Coupled mesoscale–microscale (CMM) modelling of airflow at Hong Kong International Airport

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1 INTRODUCTION

Coupling mesoscale (several kilometres) and microscale (meters to tens of meters, CMM) models is an important step forward in the microscale turbulence forecasting in the atmospheric boundary layer (ABL). The mesoscale models adopt the physical parameterizations to model the outer flow phenomena while the microscale models resolve the terrain details and microscale flows around buildings/man-made structures. For example, Esparza et al. (2018) firstly proposed multiday dynamic downscaling from numerical weather prediction (NWP) forecasts to eddy-resolving scales with a grid resolution of 25 m and realistically reproduced turbulence levels and peak events at subminute intervals in the daytime ABL. Due to the complex coupling mechanisms of atmospheric flows at several scales, such as street scale (~ 100 m) and city scale (~ 10 km), the development of simulation techniques and tools to resolve these multi-scales is challenging and needed to better forecast and understand these microscale turbulences in the ABL.

At present the operational mesoscale models are unable to predict the details at street scales and the eddy-resolving simulations are still impractical to extend to city scales. On the one hand, several studies have developed the multiscale capabilities in numerical weather prediction (NWP) models (Mirocha et al. 2013; Esparza et al. 2014). On the other hand, with advances in computing power, computational fluid dynamics (CFD), including large eddy simulation (LES), has been performed to provide physical insights into atmospheric turbulence, which can further improve spatiotemporal resolution information (Flores, Garreaud & Muñoz, 2013). Fossum & Helgeland (2020) performed LES of Oslo city using a domain of 150 km^2 at a spatial resolution of 2 m. However, few studies have coupled CFD-LES with mesoscale models to predict microscale turbulence and evaluate its multiscale performance in forecasting realistic atmospheric turbulence.

Hong Kong International Airport (HKIA) is well known for its susceptibility to low-level wind shear, which is a potential hazard for airport during landing and take-off. On average, there are 115 days per year (almost every 3.2 days) with wind shear reported (Hon & Chan 2022). A short-range LIDAR (SRL) facility with a spatial resolution of 30 m and a temporal resolution of 20 s was deployed near aircraft touchdown by the Hong Kong Observatory (HKO) to alert building-induced turbulences (Chan & Lee, 2012). Velocity streaks and tiny anticyclones (~100 m in size) coming out of a building situated at the north part of HKIA were occasionally observed during the routine scanning of the SRL near the airport (Hon et al., 2021). Much less is known, however, about the origin of such vortices. It is supposed to be related to the buildings over there, such as the Passenger Terminal Building (PTB) and the AsiaWorld-Expo (AWE).

This study documents a study of combining meteorological observations and multiscale coupled mesoscale–microscale (CMM) modelling during a tiny anticyclonic vortex event detected by the SRL to investigate the relationship between the anticyclonic vortices and the surrounding buildings such as the PTB and AWE under realistic meteorological conditions.

2 METEOROLOGICAL CONDITIONS

In June 2021, Hong Kong was hit by an active southwesterly monsoonal airstream and a very hot weather warning was issued by the Hong Kong Observatory (HKO) from 16 June 2021 to 21 June 2021. A Doppler Lidar instrumented near the 25RA at HKIA was in operation to monitor low-level windshear on flight runways. At 03:25 UTC (Coordinated Universal Time; 0000 UTC is 0800 HKT; Hong Kong Time), a sequence of anticyclonic vortices was observed downstream of the AWE at the airport in the morning of 17 June 2021. The wind fields by the surface observations in that morning showed that

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moderate southwest monsoon exceeding 6 m/s was prevailing over the south China coast and thus southwesterly flow over the airport area throughout the day. As will be detailed later, this weather condition is quite favorable for the occurrence of anticyclonic vortices.

