High-resolution (40 m) simulation of a severe case of low-level windshear at the Hong Kong International Airport—Comparison with observations and skills in windshear alerting

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\textbf{Abstract}

A case of severe low-level windshear at the Hong Kong International Airport was investigated in this study using large eddy simulation (LES) with a spatial resolution of 40 m. The computer simulation results were compared with the actual observations at the airport, including Doppler light detection and ranging (LIDAR) systems and surface automatic weather stations. The LES was found to be capable of reproducing the tiny vortices associated with the terrain-disrupted airflow. Some interesting features of surface temperature and vertical velocity were also observed in the computer simulation. The simulated and observed meteorological parameters had satisfactory comparison results, although the micro-scale variability of such parameters still could not be captured by the high-resolution LES. Finally, the computer-simulated headwind profiles appeared to have skills in capturing the low-level windshear reports from the pilots. The headwind refers to the component of the wind along the direction of the flight path to be encountered by the arrival/departing aircraft. The study was novel in the use of the rather large domain for LES simulation and in the application to low-level windshear alerting.

\textbf{Keywords}

forecasting, nowcasting, severe weather

\section{INTRODUCTION}

The Hong Kong International Airport (HKIA) is located in an area of complex terrain. There are seas to the north, east and west of the airport. To its south is the mountainous Lantau Island, with peaks reaching 1000 m above mean sea level and valleys as low as 400 m in between. The terrain nearby HKIA is shown in Figure 1b. The major mountain ranges are U-shaped, consisting of Nei Lak Shan, Yi Tung Shan. At the middle of the U-shaped mountains, there is a valley called Pak Kung Au. On the two sides (east and west) of the U-shaped mountains, there are also valleys. As the air flows over the mountains, terrain-induced airflow disturbances may occur over the airport island, which may be hazardous to the arriving and departing aircraft.

The major wind direction in Hong Kong is easterly. As the easterly flows over and through the complex
terrain of Lantau Island, a number of valley jets would appear. The mountain ranges may also generate mountain wakes downstream of them. The complexity of airflow arising from the jets and the mountain wakes could cause terrain-induced low-level windshear and turbulence to the aircraft of HKIA.
Most of the terrain-disrupted airflow at HKIA occurs in non-rainy weather. They are readily detected by Doppler light detection and ranging (LIDAR) systems. An algorithm has been developed by the Hong Kong Observatory (HKO), the meteorological authority in Hong Kong, to alert the aircraft based on the LIDAR observations. This is a detection-based system for alerting windshear (called LIWAS, LIDAR Windshear Alerting System) and is found to be skilful (Shun & Chan, 2008). Aviation safety could be enhanced if it is possible to forecast the occurrence of such terrain-disrupted airflow.

An aviation model (AVM), with a spatial resolution of 200 m, has been developed by HKO to forecast the complex airflow near HKIA (Wong et al., 2013). It is largely based on the Weather Research and Forecasting (WRF) model. The outputs of AVM, particularly the wind along the flight path, have been applied to the LIWAS algorithm to provide forecast windshear alerts to the pilots. AVM is found to have skills in predicting the occurrence of low-level windshear (Hon, 2020).

One major limitation of AVM is that it may still have not high enough spatial resolutions to resolve the

**Figure 2** The statistical distribution of the residual headwind velocity (i.e., the difference between the raw LIDAR velocity/direct model output of the velocity and the fitted value of the velocity to the headwind profile) for the model simulation (a) and LIDAR (b) for headwind along 07LA runway corridor (i.e., arrival runway corridor to the west of the north runway of HKIA). HKIA, Hong Kong International Airport; LIDAR, Doppler light detection and ranging
FIGURE 3  (a) Is the LIDAR velocity imagery at about 04 UTC. The red circle encloses the areas of reverse flow to the west of the airport, possibly associated with vortices. The white circle has a radius of 10 km, namely, the maximum measurable range of the LIDAR. (b) Is the computer-simulated LIDAR picture, with the simulated velocity field given in (c). The location of the vertical cross section is also shown in (c). (d-f) Show the vertical cross sections of vertical velocity, u component of the flow and v component of the flow. U is positive for westerly wind, and v is positive for southerly wind. (g) Is a 3D view of the vortex. The instantaneous times of the figures are shown in the upper part of the figures. LIDAR, Doppler light detection and ranging.
terrain-induced vortices and waves, which are commonly observed from LIDAR data. One such case occurred on 5 March 2015. This is an episode with the largest number of pilot windshear reports of significant windshear (65 reports) in a day without thunderstorms and tropical cyclones. A detailed investigation of the case could be found in Chan and Hon (2016) using AVM. Reverse flow could be observed downstream of the terrain of Lantau Island in the AVM simulation. However, the spatial extent of the reverse flow is still considered to be rather large, much greater than the tiny vortices observed from LIDAR data (with a spatial scale in the order of several hundred metres). Accurate simulation of the tiny vortices and waves would be useful for making more realistic forecast of low-level windshear for the pilots.

