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Wind profile observations in tropical cyclone events using wind-profilers and doppler SODARs

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ABSTRACT

Since the mean wind profile in the tropical cyclone boundary layer is important in both the fields of meteorology and wind engineering, the wind measurements taken during the passages of several tropical cyclones or typhoons in Hong Kong by the wind-profilers and the Doppler Sonic Detection And Ranging (SODAR) have been utilized to calculate both the hourly and 10-min mean wind profiles. These observed profiles were then fitted to the log-law, the power-law and an empirical profile model taking into consideration the low-level jet. The results showed that the low-level jet, which is commonly observed for the mean wind profile in the tropical cyclone boundary layer over the sea, was not found. In addition, we found that the surface roughness derived by fitting the observed profile to the log-law was unusually high ($z_0 > 1.5$ m). The possible explanations include (1) the influence of large scale topography and (2) the high waves introduced by strong typhoon winds.

1. Introduction

Mean wind profiles in the tropical cyclone boundary layer are important in the fields of both meteorology and wind engineering. For meteorology, the knowledge of the mean wind profile in the tropical cyclone boundary layer is critical to understand the overall tropical cyclone dynamics since the mean wind profile shape reflects air–sea momentum exchanges which are crucial in the numerical weather prediction concerning tropical cyclones (Powell et al., 2003). For wind engineering, the mean wind profile in the lower portion of the tropical cyclone boundary layer determines the wind loads acting on structures built in hurricane-prone regions. While the log-law and the power- law are universally used to describe the vertical variation of the mean wind velocity below the gradient height, Vickery et al. (2009) found that the log-law is inadequate to describe the mean wind profile in the entire tropical cyclone boundary layer over the sea, and both Vickery et al. (2009) and Giammanco et al. (2012) reported that the low-level jet was observed below the conventionally defined boundary layer height. Actually, Vickery et al. (2009) introduced an empirical profile function to account for this low-level jet. Although this empirical function successfully describes the low-level jet observed for typhoon winds over the sea, its applicability to model the mean wind profile in the tropical cyclone boundary layer over land should be further investigated. Meanwhile, studies have been conducted to reconstruct the boundary layer wind field of tropical cyclones based on various observations established over land. For example, Choi (1978) and Hui et al. (2009) used measurements taken by rawinsondes and observational masts to reconstruct the mean wind profile in the tropical cyclone boundary layer over land. Different from the study of Vickery et al. (2009), Choi (1978) and Hui et al. (2009) investigated the surface roughness of the sea fetch through fitting the observed mean wind profile to the well-known power-law. They reported the power-law exponent (labeled as α hereafter) is about 0.19. Using the Doppler SODAR (SOnic Detection And Ranging), Tamura et al. (2007) calculated the mean wind profiles in the tropical cyclone boundary layer and suggested that the value of α should be 0.1. Since the mean wind profile is significantly influenced by the terrain roughness in the approaching direction, it is expected that the mean wind profile over complex terrains is different from those under the influence of the sea fetch. Pan et al. (2010) conducted a study on typhoon winds over the central mountain region in Taiwan using measurements taken by wind-profilers, which showed a diverse behavior of the wind fields in different typhoons under the influence of significant blocking effect of the Taiwan central mountain.

Hong Kong is situated on the south east coast of the Asian continent facing the South China Sea. Some tropical cyclones formed over the western North Pacific intensify into typhoons and move into the South China Sea. On average, there are 12 tropical cyclones appeared over the South China Sea each year and 6–7 of them moved close to or across Hong Kong. Given the occurrence frequency

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of typhoon events, Hong Kong is a convenient location for studying typhoon winds. Using the measurements taken by both the wind-profiler and the Doppler SODAR, which are located in Siu Ho Wan, Hong Kong, during the passages of several tropical cyclones occurred in the period of 2007–2009, the mean wind profiles in the tropical cyclone boundary layer were calculated. In an attempt to evaluate the applicability of the empirical profile model introduced by Vickery et al. (2009), the mean wind profiles were fitted to the Vickery's profile function, the log-law and the power-law. By comparing the observed mean wind profile to the fitted model profiles, not only the applicability of the Vickery's profile function was evaluated but also the surface roughness characteristics were investigated. Since the turbulent time scale of tropical cyclone winds is not well understood (Yu et al., 2008), both the hourly mean and the 10-min mean wind profiles are calculated and discussed.

In this paper, a brief description of measuring equipment (the wind-profilers and the Doppler SODAR) is first of all given. The data set and processing procedures used to calculate the mean wind profiles are subsequently outlined. Then, the procedures utilized to check the processed data quality are described in detail. Afterwards, the resulting mean wind profiles are discussed and compared to various profile models.

