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Simulation of building-induced airflow disturbances in complex terrain using meteorological-CFD coupled model

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Abstract
Tiny anticyclonic vortices have been observed at the arrival runway corridor to the east of the central runway of the Hong Kong International Airport many times. However, it is not sure about the cause of such vortices. In this paper, a meteorological model is coupled with a computational fluid dynamics (CFD) model in high spatial resolution in an attempt to simulate such vortices. The performance of this coupled model is first checked by comparing with the observed building wakes. This model is found to successfully capture the wakes and jets. It is then used to simulate the situation of anticyclonic vortex at the said region, with and without the presence of a key building called AsiaWorld-Expo. It is found that, with the presence of the building only, the anticyclonic vortex can be simulated. This adds more confidence that such vortex is a result of the interaction between the background southwesterly flow with the AsiaWorld-Expo.

Keywords: short-range LIDAR, building-induced vortex, large eddy simulation, structure function

1 Introduction

Terrain-induced airflow disturbance is the major cause of low-level windshear and turbulence to the aircraft operating at the Hong Kong International Airport. However, turbulence induced by buildings/man-made structures may also bring about instability of the aircraft. The combined effect of terrain and buildings on the airflow has been studied in high resolution computational fluid dynamics (CFD) model, e.g. in Li and Chan (2012). To alert the building-induced turbulences, the use of short-range LIDAR (SRL) has been used, namely, with a spatial resolution as low as 30 m and limited measurement range of 3–4 km. Feasibility studies were conducted by Chan and Lee (2012) and Hon et al. (2014). An operational algorithm has been later developed and put into use at the airport (Hon and Chan, 2020).

It has been observed in the routine scanning of the SRL that there are occasional anticyclonic vortices coming out of the building at the northern part of the airport, namely, for the runway corridor to the east of the central runway of the Hong Kong International Airport. Some observations have been documented in Hon et al. (2021). The origin of such vortices is not certain. It is suspected to be related to the extended building over there, namely, the AsiaWorld-Expo (AWE) which has a length of about 500 m along the runway direction and a height of around 30–40 m above the mean sea level. In order to study the relationship between the vortices and this building, this paper attempts to conduct a high resolution numerical weather prediction model simulation, namely, using the Regional Atmospheric Modelling System (RAMS) version 6.3 (https://vandenheever.atmos.colostate.edu/vdhpage/rams.php) at a spatial resolution of 40 m, coupled with a CFD model in large eddy simulation (LES) mode.

Before the tiny anticyclonic vortices are studied, the airflow around AWE is simulated for a strong east-southeasterly flow, to confirm that the coupled models are capable of simulating the building wakes in association with AWE. This is a simple test to check the performance of the coupled models. Then simulations with and without AWE are performed using the coupled models to study any sign of the occurrence of anticyclonic vortex in the background southwesterly flow.

2 The coupled models

The setup of the meteorological model is the same as that in Chan et al. (2021). The model simulation domains are shown in Fig. 1. Altogether there are 5 nests with the innermost domain having a spatial resolution of 40 m. The initial and boundary conditions are obtained from NCEP GFS 0.25 Degree Global Forecast Grids Historical Archive (https://rda.ucar.edu/datasets/ds084.1/). The Smagorinsky scheme is employed for the first two nests, and Deardorff scheme for the remaining three nests. The Smagorinsky scheme is employed for the first two nests, and Deardorff scheme for the remaining three nests. This setup is found to produce reasonable results, e.g. as in Chan et al. (2021). The choice of the other parameterization schemes, such as long wave and radiation and short wave radiation, is the same as those
Figure 1: The five nested model domains of RAMS.
Figure 2: The model domain of PALM (black rectangle), with its location relative to the 5th nest of the meteorological model, and the location of AsiaWorld-Expo (red star symbol).

in Chan et al. (2021). The land use and vegetation data are obtained from the RAMS website.

PALM, a parallelized LES model, is used to generate building-resolving turbulent flow around the Hong Kong International Airport. PALM solves the non-hydrostatic filtered, incompressible Navier-Stokes equations in Boussinesq-approximated form with subgrid-scale covariance terms parametrized by 1.5-order closure scheme (Deardorff, 1980). A fifth-order upwind difference scheme (Wicker and Skamarock, 2002) and a third-order Runge–Kutta scheme (Williamson, 1980) were adapted for momentum advection and time stepping respectively. Details of PALM can be found in Raasch and Schrötter (2001), Maronga et al. (2015) and Maronga et al. (2020).

