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A semi-empirical model for mean wind velocity profile of landfalling hurricane boundary layers

Reda Snaiki, Teng Wu *

Department of Civil, Structural and Environmental Engineering, University at Buffalo, State University of New York, Buffalo, NY, 14126, USA

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ABSTRACT

The existence of the super-gradient-wind region, where the tangential winds are larger than the gradient wind, has been widely observed inside the hurricane boundary layer. Hence, the extensively used log-law or power-law wind profiles under near-neutral conditions may be inappropriate to characterize the boundary layer winds associated with hurricanes. Recent development in the wind measurement techniques overland together with the abundance of data over ocean enabled a further investigation on the boundary layer wind structure of hurricanes before/after landfall. In this study, a semi-empirical model for mean wind velocity profile of landfalling hurricanes has been developed based on the data from the Weather Surveillance Radar-1988 Doppler (WSR-88D) network operated by the National Weather Service and the Global Positioning System (GPS) dropsondes collected by the National Hurricane Center and Hurricane Research Division. The proposed mathematical representation of engineering wind profile consists of a logarithmic function of the height z normalized by surface roughness z_0 (z/z_0) and an empirical function of z normalized by the height of maximum wind δ (z/δ). In addition, the consideration of wind direction in terms of the inflow angle is integrated in the boundary layer wind profile. Field-measurement wind data for both overland and over-ocean conditions have been employed to demonstrate the accuracy of simulation and convenience in use of the developed semi-empirical model for mean wind velocity profile of landfalling hurricanes.

1. Introduction

Hurricane-related natural hazards are notorious for inflicting significant damage to life and property through high winds, torrential rain and storm surge. The insured losses due to landfalling hurricanes have been increasing due partly to the changing climate and continued escalation of coastal population density (e.g., Czajkowski et al., 2011; Rappaport, 2014). In general, a mature hurricane consists of four main regions, namely a boundary layer, a region above the boundary layer with no radial motion, an updraft region, and a quiescent eye (Carrier et al., 1971). Nevertheless, the most important region for engineering applications is the boundary layer zone where the dynamics and thermodynamics are usually independently examined, or weakly coupled (Snaiki and Wu, 2017a). The existence of the super-gradient-wind region has been widely observed inside the hurricane boundary layer. The super-gradient region, where the maximum wind exists, was attributed by Kepert (2001) and Kepert and Wang (2001) to the strong inward advection of angular momentum. While the log-law or power-law wind profiles under near-neutral conditions are extensively used in engineering practice, they may be inappropriate to characterize the boundary layer winds associated with mature hurricanes. Wang and Wu (2017) indicated that the utilization of power-law or logarithmic profile may result in underestimation of the wind load effects on tall buildings under the hurricanes. As the construction of high-rise structures continues to grow in the hurricane-prone areas, it is imperative to develop a mathematical representation of engineering wind profile that could take the supergradient region into account in the wind design to ensure target safety and performance levels of civil infrastructures (Franklin et al., 2003; Snaiki and Wu, 2017a).

The hurricane boundary layer under marine conditions has been extensively investigated due to the large database collected from reconnaissance aircraft, Stepped Frequency Microwave Radiometer, moored buoy, ships data, and the Global Positioning System (GPS) dropsondes (e.g., Powell and Black, 1990; Powell et al., 2003; Uhlhorn et al., 2007; Vickery et al., 2009). The National Oceanic and Atmospheric Administration (NOAA) started deploying GPS dropsondes in 1997 to collect dynamic and thermodynamic data from the hurricanes. The composite analysis based on the GPS dropsonde data was employed by a number of

* Corresponding author.
E-mail address: tengwu@buffalo.edu (T. Wu).

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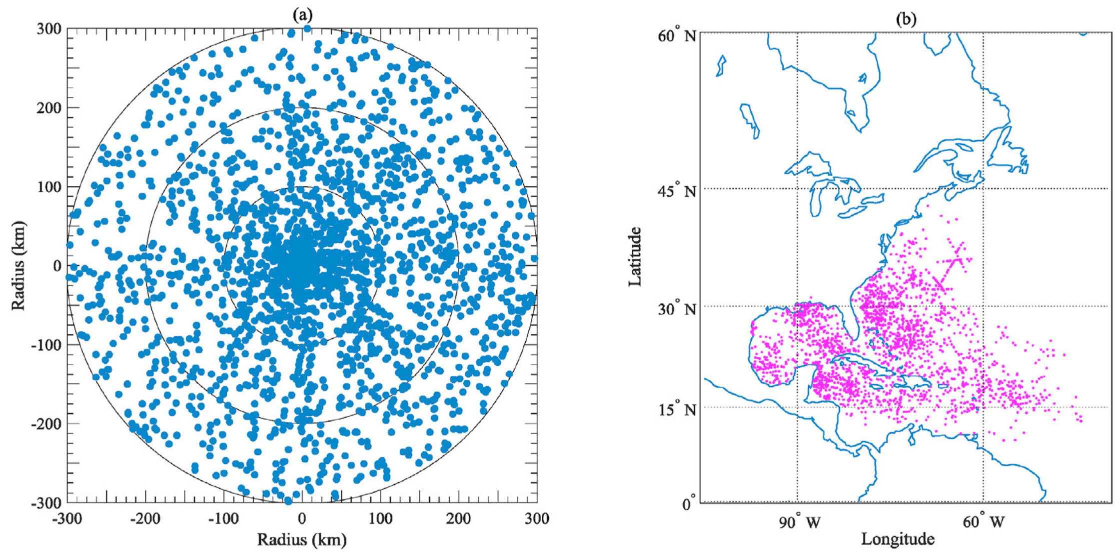

Fig. 1. GPS dropsonde data used in this study: (a) Azimuthal coverage of dropsonde data relative to hurricane center; (b) Location of selected dropsondes.

