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Vertical wind profiles for typhoon, monsoon and thunderstorm winds

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ABSTRACT

The vertical profiles of mean wind speed within the atmospheric boundary layer have always been a focus of attention in wind engineering. In particular, the characteristics of wind speed profiles associated with different wind phenomena are of great significance in many engineering fields. Hence, this study presents a comparative analysis on the wind profile characteristics in connection with typhoon, monsoon and thunderstorm winds respectively, in which the wind profiles are constructed by synchronizing the wind measurements taken from a surface cup-anemometer and a Doppler radar profiler equipped at a coastal weather station in Hong Kong. For each type of wind phenomenon, the shape of the wind speed profiles is examined, and the fitting parameters contained in the logarithmic-law and the power-law model are derived. In addition, some other characteristic parameters associated with the wind speed profiles, such as wind shear coefficient and gust factor, *etc,* are determined as well to enhance the understanding of the characteristics of wind profiles in connection with different wind phenomena.

1. Introduction

The vertical profiles of horizontal mean wind speed within the atmospheric boundary layer (ABL) have long been a focus of attention in wind engineering. In particular, as many high-rise buildings are springing up worldwide, the variation of mean wind speed with height should necessarily be well understood to facilitate the structural design of high-rise buildings and therefore enhance their safety and serviceability. Besides, the height-dependence of mean wind speed also plays a significant role in relation to many other engineering applications, such as aviation meteorology and wind energy industry. It is stated that the vertical profiles of mean wind speed within ABL depend on a whole range of parameters, including upwind terrain condition, surface roughness, atmospheric stability and averaging time, *etc*. Meanwhile, the characteristics of wind speed profiles may also show marked differences depending on various wind phenomena, such as typhoon, monsoon and thunderstorm winds. There have been numerous studies that related the profiles of mean wind speed with different terrain conditions and atmospheric stability, and the research outcomes have been well adopted in design codes and standards. However, the knowledge of the vertical wind profiles associated with different wind phenomena is still insufficient. Under such circumstances, a comprehensive assessment on the characteristics of the vertical wind profiles under various wind conditions is of great significance.

Hong Kong is a highly-developed international metropolis where a great many of high-rise buildings have been constructed. The wind climate of Hong Kong, as previously addressed by Choi (1984) and Jeary (1997), is primarily subjected to two types of wind phenomena, namely monsoon and tropical cyclone. Monsoons can be considered as large-scale see breezes that have larger influenced areas and longer sustained time than tropical cyclones (Cao, 2013). The monsoon wind in Hong Kong is mainly driven by the thermal contrasts between the Eurasian Continent and the Indo-Pacific Ocean (Chang, 2011), and it is characterized with distinct seasonal variation. The north-easterly monsoon wind dominates in the months from November to April, while the south-westerly monsoon wind prevails during the summer (Choi, 1984).

Meanwhile, as is well known, Hong Kong is located in a typhoon-prone region. Typhoon, in general, refers to an intense tropical cyclone whose maximum sustained wind speeds (10 min) near its center is greater than 32.9 m/s (Choi, 1984). The typhoon winds in Hong Kong arise mainly from the Pacific Ocean, and they occur prevailingly during the months from June to October. Statistical results highlighted that the records of the annual maximum hourly speeds and the annual maximum gust in Hong Kong are attributed mostly to typhoons rather than monsoon winds (Choi, 1984).

In addition to the monsoon and typhoon winds, it is worthwhile mentioning that thunderstorms are also commonly experienced in Hong Kong, particularly during the spring and summer. Thunderstorms are

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mesoscale weather systems that affect a relatively small area and are generally short-lived (Moran and Morgan, 1991). They are often considered to be statistically less important as they are more transient and localized in nature. Although thunderstorms are small disturbances in horizontal extent as compared with extra-tropical depressions and tropical cyclones, they are capable of generating severe winds (Cao, 2013). Thunderstorm winds contribute significantly to the strongest gust records in many countries and regions across the world (Twisdale and Vickery, 1992; Holmes, 2003; Lombardo et al., 2014), and they are also the main source of high wind speeds in the Equatorial regions (Holmes, 2003).

Given the above discussions, Hong Kong is considered as an ideal place to investigate the characteristics of the vertical wind profiles associated with different wind phenomena. The objective of this paper is to present a comparative study on the vertical wind profiles between monsoon, typhoon and thunderstorm winds based on wind measurements in Hong Kong. The structure of this paper is organized as follows: Section 2 provides a brief review of the early works in relation to the vertical wind speed profiles under various wind conditions. Section 3 gives the introduction of the selected meteorological station and the measurement instruments. Assessments of the characteristics of vertical wind speed profiles corresponding to typhoon, monsoon and thunderstorm winds are presented in Sections 4–6, respectively, and the last section summarizes the major conclusions of the present study.

2. Early works on vertical wind profiles

As addressed previously, vertical wind speed profiles have received much attention over the years owing to their significance in many fields of engineering applications. Hence, there have been many studies that attempted to unveil the characteristics of the vertical wind profiles by means of field measurement, particularly in connection with typhoon winds.

