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Observational study of power-law approximation of wind profiles within an urban boundary layer for various wind conditions

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ABSTRACT

This paper investigates the accuracy and limitations of wind profile modeling using the power-law (PL), especially for low speed conditions in which air and thermal pollution can prevail. A Doppler lidar system and ultrasonic anemometer were installed to measure wind profiles and turbulence statistics in the urban boundary layer of Tokyo, Japan over seven months. The wind speeds at a height of 67.5 m (u_b) at average intervals of 10 min were < 6 m/s for 80% of the observation period. For low wind speeds, the difference in wind direction with height is significant, making it difficult to determine the prevailing wind direction. The PL could be used to model the wind profiles for high wind speeds ($u_b > 6$ m/s), whereby the power-law index (PLI) converges to 0.25. Although the PL model can be used for an ensemble-averaged profile composed of all profiles from the observed period, the accuracy of the PL decreases for profiles with low speeds and short average time intervals. The PLI on average decreases to ~0.21 for low speeds and shows diurnal changes with small PLIs during the daytime. This research quantitatively discusses the application limits of the PL for wind profiles under low speed conditions.

1. Introduction

Modeling the behavior of a flow approaching an area of interest is one of the most important aspects of wind engineering. The analysis is either based on physical or numerical modeling of features such as the profile of mean velocity, as well as other turbulence statistics, which significantly influence wind characteristics in the analysis domain. For this reason, wind engineers and climatologists seek a model that can illustrate wind behavior in the atmospheric boundary layer (Counihan, 1975; Davenport, 1960; Holtslag, 1984; Hsu, 1982; Hsu et al., 1994; Panofsky and Dutton, 1984). Several theoretical and empirical models such as logarithmic law, power law, and the Deaves-Harris model have been applied to describe mean velocity profiles in atmospheric boundary layers (Davenport, 1960; Deaves, 1981; Drew et al., 2013; Li et al., 2010). Because the roughness of terrain and atmospheric stability are major factors affecting the characteristics of wind profiles (Monin and Obukhov, 1954), previous research has investigated the relationships between wind profile model parameters and terrain roughness or atmospheric stability (Counihan, 1975; Irwin, 1979; Kanda et al., 2013; Tamura et al., 2001).

The power law (PL), described in Eq. (1), is one of the most common methods in wind engineering for expressing the relationship between wind speed and height above ground (z):

$$U_{PL}(z) = U_n \left(\frac{z}{z_n} \right)^{\alpha}, \tag{1}$$

where z_n is the reference height, U_n is the reference speed at z_n, and α is the power-law index (PLI). Although the theoretical foundation is not as clear as for the logarithmic law, past observations have shown the potential of PL in modeling wind profiles in the atmospheric boundary layers above urban terrains (Counihan, 1975; Li et al., 2010; Tamura et al., 1999, 2001, 2007).

In wind engineering, PL was originally proposed for wind profiles of extremely high speed for use in designing the wind load in structural engineering (Davenport, 1960). High speed and neutrality were thus prerequisites for the use of this model. In this respect, a unique parameter in the PL, the PLI, is recommended and determined according to the surface roughness of the terrain (Architectural Institute of Japan, 2004). However, because the PL is a simple mathematical expression and can be applied to a relatively large range of heights compared to the logarithmic law (Counihan, 1975), the PL has been employed in many research fields and under various condi-

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Nomenclature

ECM	eddy covariance method
DLS	Doppler lidar system
PL	power law
PLI	power-law index
UA	ultrasonic anemometer
L	the Monin-Obukhov length L
R^2	coefficient of determination
u_b	wind speed for the lowest DLS level (z=67.5 m)
U	measured horizontal wind speed
U_n	reference speed in the PL
U_{PL}	speed expressed by the PL
$\overline{U}$	averaged speed along the DLS height levels
wd_b	wind direction for the lowest DLS level (z=67.5 m)
z	height above the ground
z_n	reference height above the ground in the PL
α	value of the power-law index

tions. For example, the PL has been used in the analysis of environmental problems such as wind environment, air pollution (Li and Meroney, 1983; Pavageau and Schatzmann, 1999; Tominaga et al., 2008), and wind power potential (Emeis, 2014; Farrugia, 2003; Peterson and Hennessey, 1977; Wharton and Lundquist, 2012). In such cases, the high speed and neutrality of the boundary layer is not assured and the accuracy of the PL can change depending on the conditions. Previous studies have revealed the dependence of the PLI on the wind speed, atmospheric stability, and the height and time of the day at which the PL is evaluated (Farrugia, 2003; Hanafusa et al., 1986; Hussain, 2002; Irwin, 1979; Touma, 1977; Zoumakis, 1993; Zoumakis and Kelessis, 1991).