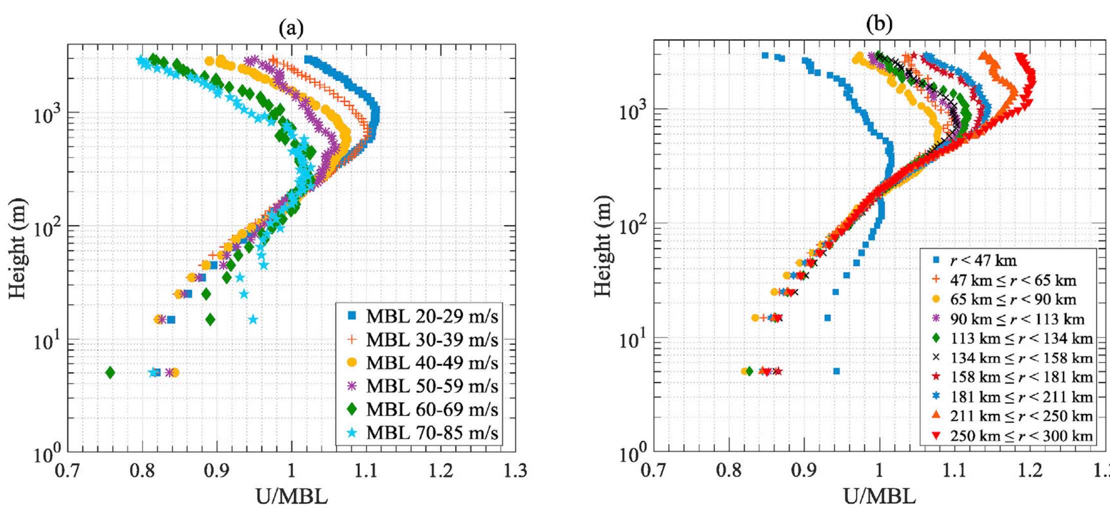

Fig. 2. Composite dropsonde wind profiles grouped by: (a) MBL wind speed and (b) storm radius.

researchers to inspect the vertical profile of the mean wind speed inside the boundary layer region (e.g., Franklin et al., 2003; Powell et al., 2003; Vickery et al., 2009). Franklin et al. (2003) and Powell et al. (2003) observed the existence of a supergradient region characterized by a wind maximum in the eyewall region of the hurricane boundary layer. They also noted a logarithmic increase of the mean wind speed profiles from the surface to the height of the supergradient region, whereas the wind speeds decrease above the supergradient region due to the weakening of the horizontal pressure gradient (Franklin et al., 2003; Snaiki and Wu, 2017b). The studies by Kepert (2001) and Kepert and Wang (2001) indicated that the height of maximum wind actually decreases with the increase of wind speed. A pronounced supergradient region near the radius of maximum winds was also highlighted by Vickery et al. (2009) using the GPS dropsondes data from 1997 to 2003. In addition, it was found that the lower few hundred meters of the boundary layer can be well represented by the classical log-law profile. Accordingly, Vickery et al. (2009) introduced a logarithmic-quadratic hurricane boundary layer model for vertical mean wind speed profile, where the lower and upper altitudes are normalized using the roughness length and boundary-layer height, respectively. The hurricane boundary layer wind model in Vickery et al. (2009) is best suited for marine conditions. Giammanco et al. (2013) also demonstrated the applicability of the log-law wind profile below the region of supergradient winds by examining the data from 1997 to 2005.

Although the implementation of GPS dropsondes has provided a rich source of data for the investigation of hurricane vertical mean wind profile, it is essentially restricted to the marine conditions. The landfalling hurricane dropsonde data is scarce due to the limited inland observations. The conventional approach to acquire the landfall wind data using the portable towers is limited in terms of vertical coverage and hence cannot capture the supergradient region (e.g., Schroeder and Smith, 2003; Schroeder et al., 2009; Masters et al., 2010). The Weather Surveillance Radar-1988 Doppler (WSR-88D) network operated by the National Weather Service, on the other hand, offers more flexibility to thoroughly examine the hurricane wind profiles over land conditions. Based on the Velocity Azimuth Display (VAD) technique (Lhermitte and Atlas, 1961; Browning and Wexler, 1968), the mean velocity is represented by a function of azimuthal angle for each conical scan at a constant elevation. Giammanco et al. (2012, 2013) used the WSR-88D retrieved data to examine the boundary layer vertical mean wind profile overland based on the VAD method. To avoid the challenges in the determination of gradient wind speed (Willoughby, 1990; Powell et al., 2003; Vickery et al., 2009), Giammanco et al. (2013) used the mean boundary layer (MBL) wind speed, defined as the mean wind speed averaged over a