The location of the PALM simulation domain is shown in Fig. 2. It has a horizontal area of 3200 m × 3200 m and spatial resolution of 4 m. Terrain height and building height relative to the underlying terrain are provided via static driver in PALM. The vertical grid space is initially 4 m. Stretching in vertical direction is applied starting from 50 m with a stretch factor of 1.08, the maximum grid space is limited to 12 m and the top of the simulation domain reaches about 1650 m. PALM and RAMS are coupled through one-way offline nesting: initial condition and time varying boundary conditions are generated from RAMS to provide larger-scale forcing tendencies for PALM.

The coupling between RAMS and PALM is explained here. PALM provides python scripts that can convert WRF output data into a dynamical file (netcdf format) that can be used as mesoscale forcing to drive PALM simulation. The dynamical file was generated by interpolating WRF data spatially and temporally to provide the initial conditions and boundary conditions for the PALM simulation. For details, please refer to (https://palm.muk.uni-hannover.de/trac/wiki/doc/app/iofiles/pids/dynamic). A similar approach was used in this paper: Wind speed, potential temperature, mixing ratio and other variables obtained from
Figure 3: The surface isobaric chart at 8 a.m., 9 October 2021 (a) and the surface observation in that morning (b).
RAMS simulation were interpolated spatially and temporally by custom python scripts to determine the required input variables in the dynamical input file (e.g., init_atmosphere_pl, ls_forcing_ug) that can be used as initial condition and boundary conditions to drive PALM.

To help with the generation of microscale turbulence, a synthetic turbulence generator method proposed by Xie and Castro (2008) and Kim et al. (2013) was used to generate a turbulent inflow condition by imposing spatially and temporally correlated perturbation. For details, please refer to the document of PALM (https://palm.muk.uni hannover.de/trac/wiki/doc/tec/bc#SyntheticTurbulenceGenerator).

Furthermore, there should be more than sufficient distance for the turbulent to develop before the flow reaching around AWE. Letzel et al. (2012) suggested a buffer region of H for LES study where H is the height of the tallest building. In our cases, the distance between boundary to region of interested around AWE is more than 10H.

### 3 The east-southeasterly case

The case under consideration is the strong east-southeasterly flow brought about by the combined effect of Tropical Storm Lionrock and the background northeast monsoon on 9 October 2021. The surface isobaric chart at 8 a.m. (00 UTC, with Hong Kong time = UTC + 8 hours) on that day is shown in Fig. 3(a). A typical snapshot of surface winds around the airport in that morning is shown in Fig. 3(b). The winds over the airport are generally fresh to strong (coloured blue for the wind barbs) east-southeasterly. The mountain top winds could reach storm force (coloured purple for the wind barbs).

The strong east-southeasterly flow was rather steady on that morning. From the SRL observations (Fig. 4, Doppler velocity from 5-degree plan position indicator...
Figure 6: The simulated SRL Doppler velocity field (m/s) from PALM model is shown in (a). The stronger and weaker wind streaks are marked by solid lines and dotted lines respectively. The corresponding 2-dimensional wind field (m/s) is shown in (b).
Figure 7: The surface isobaric chart at 8 a.m., 17 June 2021 (a) and the surface observations in that morning (b).
Figure 8: The sequence of anticyclonic vortex as observed by SRL. The vortex is marked by a red circle. The time of the scan is given at the top of the figure. (a) also shows the location for the calculation of structure function (the red line).
scan centred at the AWE), there were streaks of strong and weaker winds emanating from the building. The strong winds (pink) appear to be related to the background flow and gaps in between buildings, whereas the weaker winds (orange and yellow) are associated with the major blocks of AWE. This pattern has been observed for a couple of hours.

The RAMS model provides background meteorological flow when the airport is under the influence of the strong east-southeasterly flow associated with Lionrock. Buildings are not present in the simulation. Only the effect of natural terrain and the airport island has been included. A typical surface wind pattern at around the time of Fig. 4 is shown in Fig. 5. Rather steady east-southeasterly flow appears at the northeastern part of the airport island.

With the coupled model, the simulation result around the time of Fig. 4 is shown in Fig. 6. As explained in this figure, the stronger and weaker wind streaks are nicely reproduced, and they are associated with the gaps and blocks of AWE. By this simple checking, it appears that the coupled model is capable of reproducing the wind features around AWE as a result of the complex nature of this building.

4 The anticyclonic vortex

Anticyclonic vortices are observed downstream of AWE in the early afternoon of 17 June 2021. The surface iso-
bar chart on that morning is shown in Fig. 7(a). Moderate southwest monsoon was prevailing over the south China coastal areas. The surface wind pattern in the early afternoon on that day is shown in Fig. 7(b). While southwesterly flow prevailed over the airport area, there appeared to be a cyclonic flow pattern in the northeastern part of the airport.

