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Multi-scale simulation of time-varying wind fields for Hangzhou Jiubao Bridge during Typhoon Chan-hom

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ABSTRACT

This paper proposes a downscaled simulation framework aimed to resolve micro-scale wind velocity fields around a targeted site influenced by a typhoon. The framework is consisting of three procedures: (1) typhoon evolution reanalysis by the Advanced Hurricane Weather Research and Forecasting (AHW) model, (2) the large-eddy simulation (LES) coupled in the Weather Research and Forecasting (WRF) model (WRF-LES), and (3) stochastic generation of local turbulent flows. The framework incorporates high-resolution Geographic Information System (GIS) data to capture the effects of urbanization and complex local topography. The framework is applied to carry out multi-scale simulation of time-varying wind fields for Hangzhou Jiubao Bridge during Typhoon Chan-hom in 2015. The AHW model is able to resolve the three-dimensional wind velocity fields of Chan-hom, which provide the initial and lateral boundary conditions for further downscaled simulation over Hangzhou area. The kinematic simulation (KS) method due to its computational efficiency is employed to generate zero-mean turbulent wind velocities, which are then combined with the outputs of WRF-LES mode to reproduce full turbulent wind velocity fields for Jiubao Bridge. The simulation results of real application demonstrate the effectiveness and applicability of the framework, which provides a cross-scale simulation capability of reproducing typhoon wind fields.

1. Introduction

Eastern Asian is one of many regions, which are exposed to the threat of tropical cyclones (TCs) or typhoons and suffer great damages and huge loses. A typhoon is a mature TC that develops in the western part of the North Pacific Ocean between 180°E and 100°E. Currently parametric TC wind field models (Vickery et al., 2009) are widely applied for the simulation of devastating TC wind fields and TC-induced wind hazard risk assessments (Li and Hong, 2015). However, these wind field models are based on the simplified governing equation of horizontal motion with key parameters of a TC, i.e., the central pressure, the radius of the maximum wind speed and the horizontal pressure gradient profile, and are limited in reconstructing the real three-dimensional typhoon structure and its evolution, which are critical for assessing the wind-induced dynamic effects on structures to ensure structural safety against typhoon hazards. In reality, the genesis and evolution of typhoon are greatly affected by the mesoscale convection (Gray, 1998) and air-sea interaction (Emanuel, 1986; Rotunno and Emanuel, 1987). Thus the multi-scale interaction between internal dynamics of typhoon vortex structure and synoptic environments has to be considered for accurate simulation of the mesoscale typhoon vortex structure (Liu et al., 1997).

Recently, the meteorological numerical weather prediction (NWP) model become more and more mature with increasing computational power and steady accumulation of scientific knowledge in meteorology (Bauer et al., 2015). Intensive research has been conducted to study the influence of the initial and boundary conditions and the complex physical processes parameterized in NWP model on the simulation of a TC or typhoon and its evolution (Liu et al. 1997, 2013; Braun and Tao, 1999; Montgomery et al., 2010; Smith and Thomsen, 2010; Yun et al., 2012; Li et al., 2013; Srinivas et al., 2014; Khain et al., 2016). It was found that high-resolution grid configurations, realistic physical schemes and turbulence boundary layer mixing, proper initial vortices in relation to their synoptic weather conditions and proper land-surface conditions play critical roles in the simulation of TCs using NWP models. The Advanced Research Hurricane WRF (AHW) model (http://www2.mmm.ucar.edu/wrf/users/hurricanes/wrf_ahw.html) is one of specifically designed NWP models for performing numerical simulations of TCs by employing two-way interactive moving nested domains, one-dimensional Ocean Mixed Layer (OML) model and surface-drag formulation of ocean in the extreme wind speeds that occur in typhoons or hurricanes. Many case

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studies (Davis et al., 2008; Xiao et al., 2009; Yeh et al., 2012) demonstrate that AHW model is capable of simulating TCs in an increasing accuracy.

