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A comparative study of typhoon wind profiles derived from field measurements, meso-scale numerical simulations, and wind tunnel physical modeling

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ABSTRACT

To investigate the applicability and limitations of both physical (wind tunnel test) and numerical (weather prediction) simulations of the atmospheric boundary layer, field measurements from a Doppler SODAR and a wind-profiler were combined to serve as validation criteria when comparing the results from a numerical simulation conducted by the Weather Research and Forecast model (WRF) and from wind tunnel testing. The comparisons focused on the simulation of the typhoon boundary layer, and revealed that a major drawback of wind tunnel testing is the use of an unrealistic approaching wind profile. As a result, the wind tunnel test results should only be considered valid when the measured wind profile is influenced predominantly by the underlying terrain. Meanwhile, the relatively coarse resolution of the underlying terrain model used in the numerical weather prediction system may lead to an inaccurate mean wind speed profile at lower altitudes, especially when the winds are coming from the land fetch.

1. Introduction

Simulating the atmospheric boundary layer (ABL) in a controlled environment, which makes a detailed analysis of the flow field possible, is of great importance in the fields of meteorology, civil engineering, and environmental engineering. There are currently two options for simulating ABL wind flow: boundary layer wind tunnel simulation and numerical simulation. As pointed out by Bowen (2003), a topographic study using wind tunnel techniques faces a series of challenges when the model scale is smaller than some critical value. Making reliable weather predictions based on numerical simulations is, on the other hand, rather difficult due to the complexity of the various meteorological processes. In particular, the numerical prediction of tropical cyclone intensities is known to be an issue for the Numerical Weather Prediction (NWP) model (Hill and Lackmann, 2009; Nolan et al., 2009a, 2009b).

There has been a long history of using the boundary layer wind tunnel to simulate natural winds. In particular, boundary layer wind tunnel techniques have been used to simulate the wind above complex terrains following the studies of Meroney (1980) and Cermak (1984) in the 1980s. In a review of past developments and future trends in the application of wind tunnel techniques in civil engineering practice, Cermak (2003) reported that wind tunnels were increasingly being used to study the topographic effects on wind characteristics. Although some progress in the development of wind tunnel techniques has been observed for simulating wind flows in topographic studies, there are still difficulties that need to be overcome for wind tunnel flows to accurately and reliably simulate wind flows in the ABL, especially when the geometric scale is lower than 1:500 (Bowen, 2003). First, the approaching wind profile commonly used in wind tunnel testing follows a perfect power-law, with the power exponent selected according to the exposure category. While the crude categorization of the power-law exponent is acceptable from a wind engineering point of view, the surface roughness categorization adopted in the code of practice – which is commonly used to modulate the approaching wind profile in wind tunnel tests – is often found to be inadequate (Choi, 1978; Tse et al., 2013). As a result, wind tunnel simulations of the ABL can be improved if the approaching wind profile is adjusted according to the observed approaching wind flow. Bowen (2003) also pointed out that atmospheric stability may affect the accuracy and reliability of a topographic wind tunnel study in which the terrain is modeled at

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a small geometric scale ($<1:500$). In the discussion, he pointed out that the atmospheric stability issue, or the Rossby number similarity, requires the thermodynamic structure observed in the ABL to be simulated in a wind tunnel. Because conventional wind tunnel facilities lack the ability to generate any vertical variation in thermodynamic variables, this requirement poses challenges for improving wind tunnel test techniques for use in topographic studies with small geometric scales ($<1:500$).

The Weather Research and Forecast (WRF) model (Xie et al., 2012) has become a popular NWP software package for conducting numerical simulations. Despite its popularity, the accuracy and reliability of WRF simulations, and the NWP results in general, have only been assessed on a case-by-case basis (Shimada and Ohsawa, 2011; Jimenez et al., 2007; Draxl et al., 2010). No consensus has been reached in meteorological circles regarding the best practices for setting up the model, including the selection of the Planetary Boundary Layer (PBL) scheme, and the formulation of the boundary and the initial conditions (Shimada et al., 2011; Carvalho et al., 2012). In particular, the numerical simulation of tropical cyclones suffers from the inaccuracy of the intensity prediction. When compared with track prediction, there has been no significant progress in intensity prediction over the past decade despite the significant increases in computational power (Hill and Lackmann, 2009). It has been argued that both the horizontal grid spacing and the PBL scheme may contribute to the inaccuracy of tropical cyclone intensity predictions (Hill and Lackmann, 2009; Nolan et al., 2009a, 2009b).

As an extreme weather condition, the typhoon and its boundary layer wind field have been a focus of meteorological research for nearly a century (Kepert, 2002). Due to the strong winds in the typhoon boundary layer, the observations taken during typhoons should serve as a useful validation criterion for comparing physical (wind tunnel tests) and numerical (WRF) simulations of the ABL, because it (a) reduces the noise-to-measurement ratio and (b) reduces the influence of atmospheric stability to a minimum level. As Zhang et al. (2009) noted, under conditions of high wind strengths, the shear mechanism dominates turbulence production and dissipation in the typhoon boundary layer, making the atmospheric stability close to neutral.