Numerical simulation of even higher spatial resolution has been attempted to forecast the occurrence of vortex shedding at HKIA, for example, the study by Chan (2014). In his study, a spatial resolution of 50 m has been adopted using Regional Atmospheric Modeling System (RAMS). To study the vortices in a non-typhoon case, the latest version of RAMS model with a spatial resolution of 40 m is adopted in the present study to re-visit the windshear case of 5 March 2015. The study is novel in a number of ways:

a. RAMS simulation would be validated by comparing with LIDAR observations and data from automatic weather stations, at a temporal resolution of a couple of minutes, in order to see the capability of RAMS in simulating the highly varying features; and

b. RAMS outputs are used to generate windshear alerts based on LIWAS algorithm by treating the simulated wind profiles as actual LIDAR observations, and the results are compared with the pilot windshear reports.

2 NUMERICAL MODEL

The latest version of RAMS (Pielke et al., 1992), namely, RAMS 6.3, is used for this study (downloaded from https://vandenheever.atmos.colostate.edu/vdhpage/rams.php). The model configurations are similar to those of Chan (2014). Five nested domains are used in the simulation. 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/). Analysis of the meteorological fields at 6-h separation was used. The model domains are shown in Figure 1. The spatial resolution of the simulation is increased by a factor of five, namely, 25 km, 5 km, 1 km, 200 m and 40 m. The coarse domain has a time step of 10 s, with a time-step ratio of 10. The first model level is about 30 m above sea surface. There is a stretching ratio of 1.08 (i.e., the ratio of the model level heights between the adjacent model levels). The simulation is essentially a

FIGURE 4 Same as Figure 3a–c but at a time of around 08 UTC. The instantaneous times of the figures are shown in the upper part of the figures
large eddy simulation (LES) of terrain-disrupted airflow at HKIA.

FIGURE 5  Same as Figure 3a–c but at a time of around 12 UTC. The instantaneous times of the figures are shown in the upper part of the figures.

FIGURE 6  The simulated surface wind and temperatures at two times (first time, 03:01 UTC (a) and (b), and second time, 08:54 UTC (c) and (d)). They refer to the surface outputs from the RAMS model. Times (a) and (c) show that the temperatures are higher downstream of the mountains. The feature is persistent over time (not shown), and this is related to Foehn effect. RAMS, Regional Atmospheric Modeling System

The height of the first model level is sufficient to resolve the surface flow features in the simulation. However, much denser model levels within the first couple of hundred metres would be desirable. The sensitivity of the model results to the choice of vertical levels would be considered in a future study.

Of particular importance is the choice of turbulence parameterization schemes. The Smagorinsky scheme (1963) is employed for the first two nests, and Deardorff (1980) scheme is employed for the remaining three nests. The sensitivity of the simulation results to the choice of turbulence parameterization schemes would be considered in a follow-up study. The existing combination is found to produce reasonable results, for example, as in the study by Chan (2014).
The choice of the other parameterization schemes, such as long wave and radiation and short wave radiation, is the same as those in Chan (2014). The land use and vegetation data are obtained from the RAMS website.

In the innermost domain, the 100-m resolution terrain data of Hong Kong as provided by Lands Department of the Hong Kong SAR Government is employed. Compared with a previous study, for example, the study by Chan (2014), the existing 40-m resolution model domain is much larger, covering most of the Lantau Island, the airport island and three nautical miles away from the runway end. The 3-nautical mile region is the alerting region of low-level windshear. In LIWAS, the headwind profile in this region is input into the algorithm for automatic detection of windshear. The size of the high-resolution domain (40 m) is another novelty of the present study. Such a large domain has not been considered before for HKIA, according to the knowledge of the authors, in the published literature.

The model was initialized at 00 UTC, 5 March 2015 and run for 14 h. This covers the main period in which the pilot windshear reports were collected for the episode. The number of grid points for the various domains is as follows:

- Grid 1 (25 km): 35 \times 35.
- Grid 2 (5 km): 82 \times 82.
- Grid 3: (1 km) 102 \times 102.
- Grid 4 (200 m): 207 \times 207.
- Grid 5 (40 m): 407 \times 407.

The vertical levels are around 50. The first model level has a height of 30 m. The model level heights remain roughly the same up to about 500 m. The model level height then increases for higher altitudes. The largest vertical level has a height of about 1200 m.

