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Aerodynamic drag coefficient over equatorial coastal industrialized and urban areas

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ABSTRACT

Drag coefficient (C_D) in the urban roughness sublayer over industrialized and urban equatorial areas under low wind conditions are reported in this paper. An observation tower was set up in (1) the field of the Institusi Teknologi Tunku Abdul Rahman in the middle of the Prai Industrial Park (5°22′N, 100°23′E), employing a Gill UVW propeller anemometer and a temperature sensor placed at a height of 10 m above the ground level and (2) on the top of a faculty building in Universiti Sains Malaysia (USM) (5°21′N, 100°18′E), employing a sonic anemometer at 18 m above the ground level. Meteorological data were collected for three months in the years 2006 and 2010. Monin–Obukhov similarity theory using local scales was first tested at the sites studied and was found to be applicable. The relationships between C_D and mean wind speed, V, local friction velocity, u_{*l}, and atmospheric stability, ζ_l, are also discussed (subscript "l" denotes local). Generally, C_D is strongly dependent and increased with u_{*l} for both sites. C_D was also confirmed to be influenced by atmospheric stability where it is at its maximum when u_{*l} (and V) is large, which generally occurs in neutral atmospheric conditions. This relationship was seen at both sites, suggesting its generality. Lastly, the measured C_{DN} value obtained was also used to calculate C_{GN}, geostrophic drag coefficient ($=1.9\times10^{-3}$), which is similar to the reported values in the literature.

1. Introduction

1.1. Problem statement

Most micrometeorological research in urban or industrialized areas were based on the atmospheric surface layer (ASL) and its underlying urban roughness sublayer (URS) that extends up to three times the average building height (Rotach, 1999), created at the rural–urban (or smooth–rough) interface (coined as the internal boundary layer, IBL). Research is done to gather data for air pollution and weather forecasting models. Even though, ASL data for these models in developing countries such as Malaysia and other equatorial areas are few and far between, with the majority of data were collected from countries in the European continent and in the Americas (Bin Yusup et al., 2008; Patil, 2006). Some studies have been conducted in Asia where the most relevant work are from India (Agarwal et al., 1995; Krishnan and Kunhikrishnan, 2002; Patil, 2006; Ramana et al., 2004; Rao et al., 1996). Furthermore, interests in the effects of changing surface condition on the various atmospheric layers have risen in the past decade because of the increasing reliance on air pollution and weather forecasting models that depend on obtaining accurate parameterization of the various properties of the atmospheric layers.

1.2. Drag coefficient

Aerodynamic drag coefficient, C_D, can exhibit the influence of the "mechanical" factor in the generation of turbulence as well as estimate the surface roughness length of a given surface condition, z_0 (Grant, 1991). Logical deductions on C_D imply that it is a function of aerodynamic surface roughness that is influenced by the height of the measurement and horizontal position (Grant, 1991) and atmospheric stability.

Another iteration of the drag coefficient is the geostrophic drag coefficient or C_G, which is normally used in macro-scale numerical models that relate C_G to large-scale wind, such as wind at the top of the planetary boundary layer for large-scale energy flux parameterization (Esau, 2004; Esau and Zilitinkevich, 2006). This can also be used to estimate C_D over large areas and duration (around one year) while following the requirement of the angular momentum flux balance.

To give some perspective on C_D, its value is known to range from 0.002 to 0.003 in the Salisbury Plains (homogenous surface conditions) and from 0.004 to 0.007 when measured at the elevated position (on a balloon) over a similar characteristic area

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(0.0004 over sea given as a comparison where virtually no obstruction is present) and follows the square law over land at low wind speeds (Garratt, 1977).

1.3. Similarity theory

Assuming that the atmospheric layer above a homogeneous surface is in constant flux (which is true in the ASL), C_D can be estimated using Eq. (1) or (2). This is related to the Monin–Obukhov similarity theory (MOST), which is able to profile mean gradients and turbulence characteristics in a stratified ASL

$$C_D = \left(\frac{u_*}{V}\right)^2 = \frac{C_{DN}}{(1-k^{-1}C_{DN}^{1/2}F(\zeta))}^2 \quad (1)$$

where V is the mean wind speed, $C_{DN} = k^2/(\ln[z/z_0])^2$ is the drag coefficient in neutral atmospheric condition,

$$F(\zeta) = \int_{\zeta_0}^{\zeta} \frac{1-\varphi(\zeta')}{\zeta'} d\zeta'$$

$$\tau = \rho C_D V(z)^2 \quad (2)$$

where τ is the shear stress at measurement height, ρ is the air density, $V(z)$ is the wind speed as a function of height, z.

Since this work was done in the URS, in oppose to the ASL, a special set of scaling parameters known as "local" scales (throughout this paper, the subscript "l" denotes local), such as the local Obukhov length and friction velocity (similar to the MOST scaling), was used to normalize the measured turbulent parameters of the URS. This theory is known as a subset of MOST. Local scales have been applied successfully in various papers published characterizing the URS (Quan and Hu, 2009; Rotach, 1993, 1999). It must be pointed out that henceforth, all definitions of turbulence parameters presented in the following paragraphs refer to the local variant of the MOST scaling.