3 COUPLED MESOSCALE–MICROSCALE MODELLING (CMM) METHODOLOGY

A multiscale numerical framework by coupling large eddy simulation (LES), e.g., the Open Field Operation and Manipulation (OpenFOAM) at a spatial resolution of ~1 m, with a mesoscale model, e.g., the Regional Atmospheric Modelling System (RAMS) at a spatial resolution of 40 m, is developed. In the RAMS simulation, five nested domains are adopted (hereafter, RAMS-run) shown in Fig. 1. The initial and boundary conditions are obtained from NCEP GFS 0.25 Degree Global Forecast Grids Historical Archive. The Smagorinsky scheme is employed for the first two nests, and the Deardorff scheme for the remaining three nests that has been shown to produce reasonable results. The LES simulation domain in Fig. 2 has overall dimensions of 3.20 km (approximately 40 H) × 3.20 km (approximately 40 H) × 1.65 km (approximately 20 H) at a spatial resolution of 8 m. The vertical grid space is initially 1 m and stretches to approximately 2.5 m in the near ground region until twice the height of the tallest building in the simulation domain. Then a coarse grid resolution with approximately 20 m is used until the top of the simulation domain at 1.65 km. The LES and RAMS are coupled through one-way off-line nesting; the initial and time varying boundary conditions are generated from RAMS to provide larger-scale forcing for LES. In the present work, the meteorological fields at 6-*h* separation from 00:00:00 UTC to 06:00:00 UTC on 17 June 2021 are analyzed.

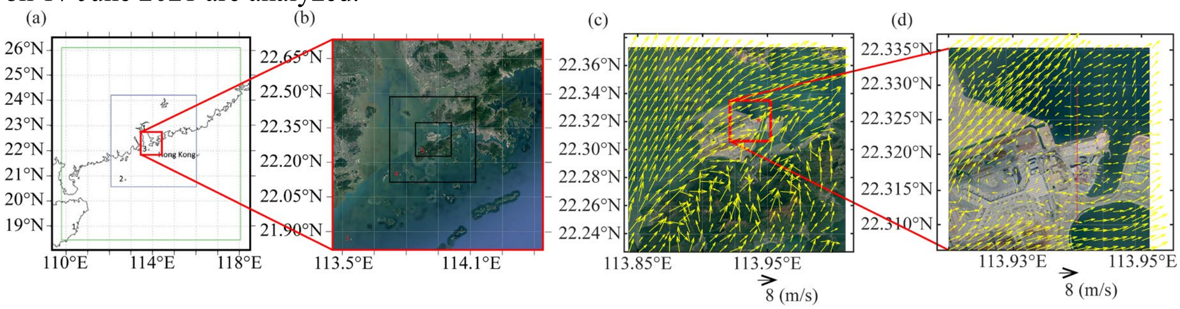
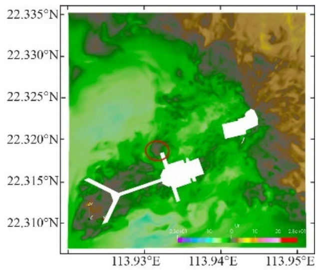
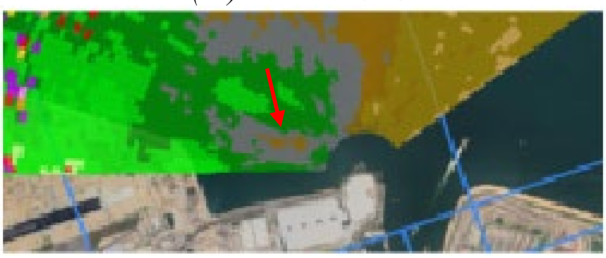


Figure 1, (a-b) The five nested model domains D01-D05 of RAMS for the HKIA site, and calculation domains of (c) the RAMS-run and (b) the LES-run at 40 m height. The color shadings over the land surfaces in (c) and (d) indicate the topography. The red box in (c) is the domain for the LES-run. The arrows in each panel show simulated surface wind vectors at 02:46 UTC on 17 June 2021. The spatial resolution of wind vectors is 800 m in (c) and 160 m in (d).