Choi (1978) stated that typhoon winds behave quite differently from the monsoon winds due to their high mean wind speed and severe gustiness. The values of turbulence intensity and surface roughness during typhoons were much higher than those of monsoon winds. Ishizaki (1983) examined the characteristics of wind profiles, turbulence intensities and gust factors in typhoon winds, which aimed to facilitate the structural design in typhoon-prone regions. A field measurement study of Typhoon Hagupit (2008) presented by Song et al. (2012) indicated that there were salient differences with respect to the wind speed profiles during different typhoon stages. Moreover, with the increasing use of remote sensing techniques (e.g. Radar sounding system (SODAR), Wind profiler), the features of wind speed profiles during typhoons have been investigated extensively. Choi (1983) found that the gradient height during typhoons was approximately half of the expected value for monsoon winds. A value at 150–160 m was predicted as the gradient height for open sea terrain. A similar value of the gradient height was obtained by the Doppler SODAR measurements during three typhoons in Okinawa (Amano et al., 1999), in which the wind profiles were distinctly divided into two layers. However, it should be noted that some of the measured wind speed data reported by Amano et al. (1999) appear to be too low to achieve a thermally neutral condition such that the obtained wind profiles may not be considered as a typical model for typhoons (Giang et al., 2007). A much higher value for the gradient height under typhoon conditions was suggested by Giang et al. (2007), which ranges from 500 to 700 m for the eye-wall region to 900 m or higher for the outer vortex region. Knupp et al. (2000) presented Doppler profiler observations of Hurricane Georges at its landfall, in which a prominent jet structure was revealed with the maximum wind speed occurred at near 0.5–1.0 km above ground level. Tse et al. (2013) compared the profiles of tropical cyclone winds with several existing models, in which the wind measurements from a wind profiler and a Doppler SODAR were used. Their results showed that both the logarithmic-law and the power-law model can give a reasonable description for the variation of mean wind speed up to 300 m. He et al. (2013) investigated the dependence of tropical cyclone wind profiles with various upwind terrain conditions. It was indicated that for both hilly upwind terrain and open sea upwind terrain, the wind speeds can be well approximated by the logarithmic-law and the power-law up to a height of 500 m.

In addition, the Global Positioning System dropwindsonde (GPS sonde) has also been widely used to document wind and thermodynamic structure of typhoon eyewall due to its high accuracy and resolution (Franklin et al., 2003). Powell et al. (2003) examined the characteristics of mean wind profiles in marine boundary layer using 331 wind profiles measured by GPS sonde in tropical cyclone winds. Logarithmic-type profiles were consistently observed below a height of 200 m, and the wind maxima generally occurred at around 500 m. The field data presented by Franklin et al. (2003) showed that the mean wind profile of eyewall was characterized by a broad maximum centered at 500 m. Below this broad maximum, the wind descended logarithmically as the altitude decreased. Kepert (2006a, b) provided detailed discussions on the boundary layer wind structure based on GPS sonde observations during two hurricanes, namely Hurricane Georges (1998) and Hurricane Mitch (1998). The wind profiles in both hurricanes were characterized with a distinct low-level maximum, and the jet became closer to the surface and sharper as the radius decreases. The correlations of low-level maxima with mean wind speed, radius (i.e. the distance from the center of a tropical cyclone) and storm-relative azimuth were further identified and discussed in detail by Giammanco et al. (2012, 2013).

Apart from the aforementioned studies for tropic cyclone winds, field measurement studies were also conducted to assess the structure of thunderstorms. Letchford and Kwok (2004) suggested that thunderstorm wind profiles are characterized by a low-level jet between 50 and 100 m, and the mean wind speed above such a height tends to decrease slowly to the environment flow. Choi (2000, 2004) found that at the gust front and out-flow regions during a thunderstorm event, wind speed increased with height and reached a maximum at a height between 100 and 200 m. A similar altitude for the low-level jet was reported by Gunter and Schroeder (2015), in which the wind speed peaked at around 200 m.

3. Data collection and processing

The meteorological station selected in the present study is located in the Cheung Chau Island (CCH, hereafter)—an outlying island with a distance of 10 km to the southwest of Hong Kong Island. As shown in Fig. 1, CCH (22°12′04", 114°1′36") is fairly exposed to open water terrain in the SW-S-SE directions. Lantau Island, with a peak of 934 m, is located at the northwest of CCH with a nearest distance of 1.16 km.

The field measurement data were obtained by a cup anemometer and a wind vane at the surface weather station and a Doppler radar profiler. The cup anemometer is installed at a height of 26.7 m above ground level (AGL), or 98.6 m above mean sea level (AMSL). It has a sampling frequency of 1 Hz and can provide minute-to-minute updated horizontal wind components including 1-min scalar mean speed, as well as 3-s peak gust. Meanwhile, the information of 1-min mean wind direction is provided by a wind vane mounted near the cup anemometer. The wind radar profiler is of the boundary layer type. It is located in the vicinity of the surface weather station with an elevation of 71.9 m AMSL. This profiler can operate at a frequency of 1299 MHz, and provides two modes of outputs. For the low-mode, wind measurements are taken at 25 height levels (or gates), ranging from 213 to 1656 m with a height increment of 60 m. For the high-mode, wind measurements are taken between 459 and 5371 m (total 25 gates), with a height increment of 206 m. Owing to the overlapping average technique, each gate can provide 10 min averaged values of wind speed and wind direction at a time interval of 2 min. In this study, a complete vertical wind profile was constructed by synchronizing the wind measurements taken by the surface anemometer and the radar profiler. The wind data between two adjacent measurement levels were estimated through polynomial interpolation. Given the differences in terms of the sampling frequency and data output format