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Original article

Similarity theory and nocturnal locally scaled turbulence variances in the tropical urban roughness sublayer

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ABSTRACT

We assessed the potential of the "local" Monin–Obukhov similarity theory to predict the relationship between scaled turbulence standard deviations (σ_i; i = turbulence quantity) and atmospheric stability (ζ) in the nocturnal urban roughness sublayer using data collected in a tropical city of which data and research have been lacking as most works previously reported mainly concentrated on temperate mid-latitude regions. The site was LCZ 5_B in the Local Climate Zone classification system with open midrise buildings with scattered trees. Unstable (convective) atmospheric conditions persisted through the night with infrequent and intermittent stable conditions. Nighttime turbulence statistics were lower than daytime turbulence statistics due to the weak (<1 m/s) and variable mean wind speeds. Using local scales, the Monin–Obukhov similarity theory failed to predict the trend in the standard deviation of vertical wind velocity (σ_w) scaled by local friction velocity (u_{*l}) with local atmospheric stability (ζ_l) but the standard deviation of temperature (σ_T) scaled to the local friction temperature (T_{*l}) fared better. However, we found that by using the local free convection velocity ($u_{f,\,l}$) as the normalising scale with σ_W, the trend was better described with ζ_l using simple power law relations for both unstable and stable conditions, but this situation was limited to neutral conditions.

1. Introduction

Turbulence drives atmospheric mass (air pollution) and energy transfers (latent and sensible heat) in the planetary boundary layer. The urban roughness sublayer is the atmospheric layer directly above an urban surface. The "roughness" of the underlying urban surface determines its height and influence on the turbulence of the air flow above it (Christen et al., 2009). Most turbulence parameterisations employed in numerical weather, climate, and large-scale air pollution dispersion models are based on planetary boundary layer similarity theories (Stull, 1988; Hanna et al., 2007). Similarity theories are also used to model turbulence statistics within the surface layer and sometimes extended (or modified) for the urban roughness sublayer (Rotach, 1993).

Published works on turbulence parameterisations have been concentrated in the temperate mid-latitude regions (Hanna et al., 2007; Mauder et al., 2007; Al-Jiboori, 2008; Wilson, 2008; Christen et al., 2009; Quan and Hu, 2009; Pelliccioni et al., 2013), while only a handful of researchers working in tropical and urban locations (Krishnan and Kunhikrishnan, 2002; Yusup, 2012; Yusup and Lim, 2012). This paper reports data and analysis that describes the turbulence characteristics under unstable and stable conditions of an urban tropical location, which makes this dataset unique and rare. An understanding of the turbulence characteristics from derivation of semi-empirical equations commonly used from simple to advanced air pollution models would greatly increase the latter's accuracy to estimate ground-level pollutant concentrations (Rotach, 1999). For example, the increased kinematic heat flux that was observed in a previous daytime study (Yusup and Lim, 2012) suggested that the increased convective nature of the tropical urban surface could overestimate dispersion of ground-level air pollution. Furthermore, little is known on the turbulence characteristics of the nocturnal tropical urban surface, which is known to experience frequent low wind speeds commonly averaged at <1 m/s (Lim and Azizan Abu, 2004; Bin Yusup et al., 2008).

This work employs a theoretical framework akin to that of similarity theory to examine the atmospheric surface layer. The Monin–Obukhov similarity theory states that in this layer, only

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height, kinematic surface stress, kinematic heat flux, and buoyancy influence the mean gradients of turbulence quantities (Foken, 2006). The standard deviation of the three instantaneous wind velocity components (σ_u, σ_v, and σ_w), the standard deviation of absolute temperature (σ_T), friction velocity (u_*), and friction temperature (T_*) are functions of dimensionless height or atmospheric stability, $\zeta = z/L$, where z is height above the surface and L is Obukhov length (Lumley and Panofsky, 1964; Panofsky and Dutton, 1984). The variables, u, v, and w are parallel to the orthogonal axis directions (x, y, and z), and T is absolute temperature. This theory assumes that within the atmospheric surface layer, heat and momentum turbulence fluxes are nearly constant and the general velocity and temperature "scales" (u_* and T_*) can be used to describe the standard deviations for the turbulence of the entire height of the atmospheric surface layer, as is usually the case for simple and homogeneous underlying surfaces.

In this experiment, "local" versions of the scaling parameters (u_{*l} and T_{*l}) – locally estimated scaling parameters – were used (the subscript "l" denotes "local"). Studies have provided some evidence that Monin–Obukhov similarity theory is applicable to local scales in the urban roughness sublayer (Rotach, 1993; Oikawa and Meng, 1995; Roth, 2000) and specifically for σ_w and σ_T during the day at a tropical urban location (Yusup and Lim, 2012). Equations for locally scaled velocity and temperature variances/standard deviations have been published and proven valid for some measurement positions close to urban rooftops. In addition, the non-dimensional gradient of mean wind speed using local scales in the urban roughness sublayer was also found to obey semi-empirical functions in the atmospheric surface layer of Zürich, Switzerland (Rotach, 1993), a site within the temperate climatic zone. Hogstrom et al. (1982) stated that local measurements and their local-variant scales can act as an alternative method to simplify the calculation of the standard deviation of turbulence within the roughness sublayer.