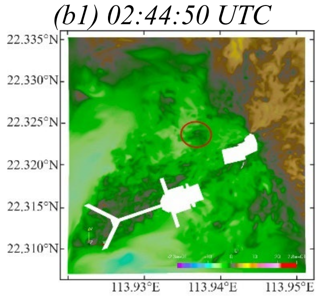
(a1) 03:26:00 UTC



(b1) 02:44:50 UTC



(a2) 03:27:00 UTC



(b2) 02:48:10 UTC

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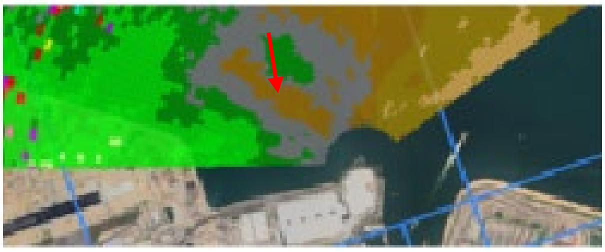
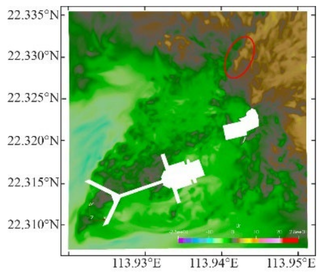




(a3) 03:28:00 UTC *(b3) 02:51:10 UTC*

(a) SRL observations *(b) CMM predictions*

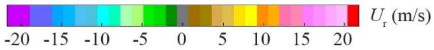


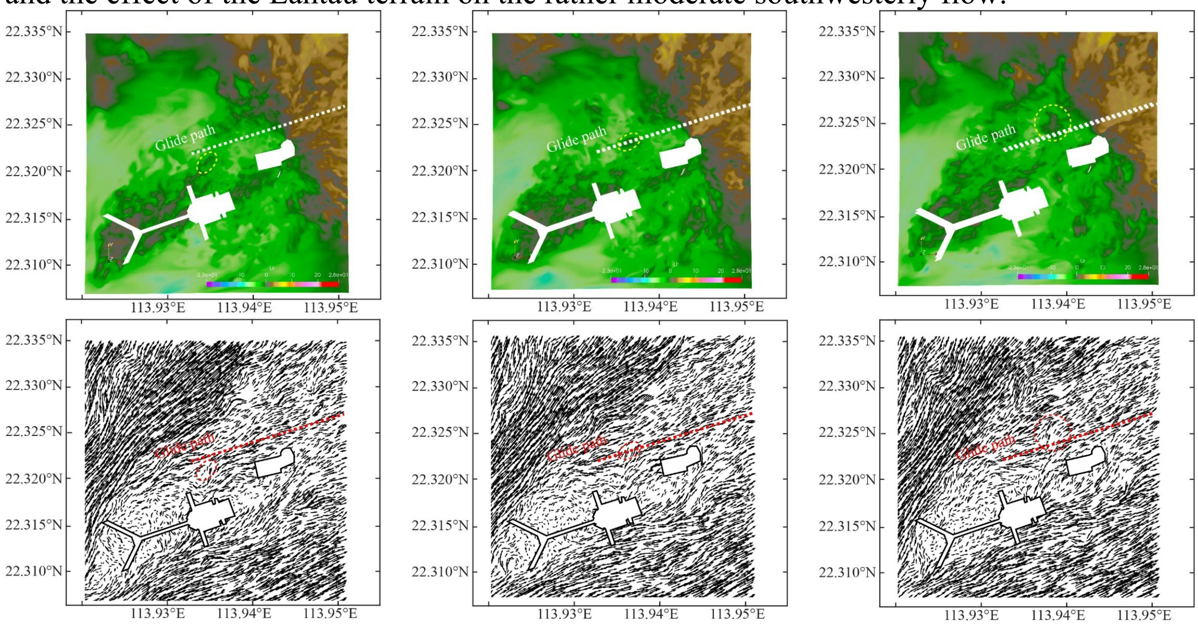
Figure 3, Comparisons of the time sequence of tiny anticyclonic vortices in the Doppler velocity map: (a) observed by SRL and (b) predicted by the CMM model.

4 COMPARISONS WITH MEASUREMENTS AND DOPPLER LIDAR OBSERVATIONS

Fig. 3 shows the comparisons of SRL observations and simulated Doppler velocity in the LES-run. Comparisons with the SRL observations and wind station measurements testify the performance of the current CMM model.