In the following sections of the study, the snapshots of the LES simulation are compared with actual LIDAR observations. To take into account the non-stationarity of the turbulent flow, a brief statistical analysis of the simulated wind and the actual LIDAR observations are compared. The headwind along the flight path 07LA, which is the most commonly used arrival runway corridor, is considered. The 07LA runway refers to the flight path arriving at the north runway of HKIA from west. Data up to 3 nautical miles away from the runway end are considered. The actual (from LIDAR) and simulated (from RAMS model) headwind profile (i.e., wind velocity resolved along the runway direction) are used, and the headwind data are fitted with a best-fit straight line to calculate the residual velocity (i.e., actual headwind minus the linearly fitted headwind profile). The resulting residual velocity distribution in an hour is plotted. The mean velocities are in the order of 6–7 m/s. Figure 2 shows the type of residual velocity plot from the LIDAR and from the RAMS simulation between 04 UTC and 05 UTC of the simulation. It could be seen that, statistically, the two are very similar to each other. The residual velocity would also be used to calculate the structure function for comparison purpose. The results will be reported in a follow-up paper.

3 | SIMULATION OF THE VORTICES

In the morning to around noon time of 5 March 2015 (00 UTC to 04 UTC, which is 8 AM to 12 PM local time, with Hong Kong time = UTC + 8 h), a fresh to strong easterly airstream was prevailing over the airport area. The tephigrams during the event are shown in Figure 1c. It could be seen that there is temperature inversion between 500 and 1000 m above mean sea level. Also, the
surface wind is easterly and the wind direction veers with height. The east to southeasterly airstream is separated by the mountain ranges of Lantau Island into a number of airflow branches below the temperature inversion. One prevailed over the airport island, originating from the rather low terrain at the eastern part of Lantau Island. Another flowed through the gap of Tai Fu Au into Sham Wat (locations could be found in Figure 1). Even

FIGURE 7 (a) Is a sample vertical velocity imagery at a height of about 400 m. Time is 02:13:50 UTC. The blown dot is a location upstream of the terrain, and the potential temperature profile and Scorer parameter profile at that time are shown in (b) and (c), respectively.
another branch of the airflow took on a southerly airstream at the western side of Lantau Island. The various airstreams converged over the area to the west of airport, affecting the aircraft landing at the airport from the west (which was the major landing direction given easterly flow over the ground). At the convergence zone, various airflow disturbances such as tiny vortices and waves might be expected. This is supported by the actual LIDAR observations, as shown in Figure 3a. The figure is based on 3-degree elevation plan position indicator (PPI) scan of the north runway LIDAR.

The RAMS simulated LIDAR velocity picture at around that time is shown in Figure 3b. The RAMS simulated velocity is resolved along the laser beam component from the LIDAR, that is, the line-of-sight velocity or radial velocity along the radial from the LIDAR. The radial from the LIDAR has an elevation angle of 3 degrees from the horizon, that is, in the form of a conical scan. The RAMS simulated velocity is resolved along the radial from the LIDAR with an elevation angle of 3 degrees from the horizon to construct the so-called ‘simulated LIDAR velocity imagery’ for the arrival runway corridors. Similar simulated imagery is also produced for 6-degree elevation angle from the LIDAR for the departure runway corridors. It could be seen that the model correctly reproduced the tiny vortices and waves to the west of the airport. Their locations and magnitudes are similar to the actual observations. A zoom-in figure of the vortices is given in Figure 3b. In the study by Chan and Hon (2016), when the same case was analysed, only extended area of reverse flow could be simulated because of the rather coarse resolution of the model by that time (200 m). It could be seen that, with even higher spatial resolution (40 m), more features of the airflow disturbances could be reproduced.

FIGURE 8 A sample surface pressure pattern (instantaneous output at 01:59:50 UTC) in the simulation

FIGURE 9 (a) Shows a times series of the potential temperature output at the surface and the shedding as indicated by arrows. (b) Shows a time series of the turbulent kinetic energy output at the surface, with shedding indicated by arrows as well. The instantaneous times of the figures are shown in the upper part of the figures

It is noted that, in Figure 3b, the simulated radial velocity to the northwest and southeast of the airport is larger than actual observations in Figure 3a. The RAMS
simulation, similar to WRF simulation in Chan and Hon (2016), may tend to exaggerate the background southeasterly winds at times.

