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Evaluation of rare velocity at a pedestrian level due to turbulence in a neutrally stable shear flow over simplified urban arrays

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ABSTRACT

The geometric dependency of the wind environment at a pedestrian level is an important issue that influences human comfort and safety in urban outdoor spaces. As such, this paper proposes to investigate the statistical features of wind speeds at the pedestrian level by calculating wind speed probability density functions based on flow field data from large-eddy simulations of simplified urban arrays, aiming to clarify the effects of urban geometry on rare velocity events such as strong gusts or extremely weak air flow. Though strong wind events occur infrequently, a positive correlation was demonstrated between percentile and mean wind speeds, indicating that the risk of gusty events increases with the increase of mean wind speeds. Conversely, the frequency of weak wind events shows an inverse correlation with mean wind speeds, showing that better ventilated urban arrays will retain higher wind speeds. Furthermore, these percentiles and occurrence frequencies are clearly expressed by the frontal area indices of urban block arrays. These results imply a trade-off between the following two objectives for urban area wind environments characterized by the urban geometry: enhancing air ventilation in urban areas and preventing strong wind gust events at a pedestrian level.

1. Introduction

Air flow in urban areas can be deterministic of human comfort and safety in the local outdoor environment. In general, wind distributions in an urban area are considerably affected by the local urban geometry, including building layout, height, and coverage ratio. Given the impact of this issue on daily life, numerous researchers in the past few decades have attempted to quantify the effects of buildings on wind distribution in urban areas.

Rare, high wind speed "gusty events" were originally revealed as a result of observations reported near a building in Penwarden (1973). These high velocity winds are now thought to be caused by the sheltering effects of nearby buildings. In order to evaluate uncomfortable or dangerous situations that may be caused by such events, various criteria for wind environment quantification and categorization have been suggested, primarily based on mean wind speed (Penwarden, 1973; Hunt et al., 1976), gust wind speed, effective wind speed with consideration of turbulence intensity (Hunt et al., 1976; Murakami and Deguchi, 1981), and exceedance probability of threshold wind speeds (Melbourne, 1978; Murakami and Fujii, 1983; Murakami et al., 1986) as reviewed in Blocken and Carmeliet (2004) and Stathopoulos (2006, 2009). However, prior research in this area has been limited by a lack of cohesive data, as even between researchers evaluating the same criteria, different threshold values have been arbitrarily determined. Recently, Nakamura et al. (2016) performed a comparison between the existing wind speed data-based criterion and wind-related accident reports at 320 field measurement points throughout Japan. Their results showed that, while all the above criterion can successfully identify some regions with extremely strong wind areas (where pedestrians have reported being blown down by wind – referred to as "blow-down accidents") as the most dangerous areas, they excluded several areas where blow-down accidents have occurred or preventative actions were taken to avoid blow-down incidents.

Working from the wide range of criteria, thresholds, and results seen in past research, this study was able to interpret the characteristics of gusty events as follows: the previously selected criteria used measurable quantities that are strongly correlated with wind-related accidents, but have been limited with regard to the direct evaluation of gusty events that actually cause accidents. In other words, increasing of the index values will increase the statistical probability of a gusty event, but fails to provide an accurate prediction of such occurrences. This also implies that extremely strong wind events with considerably low occurrence frequencies have the potential to cause such accidents. Given this knowledge, a statistical understanding of the effects of temporal and spatial

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variation on wind speeds becomes invaluable, allowing for future evaluations of rare gusty events with improved accuracy.

Areas of possible discomfort or danger are commonly assessed using both wind-tunnel experiments (WTE) and computational fluid dynamics (CFD) approaches under the condition of presence or absence of a target tall building (Stathopoulos, 2006, 2009; Blocken and Carmeliet, 2004). In the past decade, the CFD approach has been receiving considerable attention in both academic and professional applications. Consequently, academic societies including COST Action C14 (Franke, 2006) and AIJ (Yoshie et al., 2007; Tominaga et al., 2008) have proposed guidelines for accurately predicting regions in which wind strength has been increased by nearby buildings using the Reynolds Averaged Navier-Stokes simulation (RANS). These assessments, however, were primarily concerned with using the spatial distribution of mean wind speeds to identify areas that are likely to experience elevated mean wind speed, and overlook the unsteadiness of gusts outside this average. Current procedures for predicting gusty events use simplified estimations of gust wind speed, applying techniques such as simple gust factor multiplication or assumed applications of probability density functions such as the Weibull distribution.

While it may be plausible to consider that gusty events become stronger or more frequent as the mean wind of a region increases, the accuracy of wind gust simulations may be dramatically improved by treating the wind speed as an instantaneous distribution. This distribution can be determined from the nature of the gusts, which are unsteady, intermittent, and occur with extremely low frequency.

By means of large eddy simulation (LES), He and Song (1999) were able to report mean and turbulent flow distributions around buildings; however, they failed to establish a relationship between strong mean winds and the occurrence of gusty events. Letzel et al. (2012) also simulated realistic wind conditions in an urban district of Hong-Kong; however, their discussion was limited to the mean flow distribution in terms of urban ventilation. Due to the scarcity of scientific investigation into unsteadiness in the wind environment, relationships between gusty events and urban geometric parameters remain poorly defined.