5 RESULTS AND DISCUSSION

A sequence of anticyclonic vortices simulated by the LES results is shown in Fig. 4. Bot the simulated Doppler velocity images and wind vectors are presented. A tiny vortex first appears on the western side of the PTB at 02:46:30 UTC. It then drifts east-northeastwards following the background southwesterly flow. The anticyclone appears to grow in intensity during the evolution. The size of the anticyclone is growing as well. This kind of microscale anticyclone (i.e., rapid development with rather limited size), also observed by a LIDAR installed nearby, is believed to arise from both the building-induced turbulence and the effect of the Lantau terrain on the rather moderate southwesterly flow.



(a) 02:46:30 UTC *(b) 02:47:50 UTC* *(c) 02:49:10 UTC*

Figure 4, A time sequence of simulated Doppler velocity images (up) and corresponding wind vectors based on LES results. The anticyclonic vortices are marked by a yellow circle, and the flight glide path is indicated by dashed white line. Same legend as Fig. 3.

To study the effects of buildings on this microscale anticyclonic vortices, further simulations without the PTB and without the AWE respectively are conducted as shown in Fig. 5. It is found that without

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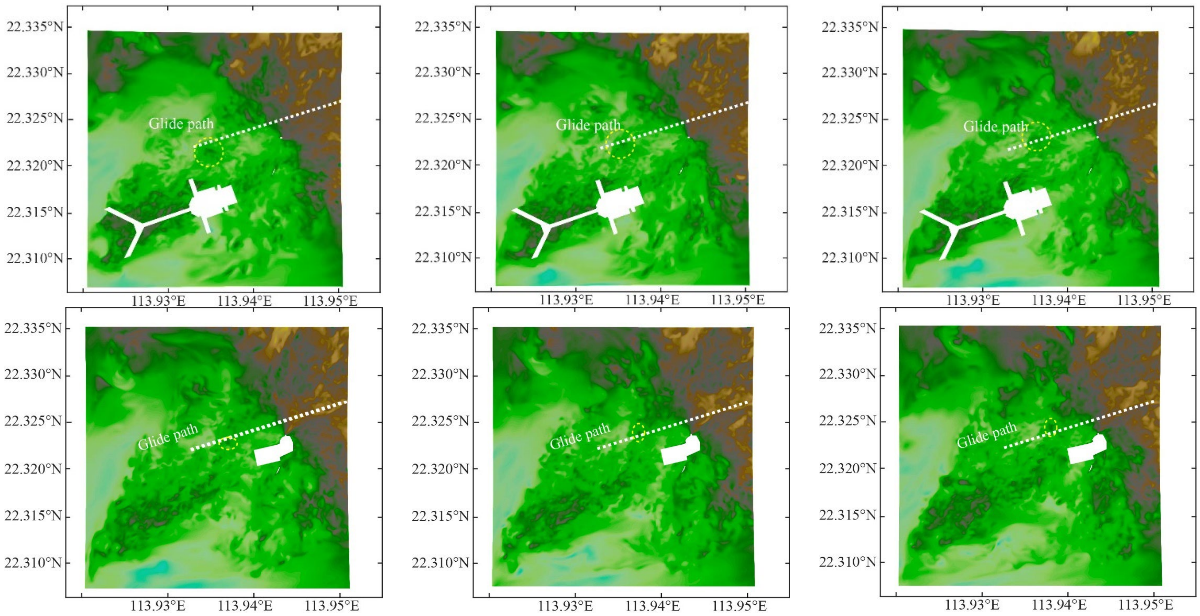
the PTB and AWE could significantly reduce the intensity of anticyclonic vortices crossing the flight path, illustrating the close relationship between the buildings and this microscale turbulence event. Our study adds evidence that the tiny anticyclonic vortices are a result of the interaction between the background southwesterly flows and the key buildings (i.e., the PTB and AWE) at HKIA, which helps enhance sustainability and resilience of the airport and fulfil the increasing demand for safe aviation services of the city.



(a) 02:46:30 UTC *(b) 02:47:50 UTC* *(c) 02:49:10 UTC*

Figure 5, A time sequence of simulated Doppler velocity images for simulations without the AWE (up) and simulations without the PTB (down), respectively. Sane legend as Fig. 3.

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