For wind engineering application, micro-scale flow characteristics in several hundred meters around civil structures or infrastructures can be resolved by performing multi-scale numerical simulation based on NWP models, in which the large eddy simulations (LESs) have been employed to reproduce the atmospheric turbulence in planetary boundary layer (PBL). The nesting capability of the WRF model enables a progressive increase in resolution from mesoscale (>1 km) to micro-scale (~50 m) to perform the nested LES within WRF (WRF-LES mode). WRF-LES is aimed to capture the local-scale spatial variability of meteorological dynamics and land-atmosphere exchanges, especially over complex terrain. Liu et al. (2011) conducted a nested mesoscale LES simulation over real terrain and showed that the simulated LES results with a grid size of 123 m revealed various micro-scale (~100 m) wind flows comparable with the wind-farm anemometer measurements. The performance of the WRF-LES mode was tested to simulate a realistic PBL flow with a horizontal grid resolution down to 50 m (Talbot et al., 2012). Joe et al. (2014) implemented a high-resolution WRF model to predict turbulent mixing of airborne particulate elemental carbon and concluded that resolving micro-scale turbulence mixing phenomena could significantly affect the weather predictions in a densely populated area with complex terrain. Cécé et al. (2016) carried out Lagrangian particle dispersion simulations using real nested LES meteorological fields with a horizontal grid resolution of 111 m and achieved satisfying results of the pollutant dispersion during a real case of calm wind regime over a complex terrain area. Many applications of LES nested in WRF model to an idealized convective PBL over an idealized regime (i.e., homogeneous surface properties and periodic lateral boundary conditions) have also been studied for testing various numerical schemes, different grid resolutions and sub-grid-scale (SGS) turbulence models (Moeng et al., 2007; Mirocha et al., 2010, 2013; 2014; Kirkil et al., 2012; Muñoz-Esparza et al., 2014; Ercolani et al., 2015).

An alternative approach to perform multi-scale simulation is to couple the mesoscale NWP model with the computational fluid dynamics (CFD) codes. Using the mean wind profiles from WRF model as initial inflow conditions, Nakayama et al. (2012) conducted an LES of urban boundary-layer flows in a real typhoon meteorological setting through a recycling technique for turbulent inflow generation. Wyszogrodzki et al. (2012) developed an integrated, cross-scale urban modeling capability to couple the community WRF model with the building-resolving LES model to investigate the fine-scale dispersion in an urban environment. Various studies have been devoted to couple CFD and NWP models (Tetsuji and Katsuyuki, 2011; Zajaczkowski et al., 2011; Liu et al., 2012; Gopalan et al., 2014). However, the coupled approach suffers the primary difficulty of “terra incognita”, defined as the range between the validity of mesoscale models and LES models (Wyngaard, 2010; Zajaczkowski et al., 2011). In this paper, a single model approach is adopted to resolve micro-scale typhoon-induced mean wind fields.

In the single model approach, the LES mode directly nested within NWP models over realistic complex terrain requires high-resolution land-surface information which are normally preprocessed by the Geographic Information System (GIS) technique and then incorporated into the Land Surface Model (LSM) within the mesoscale NWP models. Paiva et al. (2014) showed that the use of high-resolution surface databases significantly improves the ability of multi-scale simulations to predict the local atmospheric circulation. Brousse et al. (2016) proposed an integration of urban Local Climate Zones (LCZ) classification based land use data into the WRF model for high-resolution mesoscale simulation over Madrid in Spain. These studies demonstrate that integrating the high-resolution surface data produced by the GIS technique with the LES mode in NWP models opens up an efficient way to explicitly resolve the atmospheric boundary layer eddies and local micro-scale wind flows over real complex urban terrain.

