similar to those of best track dataset.

The simulated tracks are used together with a TC wind field model to estimate the typhoon or TC wind hazard. The results indicate that the estimated $v_T$ compares well to that available in the literature or estimated based on the surface wind observations, at least at four considered sites. Also, a comparison of the estimated $v_T$ to that given in the design code is provided for nine cities; their similarity and differences are elaborated. The typhoon wind hazard maps for the coastal region assessed based on the full track approach are presented and compared to those obtained based on the CSM. For overland sites that are within 250 km from the coastline, the absolute relative difference between $v_T$ estimated by full track approach and by the CSM with best fitted distribution for $\Delta p$ is about 4.8% for T equal to 50 and 100 years.

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Chapter 6

6 Conclusions and recommendations for future work

6.1 Conclusions

First, a review of model used to assess the hurricane wind hazard map for the ASCE-7 is carried out. The review indicated that currently the full track model and planetary boundary layer (PBL) wind field model are used as the basis to estimate the hurricane wind hazard which is mapped in the ASCE-7. The review also indicated that the typhoon wind hazard in China is often carried out using the circular subregion method, and that there are large discrepancies in the estimated return period value of the typhoon wind hazards in selected cities.

Four major tasks are carried out in this study: one focused on the hurricane wind hazard estimate in the US, and the remaining three focused on the typhoon wind hazard estimate in China. The first task provided the needed theoretical basis for the wind field modeling and track modeling used to estimate the typhoon wind hazard for mainland China.

The research carried out in this study contributed in the understanding of and knowledge for hurricane hazard estimation in several ways:

1) It is shown that the convection term in the governing equation for the wind field can be important and affect the wind field shape;
2) Adequate empirical full track model for west Northern Pacific basin can be developed; and
3) Well-documented typhoon wind hazard maps focused on wind engineering applications are developed coastal region of mainland China.

More specifically, from the results of the task focused on the estimation of the hurricane wind hazard in the US, it is concluded:

1) The PBL model given in Chow (1981) is solved in several studies (Cardone 1996, Vickery et al. 2000a) by neglecting the term $\vec{u}_c \cdot \nabla \vec{u}_c$ in the moment equation. This
resulted in different wind field shapes and underestimates the maximum wind speed that is obtained by including such a term. The underestimation of the maximum wind speed is small (<3.5%) for typical value of $\Delta p$ and $B$, but could be large for large value of $\Delta p$ and $B$. The modeled wind field provide a closer resemblance to the wind fields in H*Wind if $\vec{u}_c \cdot \nabla \vec{u}_s$ is considered.

2) A simplified track model is proposed. Its use leads to the estimated hurricane wind hazard similar to one used as the basis for the hurricane wind hazard shown in ASCE-7.

3) Results from different combinations of wind field model and track model considered lead to relatively consistent hurricane wind hazard estimate, indicating the hurricane wind hazard model is robust.

From the results of tasks focused on the estimation of the typhoon wind hazard in the coastal region of the mainland China, it is concluded:

1) Typhoon wind hazard for nine major coastal cities in the mainland China is assessed by using the CSM combined with the PBL wind field model. Based on historical track dataset, probabilistic characterization is carried out for for key parameters including storm heading, translation velocity, and the central pressure difference by considering a circular region centered at each site of interest. It was indicated that the preferred probabilistic model for the central pressure difference could be site dependent.

2) The estimated wind hazards for nine cities are relatively insensitive to the size of the sub-region considered, but are affected by the adopted probability distribution model for $\Delta p$. The estimated wind hazard for Shanghai and Hong Kong is comparable to those based on surface wind observations. The code recommended return period values for several cities are lower than those obtained in this study by up to 8%. The large differences are for Ningbo and Wenzhou.

3) The spatially statistical characterizations of the key TC parameters are explored. The annual occurrence rate of TC for a considered circular region, is spatially varying, and decreases as the circle moves towards inland. The mean value of the heading
decreases from east to southwest; the standard deviation of the heading is relatively consistent as compared to the mean. The translation velocity tends to increase as the TC moves towards inland or from south to north. For modeling $\Delta p$, there are clearly identified zones where the lognormal (or the Weibull) distribution is preferred.

4) Contour maps for typhoon wind hazard are developed by using CSM combined with the PBL wind field model. The developed contour map for $v_{50}$ is compared to that given in the design code. Regions outlined by contour lines ranging from 31 to 38 m/s in the developed contour map are comparable in size and shape to those in the contour map given by the design code; but regions outlined by contour lines ranging from 22 to 28 m/s in the developed contour map are located further inland compared to those in the contour map given in the design code. Sensitivity analysis shows that $v_{T}$ ($T = 50$- or 100-year return period) is not very sensitive to the radius of the circular. The consideration of spatially varying filling-rate model or the approximate model shown in Eq. (4.4) alters $v_{100}$ by less than 6%; the use of lognormal or Weibull distribution to model $\Delta p$ when using the CSM affect the estimated $v_{100}$ by up to 12%.

5) An empirical full track model is developed to probabilistically predict the TC tracks from the genesis to lysis for western North Pacific basin. The spatially varying model coefficients are determined through regression analysis. Statistics of the key TC parameters estimated from the simulated tracks at kilometer posts compare favorably to those obtained from the historical tracks. The simulated tracks are used together with the PBL wind field model to estimate the typhoon wind hazard. The estimated $v_{T}$ compare well with those available in the literature or estimated based on the surface wind observations. The typhoon wind hazard maps for the coastal region assessed using the full track approach are presented and compared with those obtained based on the CSM. For sites that are overland and within 250 km from the coastline, the absolute relative difference between $v_{T}$ estimated by full track model and by the CSM with best fitted distribution for $\Delta p$ is about 4.8% for $T = 50$- and 100-year.
6.2 Recommendations for future work

1) Exploration of the use of the less approximated wind field, such as that given in Kepert and Wang (2001), to assess the typhoon wind hazards could be valuable. For such an exploration, efforts need to be made to parameterize the key parameters (e.g. mixing length and $C_D$) or derive the empirical models for the core input (gradient pressure field, if the Holland pressure field is to be used, and the parameter $B$ and $R_{max}$ may need to be derived for WNP specifically when observation is available) used to define the wind field.

2) More environmental input such as the wind shear may be valuable to be considered in the TC full track model in order to enhance the physical basis of the full track modeling.

3) Ocean current model may need to be included in the full track modeling process to better take into account the effect of warm eddies on the intensification of the TC.
Appendix

Appendix A: Solution steps for the PBL wind field model

The momentum equation shown in Eq. (2.1) is solved iteratively by using the finite difference method. The basic steps for solving Eq. (2.1) are:

1) For given central pressure difference and location of the TC center, estimate $R_{\text{max}}$ and $B$ by using Eq. (3.5) and Eq. (3.6), respectively, and calculate the pressure gradient field using Eq.(2.9).

2) Calculate the initial wind field by solving the gradient wind field model defined in Eq. (1.1).

3) Solving the outmost boundary condition by using Eq. (2.1) and neglecting the acceleration and the horizontal diffusion.

4) Solving Eq. (2.1) iteratively using the finite difference method.

Note that for the solution five concentric nested grids are used. The grid point spacing for the five nests is $5\times10^3$, $10\times10^3$, $20\times10^3$, $40\times10^3$ and $80\times10^3$ m, respectively. The entire grid domain covers about 1600 km$^2$. Since the solution to the wind field is with respect to the TC center, the calculated wind field needs to include (or add) the translation velocity of the TC.
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