The atmosphere above urban areas experiences unstable or convective conditions because of heat radiation from roads, buildings, and other man-made structures, which intensify mass and energy exchanges within the urban roughness sublayer. This phenomenon is known to keep the urban boundary layer well mixed diurnally. At night, the cooling (long-wave radiation emitted by the hot urban surface) of the urban surface contributes to the instability of the overlying atmosphere, which is indicated by ubiquitous strongly positive – upward-directed – kinematic heat fluxes (Christen and Vogt, 2004).

The turbulence characteristics of the nocturnal urban roughness sublayer should be investigated further because there could be large differences from the diurnal turbulence characteristics of the urban atmosphere. For instance, during the day there is constant and stable incoming solar and outgoing surface heat radiation, and at night there is only intermittent outgoing surface heat radiation from the urban surface. The daytime counterpart to this experiment is detailed in the paper by Yusup and Lim (2012) with results showing that σ_W and σ_T scaled by u_{*l} and T_{*l} are congruent with Monin–Obukhov similarity theory. Thus, we aim (1) to determine how applicable Monin–Obukhov similarity theory is during nighttime using local scales, (2) to derive the relationship between the turbulence standard deviations (especially σ_W and σ_T) and atmospheric stability, and (3) to examine the influence of kinematic heat flux on turbulence within the nocturnal urban roughness sublayer.

2. Methods

2.1. Site, sectors, and duration of experiment

This experiment was conducted in an urban area approximately 900 m from the coast of the island of Pulau Pinang, Malaysia, a small equatorial island facing the Indian Ocean [5°21′N, 100°18′E]. Data were collected between the months of January and August 2010. Measurements were taken from 21:00 until 05:00 LST (local standard time). This is the same measurement campaign as the Yusup and Lim (2012) study but the data analysis is specific to the nighttime period.

The wind sensor was mounted on top of the pole of an "open lattice" tower (tripod) 3 m above the urban (and local) rooftops (on a building of 15 m height) of Universiti Sains Malaysia (USM) (refer to Fig. 1(a) to view the schematic map). Thus, the total height of measurement from the ground was 18 m. USM is situated midway between a channel and a series of forested hills, approximately 1.5 km from the coast of the South Channel of Pulau Pinang and 1.5 km from the hills (highest point is 830 m above sea level) that stretch from the north to the south in the middle of the island Pulau Pinang. The roof where the tower was placed is flat and square in shape. The tower was situated in the centre of this roof, 2.0 m from the edges. The area-weighted average of obstacle heights (i.e., buildings and trees) was 15.0–15.9 m above ground level (Table 1) and the corresponding effective height of measurement (z') was 4.5 m (calculated by subtracting total height, 18 m, with the respective area-weighted average of obstacle height). Vertical heterogeneity (σ_h/h) was also determined, where σ_h is the standard deviation of the heights of obstacles in upwind surfaces and h is average height of buildings. This urban canopy surface parameter is a metric of surface roughness (Yusup and Lim, 2012).

The surrounding upwind surfaces were quite diverse, which resulted in different downwind flow characteristics. Thus, the data collected were conditionally analysed based on wind direction. Due to variations of terrain and contour, the collected data were initially divided into four sectors: A, B, C, and D, according to different upwind surface characteristics (refer to Fig. 1(b) for upwind views of the sectors).

2.2. Instrumentation and sampling

The three vector wind velocity components (u, v, and w) and virtual air temperature (T_v) were measured using a wind sensor: a fast response three-dimensional ultrasonic anemometer (Model No.: 81000, Young, USA). Data were recorded digitally, connected directly to a personal computer using an RS232 cable and "Hyperterm" (Microsoft®, USA) as the software interface, where each recorded run was approximately 8 h in duration. All measurements were logged at a frequency of 10 Hz, resulting in 18,000 data points per run.

2.3. Averaging time

The averaging time used was 30 min. This averaging time was chosen because it is long enough to allow the acquisition of sufficient data to determine turbulence standard deviations, but brief enough to fulfil the statistically stationary requirement for flux calculations (Vickers and Mahrt, 1997). This was chosen to mitigate flux-sampling problems, which often occur in stable atmospheric conditions. Furthermore, all cited studies thus far employed this averaging time, making it almost a standard method in the eddy covariance technique (Pasquill, 1974; Panofsky and Dutton, 1984; Roth et al., 2006; Fesquet et al., 2009). In a previous study at the same location (Yusup, 2012), we conducted an ogive analysis (Sun et al., 2006; Norris et al., 2008), and found that the best averaging time that is able to capture all relevant fluxes at this site is 30 min.