There are few studies published, as far as the authors are aware, applying the WRF-LES mode with high-resolution topographical and land use data to simulate micro-scale wind fields over an inland urban area influenced by a moving typhoon. The objective of this paper is to propose a downscaled typhoon wind field simulation framework based on single model approach combined with the random flow generation technique for wind engineering application. A historical typhoon affecting Hangzhou city, China, is regenerated to demonstrate the applicability and effectiveness of the proposed typhoon simulation framework. The evolution of the mesoscale typhoon wind field is simulated using two-way interactive nested domains in AHW model and the simulated meteorological fields from AHW model are used to improve the typhoon vortex initialization for further downscaled simulations in WRF-LES mode. The LES nested in WRF model is performed with high-resolution GIS data over Hangzhou to reproduce the micro-scale typhoon wind fields. Finally, the full turbulent wind fields could be obtained through combining the mean micro-scale wind fields from outputs of WRF model with the stochastic zero-mean turbulent wind fields which could be numerically generated in great efficiency by the spectral representation method (Carassale and Solari, 2006) or kinematic simulations (Huang et al., 2011).

The main advantage of the downscaled typhoon wind field simulation framework proposed in this paper is that the integration of the single-model downscaling approach with the random flow generation technique could overcome the difficulty of “terra incognita” (Wyngaard, 2010; Muñoz-Esparza et al., 2014). And the proposed framework provides a physical model-based and computationally efficient way to resolve typhoon processes spatio-temporally for application in wind engineering. The remainder of the paper is organized as follows. Section 2 gives a brief introduction of the governing equations in WRF model with PBL scheme and LES mode discussed. Section 3 presents an overview of Typhoon Chan-hom and field measurements of wind velocity facilitating the evaluation of the model performance. The proposed multi-scale typhoon wind field simulation framework and numerical implementations are detailed in Section 4. The simulated results of typhoon intensity, track, multi-scale wind fields and full turbulent wind velocity are reported and discussed in Section 5. Section 6 presents the summary and conclusion of this study.

2. Governing equations and numerical solutions for typhoon wind fields

2.1. Governing equations for typhoon wind field

The compressible, non-hydrostatic governing equations (Skamarock and Klemp, 2008), i.e., time-averaged Reynolds equations, that govern the mesoscale NWP model are cast in flux forms and can be expressed in a terrain-following hydrostatic-pressure vertical coordinate (Laprise, 1992) as following,

$$\frac{\partial U}{\partial t}+\left[\left(\frac{\partial Uu}{\partial x}+\frac{\partial Vu}{\partial y}\right)+\frac{\partial \Omega u}{\partial \eta}\right]+\left[-\frac{\partial}{\partial x}\left(p\frac{\partial \phi}{\partial \eta}\right)+\frac{\partial}{\partial \eta}\left(p\frac{\partial \phi}{\partial x}\right)\right]=F_U \tag{1}$$

$$\frac{\partial V}{\partial t}+\left[\left(\frac{\partial Uv}{\partial x}+\frac{\partial Vv}{\partial y}\right)+\frac{\partial \Omega v}{\partial \eta}\right]+\left[-\frac{\partial}{\partial y}\left(p\frac{\partial \phi}{\partial \eta}\right)+\frac{\partial}{\partial \eta}\left(p\frac{\partial \phi}{\partial y}\right)\right]=F_V \tag{2}$$

$$\frac{\partial W}{\partial t}+\left[\left(\frac{\partial Uw}{\partial x}+\frac{\partial Vw}{\partial y}\right)+\frac{\partial \Omega w}{\partial \eta}\right]-g\left[\frac{\partial p}{\partial \eta}-\mu\right]=F_W \tag{3}$$

$$\frac{\partial \Theta}{\partial t}+\left(\frac{\partial U\theta}{\partial x}+\frac{\partial V\theta}{\partial y}\right)+\frac{\partial \Omega \theta}{\partial \eta}=F_\Theta \tag{4}$$

$$\frac{\partial \mu}{\partial t}+\left(\frac{\partial U}{\partial x}+\frac{\partial V}{\partial y}\right)+\frac{\partial \Omega}{\partial \eta}=0 \tag{5}$$