For more direct depiction of the simulated airflow, Figure 3c shows the simulated 2D wind field at the time of Figure 3b. A particular vortex is studied in detail by vertical cross section, with location in Figure 3b. The vertical cross sections of vertical velocity, u component of the wind and v component of the wind are given in Figure 3d–f, respectively. It could be seen that the vortex has a basically vertical axis, with a height of about 600–800 m and a horizontal size of around 500–600 m. There are opposing u and v values on the two sides of the vortex. For the vertical velocity, there is an updraft at the location of the vortex with downdrafts on its two sides. From the animation of the simulation (not shown), the signature of vortex shedding from the mountain ranges of Lantau Island is not clear.

For better visualization of the vortex, a 3D view of the vortex is plotted in Figure 3g. It could be seen that the vortex cells at the various model levels are well aligned. The rotation axis is basically vertical, with higher wind speed to the northeast of the vortex centre in the lower levels. In general, the vortex occurs in a region with relatively lower wind speed.

In general, on the northern side of the vortex, the horizontal wind speed is stronger. On the other hand, on the southern side of the vortex, the horizontal wind speed is weaker. This is consistent with the general speculation of the airflow for a vortex embedded in the background easterly to southeasterly flow. As the simulated vortex is quite similar to the reverse flow given in actual LIDAR observation, it is envisaged that the ‘vortex’ in reality, if present, has an anti-clockwise rotation sense as well, as shown in the simulation results.

About 4 h later (08 UTC, i.e., 4 PM local time), the easterly weakened a bit and there was slight southerly component in the airflow over the airport. The LIDAR velocity image at that time is shown in Figure 4a. To the west and northwest of the airport, there was an extensive area of weaker wind embedded with various tiny vortices (in green in Figure 4a). The model-simulated LIDAR image at that time is shown in Figure 4b with a zoom-in of the vortices given in the inset. For more direct depiction of the airflow, the simulated 2D wind field is shown in Figure 4c. Again, vortices could be found in the simulation, and the generally weaker winds over the area to the west and northwest of the airport are nicely reproduced. However, the vortices are mainly concentrated at about 1 nautical mile to the west of the runway, whereas in the actual LIDAR observations (Figure 4a), the tiny vortices (in green) are sporadically distributed in the whole area.

Another 4 h later (12 UTC, i.e., 8 PM local time), east to southeasterly winds still prevailed over the airport area.
FIGURE 11  (a) Is the location of vertical cross section. (b) Is the cross section of the vertical velocity

(Figure 5a). There was quite an extensive area of reverse flow (in green) to the west of the airport. However, due to limitation of the NCEP analysis as boundary condition, the low-level winds had turned to southeasterly in the atmospheric boundary layer (Figure 5b). There were some differences in the orientation of the prevailing airflow and the occurrence of reverse flow between the model simulation and the actual observations. There are still limitations with the numerical simulation in the present study.

However, in general, the simulated LIDAR velocity images are capable of showing the tiny vortices to the west of the airport most of the time. They are related to the occurrence of low-level windshear and turbulence to be encountered by the aircraft, and thus their successful reproduction in computer simulation would have important application values for the assurance of aviation safety.

4 | SURFACE AND LOW-LEVEL PATTERNS

It could be interesting to see what the simulation depicts about patterns of meteorological parameters at the surface and the lower levels of the atmospheric boundary layer. Samples of the surface temperature and wind patterns are shown in Figure 6. Earlier (around 03 UTC, Figure 6a,b), the cross-mountain southeasterly flow produced Foehn effect, which is consistent with actual observations (discussed in Section 6). At a later time (around 09 UTC, Figure 6c,d), again the cross-mountain airflow produced Foehn effect. In the computer-simulated temperature pattern, there are a number of northwest–southeast oriented areas of high temperature as a result of the warming by Foehn effect.

The vertical velocity at about 400 m above mean sea level is shown in Figure 7a. In general, according to the
computer simulation, there was flow rising up and flowing down over the mountains on the eastern side of the Lantau Island. On the other hand, on the western side, there was a wave (red followed by blue) to the north of the mountains on the western side of Lantau Island. This is consistent with the vertical cross section of vertical velocity as discussed in Section 5 below. Unfortunately, there were no data to support the occurrence of this wave from the actual observations.

Figure 7b shows the model-simulated potential temperature profile at a location upstream of Lantau Island. It could be seen that the potential temperature is about a constant below 600 m or so and is increasing with height at higher altitudes. In general, it is a stably stratified atmosphere. This is consistent with the potential temperature profile observed in other mountain wave cases, for example, in the study by Grubisic and Stiperski (2009). The model-simulated vertical profile of Scorer parameter at the same location is shown in Figure 7c. The Scorer parameter is defined as follows:
\[ \hat{P}(z) = \frac{N^2}{U^2} - \left( \frac{\partial^2 U}{\partial z^2} \right) / U, \]

where \( N = N(z) \) is the Brunt–Väisälä frequency and \( U = U(z) \) is the vertical profile of the horizontal wind, both quantities determined from an atmospheric sounding upstream of the barrier. Details of the application of this parameter for the study of mountain wave could be found, for instance, in the glossary of meteorology (https://glossary.ametsoc.org/wiki/Scorer_parameter). It could be seen that the Scorer parameter is generally decreasing with height within the atmospheric boundary layer, which also favours the occurrence of mountain wave.