2. Measuring techniques

In Hong Kong, the Hong Kong Observatory has setup over 40 automatic stations all over the territory to measure wind speeds and wind directions. There are several stations equipped with the Doppler SODAR and the wind-profiler. This equipment is very useful for studying the variation of the wind speed with height. In particular, the Doppler SODAR is popular for field measurements of wind speeds because of the following advantages (Vogt and Thomas, 1995): (a) low capital and maintenance cost; (b) mobile and easy to install; (c) large measurement range up to 1 km. Since the wind measurements taken by both the wind-profiler and the Doppler SODAR are the data sources based on which the mean wind profiles were calculated, they are briefly described as follows.

2.1. Doppler SODAR

The SODAR has the same mechanism as RADAR (Radio Detection And Ranging) but uses sound waves instead of radio waves. The Doppler SODAR is a SODAR to detect the velocity of moving targets through measuring the frequency shift of backscattered AC pulses as the results of the Doppler Effect. The backscattered signals are processed to calculate the Doppler spectrum (frequency spectrum) through the fast Fourier transformation. From the measured Doppler spectrum, the component of the wind velocity in the same direction as the transmitted energy is determined. Details of wind velocity calculation using Doppler SODAR measurements can be found in the study of Chai et al. (2008). There are two mechanisms used in the Doppler SODAR system to take wind measurements, namely the Single pulse transmission and the Double pulse transmission. In single pulse transmission, one pulse length over a limited altitude range is used to obtain wind speeds (Perez et al., 2004; Latha and Murthy, 2011). In contrast, two pulse, with different pulse length, can be issued in double-pulse transmission to measure wind velocities in two different height regions (Tamura et al., 1999, 2001, 2007).

2.2. Wind-profiler

The wind-profiler measures the vertical profile of both horizontal and vertical winds by measuring the radial velocity of scatters as a function of three or five antenna beam positions. One of the beams is pointing to the zenith while others are inclined to the zenith. Adopting the Doppler beam swinging technique, the wind-profiler measures the radial projection of wind velocities along these beams by analyzing the observed Doppler-shifted returning signals. Such a configuration also enables measuring simultaneously all three wind velocity components (Sachin et al., 2009). Wind-profilers can be operated under nearly all weather conditions with a time resolution in the order of 10 min, and the vertical range resolution can be reduced to a value in the order of ~ 10 m, and useful radial velocity estimates can be made with a per-pulse signal-to-noise ratio (SNR) below 40 dB. Details on wind speed and wind direction calculation using raw wind-profiler measurements can be found in the study of Imai et al. (2007). The comparisons between wind velocities measured by wind-profilers and by radiosondes have verified that the wind-profiler is adequate to produce the accurate vertical profiles of horizontal winds (Heo et al., 2003).

Since both the Doppler SODAR and the wind-profiler measure atmospheric boundary layer winds accurately and reliably, they have been intensively used in the studies on atmospheric boundary layer wind characteristics. For example, Thomas and Vogt (1993) compared measurements taken by four different Doppler SODAR systems for more than 10 years to the measurements taken by conventional meteorological instruments mounted on a 200 m tower nearby. Their results confirmed the reliability and accuracy of horizontal wind speeds measured by a SODAR at all height levels investigated. Tamura et al. (1999, 2001, 2007) discussed the simultaneous measurements of wind speeds taken by two Doppler SODARs at altitudes ranging from 40 m to 420 m over two sites where different terrain roughness was observed. Since these two sites were in the same wind storm in the investigation, the simultaneous observations revealed the difference of the wind speed profiles that were influenced by different surface roughness. As regard to the observations established by wind-profilers, Pan et al. (2010) studied two typhoons went across the central mountain region of Taiwan using wind-profiler measurements. The observed wind speeds and directions over a height ranging from 0.235 km to 6.543 km showed the influence of the topography on the typhoon boundary layer wind field.

3. Data and processing methodology

To calculate the mean wind profile in the tropical cyclone boundary layer, the wind measurements taken by the SHW station during the passages of tropical cyclones or typhoons from 2007 to 2009 were selected and processed. The geographic location of the SHW station (22°18′21″ latitude and 113°58′45″ longitude) is shown in Fig. 1. In detail, the SHW station is located on the northern coast (about 100 m from the coast line) of Lantau Island, an island on the western part of the territory of Hong Kong. It is fairly exposed to open water fetch in the NNE-N-NW directions. To its north-west, there is a large stretch of open water where the Pearl River exits to the South China Sea. To its west, across the open water there is a piece of flat land (the Hong Kong International Airport) in a distance of 6–10 km from the station. To other directions, i.e. E-SE-S-SW, there is the Lantau Island with some tall mountains, e.g. the Lantau Peak (918 m) to the southwest and Tai Tung Shan (869 m) to the south. Thus, it is expected that the wind blown from NNE-N-NW-W directions is under the open water exposure.

Wind measurements taken by both the Doppler SODAR and the wind-profiler, which are mounted at the same location (about 250 m from the shore and 22 m above mean sea level) were utilized to calculate the mean wind profiles in the tropical cyclone