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Air ventilation assessment under unstable atmospheric stratification — A comparative study for Hong Kong

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ABSTRACT

In most current air ventilation assessment (AVA) studies, a simple neutral assumption that does not consider thermal effects is adopted, particularly for numerical simulation practices. With statistics of daytime observations during summer in Hong Kong as an example, this study demonstrates that neutral atmospheric boundary conditions occur with a very low probability, which implies that current practices are indeed far away from reality. This study is devoted to addressing this knowledge gap by cross-comparisons of field measurements, wind tunnel tests, and large-eddy simulations (LES) under neutral and unstable conditions. It is found that LES-computed velocity ratios under unstable conditions are in line with field measurements, while results of simulations under neutral conditions are close to those of wind tunnel tests. Enhanced vertical mixing due to surface heating produces improved ventilation performance in the unstable case. The neutral assumption tends to underestimate pedestrian-level velocity ratios compared to a diabatic condition; hence it is deemed conservative when it is adopted in AVA practices. Moreover, stronger wind direction variance under unstable conditions results in weaker correlation between velocity ratios and frontal area indices than neutral conditions, which implies that street orientations become less important in ventilation under unstable conditions.

1. Introduction

Wind comfort and wind safety for pedestrians are important requirements for city design and urban planning [1]. For subtropical high-density cities such as Hong Kong, in order to mitigate the negative effects of the urban heat island, good ventilation is required for healthy living and comfortable thermal sensations [2,3]. After Hong Kong was hit by the Severe Acute Respiratory Syndrome (SARS), from which many people died in 2003, the Hong Kong government started discussions among various government departments and consulted relevant professional institutes and stakeholders regarding the standards, scope, and mechanism for application of an air ventilation assessment (AVA) system to improve the urban wind environment [4].

Afterwards, a set of planning guidelines was promoted based on a series of studies. The Housing, Planning and Lands Bureau and the Environment, Transport and Works Bureau jointly issued the Air Ventilation Assessment Technical Guidelines (AVA-TC06-01) in 2006. Meanwhile, a new chapter on ventilation assessment was also incorporated into the Hong Kong Planning Standards and Guidelines (HKPSG). These two documents, setting out the framework and requiring all major government departments to include AVA as one of their planning and design considerations, were the first to address weak wind problems [5]. Unlike the guidelines of many countries for dealing with wind gust problems, the Hong Kong AVA is specifically designed to deal with weak wind conditions in congested urban areas under a hot and humid subtropical climate [4]. The world's first weak-wind urban AVA system has been applied in Hong Kong in the city's design and planning practices for more than a decade.

However, the current AVA methodology is known to have limitations in that it cannot correctly predict urban air ventilation performance in some areas of Hong Kong where convective motion is prominent due to inhomogeneous surface heating in weak wind conditions [6]. One possible cause is that the current AVA methodology adopts the neutral assumption for the atmospheric boundary condition, which is justified only when mechanical turbulence has a greater influence on ventilation than buoyancy-induced turbulence under high background wind speed. However, the neutral assumption does not adequately represent the actual situation, as the daytime atmospheric boundary is likely to be unstably stratified, particularly under clear sky and low wind conditions [7]. More importantly, the most crucial situations for

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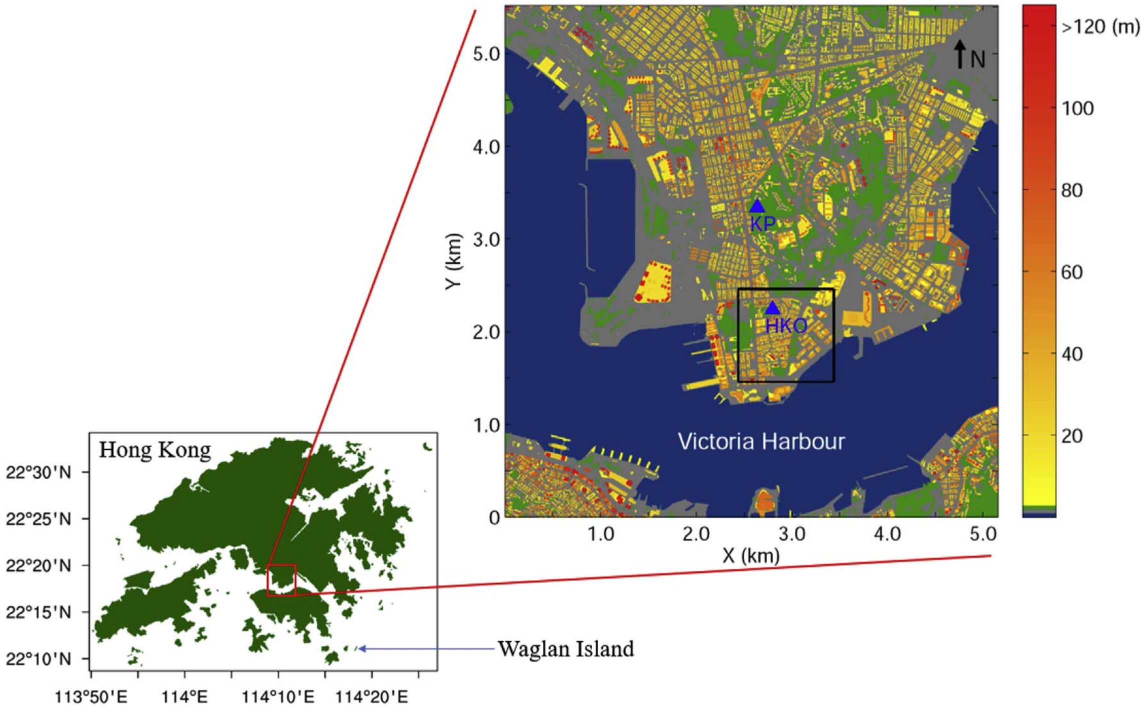