A sequence of the anticyclonic vortex is shown in Fig. 8. At 02:21 UTC on that day, a tiny vortex first appeared on the western side of AWE. It then drifted east-
Figure 12: The two-dimensional wind field corresponding to Fig. 11. (wind field in m/s)
Figure 13: (a) to (f) is the time series of plots showing wind along a vertical cross section (with increasing distance from south to north), coloured by the vertical wind speed (m/s). The red star indicates the location of an aircraft in the vertical cross section before it lands onto the corridor 25RA assuming a touchdown angle of 3 degrees. The vertical cross section is indicated by the red line in (g).
northeastwards following the background southwesterly flow, maintained its intensity for a couple of minutes and eventually dissipated at around 02:24 UTC. Similar vortices have been observed at other times on that day as well (not shown).

The RAMS simulation result at a slightly different time, namely, 04:40 UTC, is shown in Fig. 9. There is convergence between southwesterly flow and south-southwesterly flow at the northern part of the airport. As such, there appears to be a cyclonic flow feature in that region. This is consistent with the surface observations (Fig. 7(b)).

Following Hon et al. (2021), second order structure functions of line of sight velocities for radial beams with directions from 330° to 350° were calculated for short range lidar (blue line) and palm simulation (orange line) using data from 2021-06-17 04:30:00 UTC to 2021-06-17 05:00:00 UTC (Fig. 10). Only data with signal to noise ratio larger than 1.05 were used in the calculation of structure function for lidar measurement. For comparison, 2/3 power law of Kolmogorov theory was also plotted in dashed black line. The inertial range for palm simulation ranges from about 50 m up to 350 m, while those for short range lidar ranges from about 150 m up to 350 m.

Around that time, a tiny anticyclonic vortex is simulated by PALM. It first appeared at the western side of AWE (Fig. 11(a)), and then drifted to the northeast following the background southwesterly flow (Figs. 11(b) to 10(e)). Eventually it weakened and dissipated (Fig. 11(f)). The evolution is quite similar to the actual observations two hours earlier (Fig. 8). However, the intensity of the vortex is weaker as compared with the actual observations.

To better appreciate the flow field, the 2-D wind field as simulated by PALM is shown in Fig. 12. The location of the vortex is once again circled in red.

In order to show that the vortex comes from AWE and propagates to affect the flight path, a vertical cross section (location in Fig. 13(g)) is made to show the distribution of the vertical velocity. The time series is shown in Figs. 13(a) to 13(f). It could be seen that the vortex comes from the building and propagates towards the location of the flight path (red star). This again provides evidence that the vortex is the result of the interaction of the building with the background southwesterly flow and may have impact on the arriving aircraft.

The purpose of this paper is not to claim that the LES is able to simulate the vortex at the exact time and exact place. It only confirms that LES is able to reproduce the vortex in the southwesterly flow with the inclusion of the buildings, but the actual timing, location and intensity could be different.

The anticyclonic vortex is not just observed at the time of Fig. 11. At another time (Fig. 14), there appears to have another anticyclonic vortex as well, though it is not so distinct from the background flow which is rather turbulent.

5 Simulation without AWE

In order to see the impact of AWE on the formation of the vortex, another simulation has been conducted without AWE in the model. The results could be found in Fig. 15. In the absence of AWE, it has been observed that there are wave trains at the region downstream of the western side of AWE.

It appears that the flow in the region of AWE is still rather turbulent. This may be related to the convergence between the background southwesterly flow and the south-southwesterly flow. However, the flow pattern downstream of AWE is not quite the same as the actual observations, namely, the occurrence of wave-like flow feature instead of anticyclonic vortices. As such, based on the simulation results, it appears that the anticyclonic vortex is a result of the interaction between the background flow and AWE.

6 Conclusion

The impact of AWE on the airflow at the airport region in Hong Kong is studied using a high resolution coupled model. The meteorological model RAMS is coupled with the CFD model in LES model. It is first confirmed that the coupled model is capable of reproducing the building wakes around AWE in a strong east-southeasterly flow.

The coupled model is then used to study the anticyclonic vortex reported in the literature downstream of AWE. By comparing the simulations with actual observations by SRL with and without the presence of AWE, it appears that the vortex is a result of the interaction between AWE and the background southwesterly flow. In particular, without AWE, wave-like flow feature is observed in the region, instead of turbulent flow with anticyclonic vortex.
Buildings at the Hong Kong airport bring about many interesting features of the airflow. The coupled model would be used to study them under different background flow. It may also be explored to have real-time coupled model simulation for the alerting of low-level windshear and turbulence for an area with complex terrain and clusters of buildings like the Hong Kong International Airport. With increasing computer power, large-eddy simulations could in future also be helpful already in the planning phase of a new building. Right now only Reynolds averaged numerical simulation is performed in the planning stage of the new buildings at the Hong Kong airport.

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