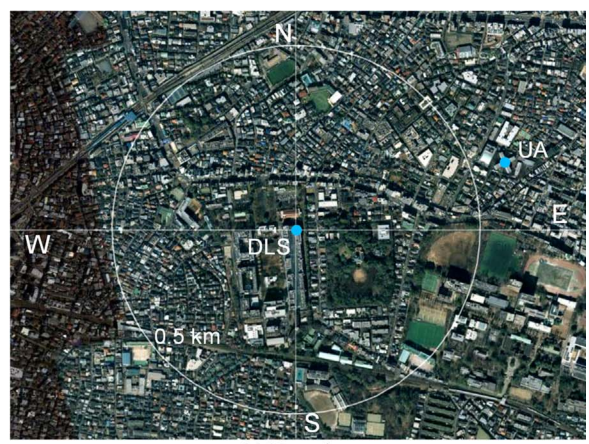
Nevertheless, the applicability of the PL is typically discussed for ensemble-averaged profiles derived from a large number of samples. Even though the ensemble-averaged profile can reflect an average wind condition, the profile is idealistic and sometimes differs significantly from an instantaneous wind profile under actual wind conditions that are affected by many disturbances. With the development of techniques related to wind engineering, the demand is increasing for the simulation of more realistic wind situations with a high accuracy. Although new methods have been developed for analyzing realistic wind situations, such as multi-scale modeling (Baklanov and Nuterman, 2009; Schlünzen et al., 2011; Yamada and Koike, 2011), the conventional method that uses the PL or other empirical profile models is still valid due to high computational efficiency. This study therefore focuses on the following questions: firstly, how well can the PL model instantaneous and real (not idealistic ensemble-averaged) wind profiles; and secondly, how accurate is the PL for low speed conditions in the absence of a dominant force driving the wind. Because the accuracy of the PL for realistic wind conditions has not been sufficiently discussed, it is necessary to investigate the applicability and accuracy of the PL for modeling profiles under various different speeds and intervals of averaged time.

Conventional wind measurements are conducted using anemometers located on a tower (Hanafusa et al., 1986; Holtslag, 1984; Li et al., 2010). However, it can be very difficult to find an appropriate location for towers in urban areas and their construction can be very expensive. Following recent developments in remote sensing techniques, remote measurements using Doppler sodar and Doppler lidar are now being applied in wind engineering (Davies et al., 2004; Drew et al., 2013; Gryning et al., 2013; Li et al., 2014; Post and Neff, 1986; Tamura et al., 1999). Doppler sodar can measure wind speed, wind direction, and turbulent structure at high spatial resolutions and was used prior to Doppler lidar for lower atmosphere measurements (Lang and McKeogh, 2011). However, Doppler lidar also enables wind profile measurement for lower atmosphere without sound noise, unlike Doppler sodar, which can annoy residents in nearby urban areas.

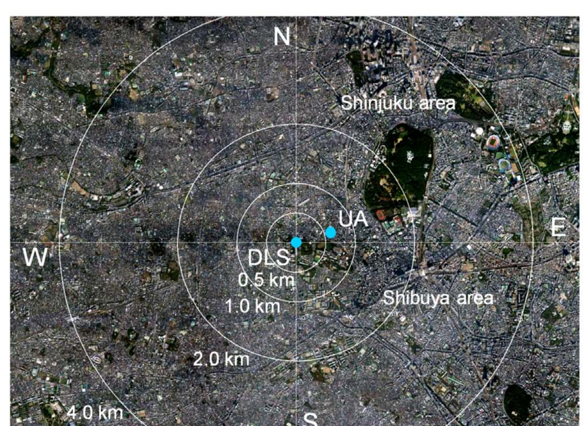
In this research, we measured wind profiles in the urban boundary layer under various wind conditions in Tokyo, Japan. A Doppler lidar system (DLS) was used for the measurement of wind profiles. An ultrasonic anemometer (UA) was simultaneously used to measure turbulent statistics in the boundary layer using the eddy covariance method (ECM). Using the observed data, we quantitatively discuss the approximation accuracy of the PL under a variety of real wind conditions related to the speed and averaging time.

2. Observation site and instrumentation

Fig. 1 shows aerial maps of the observation site and its surroundings. The DLS was installed on a building rooftop at the Institute of Industrial Science (University of Tokyo, Meguro-ku, Tokyo, Japan; latitude: 35°40′N, longitude: 139°41′E, altitude: 40 m). Velocities were measured between 67.5 and 527.5 m high at 20 m intervals (24 levels). The UA was positioned on a tower at Tokai University (Shibuya-ku, Tokyo, Japan) at a ground height of 52 m. The distance between the sites was about 600 m, with no undulating terrain between them, and their difference in altitude was 2 m. The buildings surrounding the site are mainly residential areas with a homogeneous geometry. However, there are two large commercial areas with a high density of skyscrapers, located 2 km east-southeast (Shibuya area) and 3 km north-northeast (Shinjuku area) of the DLS site. A large green area is also



(a) Near view



(b) Distant view

Fig. 1. Aerial photo map of the observation site (Tokyo, Japan; modified from Google Maps).