Fig. 1. High-density living environment in Hong Kong: urban morphology of the Kowloon Peninsula. The blue triangles denote the locations of two meteorological stations, Hong Kong Observatory Headquarters (HKO) and King's Park (KP). The black box encloses the domain of Tsim Sha Tsui. The colored bar describes building height (m). The location of Waglan Island is indicated. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

urban ventilation are those in which only a low-speed background wind is present. The neutral assumption that supposes that buoyancy-induced turbulence has only a minor influence on ventilation is not true in such a condition.

The atmospheric stability of the urban boundary layer is well known [8]. Meanwhile, many urban ventilation studies have used wind tunnel testing and computational fluid dynamics (CFD) models with a neutral assumption [9–15]. But very few studies have addressed the effects of diabatic conditions on urban ventilation. A study of thermal effects on turbulence coherent structures found that when thermal effects are included by surface heating in large-eddy simulation (LES), the spanwise flow is stronger within an idealized building array compared to the neutral case [16]. Another LES study suggested that roof heating, in combination with building walls and ground heating, is important in the strength and location of the canyon vortex [17]. Both of these LES studies used idealized urban geometries (cubical building arrays). Using Reynolds-averaged Navier-Stokes (RANS) simulations of two simplified Hong Kong city models, Yang and Li pointed out that airflow in street canyons is dependent on thermal stratification when wind speed is small relative to the buoyancy force [18]. However, how pedestrian-level ventilation under thermal stratification differs from neutral conditions in a realistic urban complex is indistinct.

The neutral assumption is widely adopted in AVA practices, mainly because of its low computational cost and the ease with which it can be realized in numerical simulations and wind tunnel tests. When thermal conditions, specifically unstable stratification, are considered in ventilation, there will be additional challenges: First, a larger model domain is required to catch the larger turbulent structures in unstable simulations than in the neutral condition, while the grid size has to be kept small to sufficiently resolve the street-level air flows [19]. Second, special attention should be paid to the lateral boundary conditions to ensure that they will not artificially modify the wind environment within the assessment region. For instance, the radiative outflow condition in the non-cyclic boundary requires a positive outflow at all times [20,21]. Therefore, while a weak background wind is provided for generating buoyancy-driven turbulence, extra model domain is needed on the leeward side of the city. This also requires extra computational cost. Third, more uncertainties will be incorporated in the estimation of initial thermal conditions. Heat fluxes are more difficult to monitor than winds. In such cases, validation of model results can be another obstacle.

The objective of this study is to demonstrate the knowledge gap between current practices and reality by comparing wind tunnel test results, field measurements, and a pair of LES experiments in Hong Kong, and to propose possible adaptations for future AVA practices based on the comparative results and knowledge of atmospheric boundaries under various conditions.

2. Data and methodology

In AVA studies, we are especially interested in pedestrian-level wind velocity. The wind velocity ratio (VR) is used as an indicator, which is calculated by $VR = V_P/V_\infty$, where V_P is the wind velocity at the pedestrian level (2 m above the ground), and V_∞ is the wind velocity at the boundary layer not affected by ground roughness. Apart from the meteorological data used in estimating the atmospheric stability class, this study includes some wind tunnel test results and field measurements from previous AVA studies, and a pair of LES experiments are undertaken for cross-comparison.

2.1. Observation and stability classification

Utilizing observations from two urban weather stations in Hong Kong during 2006–2015, we estimate the probability of stability classes according to Pasquill's atmospheric stability classification scheme [22]. Hourly cloud cover data are taken from Hong Kong Observatory Headquarters, while wind speed and global solar radiation data are taken from King's Park. The locations of these two weather stations are indicated in Fig. 1. We consider daytime hours (6 a.m.–8 p.m.) during all summer (June–August) days in 2006–2015.

As listed in Table 1, atmospheric turbulences are categorized into six stability classes, namely A, B, C, D, E, and F, with class A being the