Using wind speed and direction measurements taken by both a Doppler SODAR (SOnic Detection And Ranging) and a wind-profiler during the passage of several typhoons as the validation criterion, the applicability and limitations of both physical (wind tunnel test) and numerical (WRF) simulations of the typhoon boundary layer wind field were investigated by comparing the observed and simulated vertical profiles of the mean wind velocities and directions. The hourly mean profiles were first calculated based on the field measurements taken at a Hong Kong weather station during typhoon passages between 2007 and 2009. A wind tunnel test was then conducted, explicitly modeling the topographic features around the weather station. In the wind tunnel test, the vertical profiles of the mean wind velocities and directions were measured under various wind attack angles. A numerical simulation of the wind fields in Typhoon Fengshen (2008) was conducted using WRF. The wind profiles above the site of interest were calculated by interpolating wind information at nearby grid points from the simulation results. The observed and simulated profiles were then compared, taking into account factors such as wind direction and wind strength. The comparisons were then used to assess the applicability and limitations of either simulation technique.

The remainder of the paper is organized as follows. Section 2 describes the data and the methodology for comparing the observations, the wind tunnel test results, and the WRF simulation outputs. Section 3 presents the comparisons and discusses the applicability and limitations of the physical and the numerical simulations. Section 4 presents the conclusions.

2. Description of the data and comparison methodology

2.1. Observation data and post-processing

The Hong Kong Observatory (HKO) has set up over 40 automatic stations across the territory to measure wind speeds and directions. Several stations are equipped with Doppler SODARs and wind-profilers. A SODAR has the same mechanism as RADAR (Radio Detection And Ranging), but uses sound waves instead of radio waves. Details of wind velocity calculation using raw Doppler SODAR measurements can be found in the study of Chai et al. (2008), which also contained a validation of Doppler SODAR wind measurements. The wind-profiler produces vertical profiles of horizontal and vertical wind speeds by measuring the radial velocity of the scatter as a function of three or five antenna beam positions (Sachin et al., 2009). Wind-profilers can operate under nearly all weather conditions and the temporal resolution of the measurements can be reduced to approximately one minute. A detailed description of wind speed and wind direction calculation using the raw wind-profiler measurements can be found in the study of Imai et al. (2007). Comparisons between wind velocities measured using wind-profilers and radiosondes have verified that wind-profilers can produce accurate vertical profiles of horizontal wind speeds (Heo et al., 2003).

The field measurements that served as the validation criterion were taken at the Siu Ho Wan (SHW) station during the passages of several typhoons that occurred between 2007 and 2009. The geographic location of the station (22°18′21″ N and 113°58′45″ E) is shown in Fig. 1. In detail, the SHW station is located along the northern coast (about 100 m from the coastline) of Lantau Island, on the western part of the territory of Hong Kong. Towards the NNE-N-NW directions, the SHW station can be considered as under the exposure of the open terrain category (facing mainly toward the sea). A piece of flat land (the Hong Kong International Airport), which is surrounded by open waters, is located about 7 km away from the SHW station in the west direction. Towards the E-SE-S-SW directions of the SHW station, Lantau Island has some tall mountains, such as Lantau Peak (918 m) to the southwest and Tai Tung Shan Mountain (869 m) to the south. As a result, the SHW station faces two substantially distinguished surface conditions. In the directions of NNE-N-NW-W, the SHW station is mostly under influence of the sea surface roughness. In the directions of E-SE-S-SW, the SHW station is under the influence of the Lantau Island orography.

Wind measurements taken by both the Doppler SODAR and the wind-profiler, which were installed about 250 m from the shore and about 22 m above the mean sea level, were unitized to calculate the hourly mean wind profiles. The detection height limit for the Doppler SODAR is 100 m and the vertical resolution is 5 m. By averaging 100 raw $3-s$ Doppler SODAR wind measurements, $5-$ min mean wind velocities were calculated and stored by the HKO for further analyses. Because the Doppler SODAR wind measurements taken close to the ground were contaminated by the ground reflections, the wind measurements at the two lowest heights, i.e. 5 m and 10 m from the ground, were discarded. The wind-profiler in the SHW station is of the boundary layer type, which is able to take wind measurements in two modes, the low-mode and the high-mode. More specifically, the low mode measures wind velocities at heights ranging from 116 m to 1500 m at intervals of 60 m, and the high-mode measures wind velocities at heights ranging from 260 m to 6000 m at intervals of 260 m. By averaging 20 raw $30-s$ wind measurements, $10-$ min mean wind velocities were calculated and stored by the HKO. The low- and high-mode were consecutively switched in operation to ensure both modes produced $10-$ min mean wind velocities with time stamps close to each other.