The empirical equation of the non-dimensional wind gradient, $F(\zeta')$ and its corresponding stability parameter, ζ ($=z/L$, where L is the Monin–Obukhov or Obukhov length), and the neutral value of C_D (or C_{DN}) needs to be measured before C_D can be estimated. C_{DN} is generally constant if the measurement height follows the criteria $0.20 > z_0/h > 0.02$, where h is the height of the roughness element (Garratt, 1977). V can be calculated by taking the square root of the summation of the square of the longitudinal mean wind speed, u, and the square of the lateral mean wind speed, v, where k (≈ 0.40) is the von Kármán constant. Lastly, friction velocity, u_*, can be calculated using the eddy correlation (EC) method (Marques et al., 2008). EC is defined as the covariance between two fluctuating turbulence parameters, such as $\overline{w'\theta'}$, $\overline{w'u'}$, and $\overline{w'v'}$ (primes denote the fluctuating component of the parameter from the average and overbars denote the ensemble averages).

1.4. Research objectives

This paper intends to present some pertinent parameters of the URS (at two different locations) in the region, described as an area with intense solar radiation, high humidity, and low wind speeds all year round, specifically those that deal with aerodynamic drag caused by surface characteristic and atmospheric stability. In order to apply the locally scaled version of similarity theory at the current sites, its validity will be explored first. Following this, an investigation of the role of atmospheric stability and mean heights of obstructions in the fetch region on the local bulk C_D of the URS in an industrialized and urban equatorial area will be conducted. A hypothesis that could be confirmed in this experiment is that large-area averaged C_D values in tropical regions, possibly because of the lower global latitude of the measurement location, especially in urban or forested areas, could be high compared to the literature, with averages beyond $C_{DN}=0.0277$ (lower limit of 0.0039) and corresponding $z_0=0.85$ m (lower limit of 0.014) taken from Garratt (1977). Thus, the following questions were central to this research:

1. Is local scaling applicable in the urban roughness sublayer (at least at the sites studied) in this work?
2. What is the trend of C_D with ζ_l in the layer closest to the urban roughness sublayer in two different areas?

2. Experimental site and methodology

2.1. Site description and instrumentation

The sites chosen for the sampling of momentum fluxes and related parameters were the (1) campus of the Institusi Teknologi Tunku Abdul Rahman (ITTAR), in the center of the Prai Industrial Zone, Penang, Malaysia (5°22′N, 100°23′E) and (2) on top of a building of the Universiti Sains Malaysia (USM) (5°21′N, 100°18′E). The observational sites were an industrial and an urban location, respectively, both with relatively homogeneous surfaces. The former site consists of some major petrochemical, chemical, refineries, and fertilizers industries together with other numerous small industries, while the latter site comprises faculty buildings, such as lecture halls complexes and students' hostels (refer to Figs. 1 and 2).

The first site has been divided into two sectors (because of data availability) of 90°, labeled as sectors NW and SE. As for the second site, four sectors (A: top right panel, B: bottom right panel, C: bottom left panel, and D: top left panel), where only two sectors provide sufficient data, discovered later to be A and B were used. This was done to separate the effects of different distributions of surface obstructions on measured turbulence between the sectors depending on 30 min averaged wind direction.

2.1.1. Site 1: ITTAR

An instrumented (wind and temperature sensors detailed in the following paragraph) tower was constructed with a height of 10 m, which is the recommended height of measurement of fluxes (Grant, 1991), in the middle of a field covered with grass

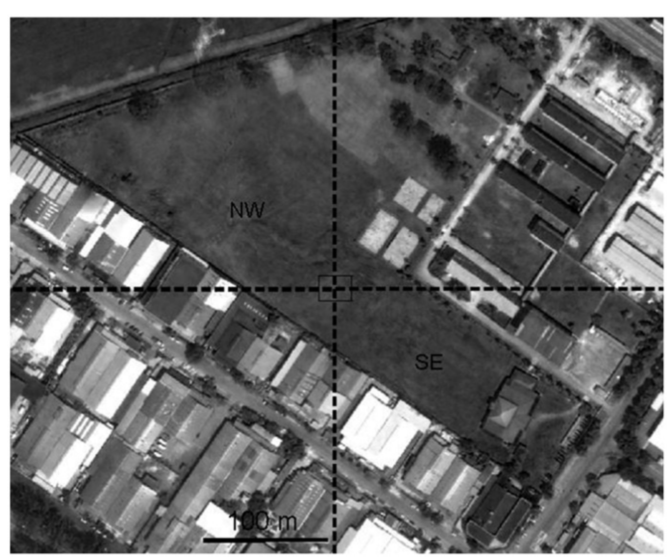

Fig. 1. Schematic map of Site 1: ITTAR showing sectors NW (top-left) and SE (bottom-right). Sampling location is marked as a box in the center.