Very recently, Ahmad et al. (2017) attempted to tackle these two objectives, and were able to provide a simulated evaluation of gusts in a realistic urban area of Tokyo using the Lattice Boltzmann-Method LES. They calculated instantaneous flow fields, and were able to demonstrate that spatial maximum wind speeds decrease with increasing building coverage ratios. Nevertheless, the number of studies that have investigated the effects of geometry on instantaneous gust events is still quite low.

Urban ventilation, another aspect of the wind environment, has lately been introduced in hopes of improving comfort, which has been affected by the considerable effects of urban heat islands or contaminant exposure from heavy traffic. The alarming spread of disease in Hong-Kong in 2003 was a secondary factor driving the improvement of urban ventilation research, can be seen in the air ventilation assessment system (AVA, reviewed in Ng, 2009).

The primary concern of this research is clarifying relationships between urban ventilation at pedestrian levels and urban geometric parameters such as building coverage ratio, mean building height, and mean open space area. In many similar studies conducted previously, the introduction of air into the canopy is evaluated by horizontally averaged wind speeds taken at pedestrian levels. For example, WTE with scale models have been performed for dozens of examples of both realistic and simplified urban geometries by Kubota et al. (2008) and Yoshie et al. (2008). Additionally, CFD has been employed for the simulation and calculation of wind speed ratios in urban geometry (additional examples of simplified geometry: Zhang et al., 2005; Hang et al., 2012; Yuan and Ng, 2012; Abd Razak et al., 2013; and realistic geometries: Letzel et al., 2012; Takebayashi and Oku, 2014; etc.) Furthermore, pedestrian wind speed prediction models have been proposed based on WTE and CFD (Kubota et al., 2008; Yoshie et al., 2008; Ikeda et al., 2015; Ikegaya et al., 2015).

Most of these studies showed that mean wind speeds at pedestrian levels become weaker as the building coverage ratio increases, indicating air ventilation is hindered in densely arranged building arrays. In addition to their evaluation of wind speed ratios, Hu and Yoshie (2013) demonstrated relationships between three indices of urban ventilation: wind speed ratio, normalized concentration, and visitation frequency of contaminant. Their results revealed that wind speed ratios have a negative correlation to both the normalized concentration and visitation frequency, indicating that the concept “the more wind the better” is a qualitatively plausible idea for improving urban ventilation and air quality.

However, all previous studies have considered only temporally and/or spatially averaged values for ventilation efficiency. As the flow fields in the urban canopy are three dimensional and unsteady, it is possible that very weak ventilation regions or periods exist which are poorly represented by these averages. Further interest and investigation is therefore needed to evaluate how the instantaneous wind speed distribution, which takes extremely high and low wind speed exceedances into consideration, affects urban ventilation.

In order to solve these remaining questions surrounding the wind environment and its effects on human comfort and safety, analysis of instantaneous flow fields is necessary. To accomplish this, the current study performed LESs of flow fields over simplified urban arrays to clarify the relationship between urban geometry and the probabilistic features of each directional wind speed. This work focused only on the turbulence generated by simplified urban arrays; however, it should be noted that multiple scale turbulences exist in more realistic urban boundary layers. As the results presented below, strong wind events – defined as percentiles with specified occurrence probabilities – are derived based on probability density functions of streamwise, spanwise, and vertical wind speeds as well as their relative magnitudes. Furthermore, the occurring frequencies of weak wind speed events are discussed for each urban array. In the conclusion, the relationship between these low-frequencies but highly influential events and urban geometry is discussed explicitly.

2. Numerical setup

2.1. Numerical model description

LES was performed using the parallelized large-eddy simulation model (PALM) developed at Hannover University (Raasch and Schröter, 2001). Urban geometric setups were implemented in the PALM, facilitating users' reproduction of both realistic and simplified urban geometries (Letzel et al., 2008). The finite deference method is employed by PALM to solve continuity equation, Navier–Stokes equations, and the transport equation to calculate the subgrid-scale (SGS) turbulence kinetic energy (TKE) as well. Turbulence closure followed the 1.5th-order Deardorff turbulence model (Deardorff, 1980).

Schematics of the selected numerical domains are shown in Fig. 1. The wind velocity is defined as $u_i(i = 1, 2, 3 \text{ for } u, v, w)$ in the $x_i(i = 1, 2, 3 \text{ for } x: \text{streamwise}, y: \text{spanwise}, \text{and } z: \text{vertical})$ direction. Four blocks with a block height of H were arranged on the floor in a numerical domain, using either a square or staggered layout as shown in Fig. 1 (a) and (b), respectively. The lateral and streamwise directions were both connected to each other by imposing cyclic boundary conditions to reproduce simplified, infinitely repeating urban arrays. Using this design, this study targeted flow fields over and within a well-developed urban boundary layer of simplified block arrays in both the lateral and streamwise directions. By employing cyclic boundary conditions, the domain sizes for each geometric condition were allowed to be relatively small in this study. Coceal et al. (2007) demonstrated the effects of numerical domain size on turbulent statistics and spatial correlation of velocity fields for the flow over a cubical block array. Their work concluded that the differences in turbulent statistics were less than 5% between small domain $(x \times y \times z = 4H \times 4H \times 4H, \text{where } H \text{ indicates the block height})$ and large domain