A typical pattern of surface pressure is shown in Figure 8. There was a southwest–northeast oriented area of low pressure downstream of the mountains of Lantau Island, which could be interpreted as the lee low. On the eastern side of the plot, there was an area of higher pressure (about 1020 hPa). No wave-like feature could be identified from the surface pressure pattern.
The surface distributions of potential temperature and turbulent kinetic energy in the simulation are shown in Figure 9. ‘Shedding’ of these quantities are observed from time to time in the simulation from the major mountains of Lantau Island. Examples of shedding are shown in Figure 9. This again illustrates the capability of the model in simulating the turbulent flow. However, there is a lack of actual observations to prove the existence of such shedding.

It is noted that the shedding of potential temperature and turbulent kinetic energy occurs at different locations/mountains of Lantau Island. The detailed analysis of this difference is beyond the scope of the present study. The difference in shedding location could be a result of the complex interaction of the flow with the complicated terrain of Lantau Island.

In the late afternoon of the day, with the prevailing airflow turning more southeasterly, the model predicted that the relatively higher relative humidity (RH) upstream of the mountains (light blue, about 80%) penetrated flow through the gap and spread into an area east

![Figure 13](image)

**Figure 13** Same as Figure 12 but for NLS and TFA. (a) NLS wind direction. (b) NLS wind speed. (c) TFA wind direction. (d) TFA wind speed
of the airport island, following the background flow direction (Figure 10). Unfortunately, due to limitation in instrumentation, there was no support by real-life meteorological measurements for the patterns of the meteorological parameters as predicted by the computer simulations in Figures 9 and 10.

To study the wave pattern in Figure 7, a vertical cross section of the flow was performed in Figure 11a, and the vertical velocity distribution in this cross section is shown in Figure 11b. Wavy feature was very apparent. So there was an airstream with higher horizontal wind speed flowing up and down crossing the mountain along the cross-section A–B in Figure 11a.

5 | COMPARISON WITH SURFACE OBSERVATIONS

To validate the computer simulation results, the model-based meteorological parameters were compared with
the actual measurements from selected stations. The computer simulation has an output frequency for every 10 s, and the results are averaged to produce 1-min mean values for direct comparison with the 1-min mean measurements from the actual observations that are updated every minute.

Figure 12 shows the comparison for two anemometers over the airport island, namely, R1W (western side of south runway) and R2C (centre of north runway, which is also the anemometer chosen for weather reporting for the whole airport). The locations of the two anemometers are shown in Figure 1. In general, the comparison results for wind speed and wind direction for R1W were quite satisfactory, even though the actual wind speed of R1W was a bit lower. For wind direction of R2C, the actual wind remained easterly or even northeasterly later on the day. However, as discussed above, the computer simulation had turned to southeasterly too quickly, due to limitation of the boundary condition of the model. From operational forecasting experience, it has been observed

\[\text{FIGURE 14} \quad \text{Same as Figure 12 for but WB2. (a) WB2 wind direction. (b) WB2 wind speed. (c) WB2 temperature. (d) WB2 relative humidity}\]
from time to time that the global numerical weather prediction model tends to have veering of the boundary layer winds from easterly to southeasterly then southerly too quickly as compared with actual observations in Spring time. In the latter part of the day (around 14 UTC), the surface winds at the airport were still easterly, but the NCEP model already gave southeasterly wind. As such it could be envisaged that the model simulation was not able to reproduce the windshear feature at the airport in the latter part of the day.

Figure 13 provided the comparison results for a mountain top (mei lak shan (NLS)) and valley (tai fung au (TFA)). Their locations are shown in Figure 1. The wind directions were generally consistent. Moreover, the trend of the falling wind speed in the actual observations was well captured by the computer simulation, although there were still discrepancies in the details of the rise and fall of the wind speed in hourly scale.

The Weather Buoy 2 (location in Figure 1) was situated at a strategic location for comparing simulated and
actual observations, because the airflow disturbances of interest in the present study were developing over that area. The comparison results are shown in Figure 14. For wind direction (Figure 14a), once again the model could not capture the maintenance of easterly and even backing to northeasterly flow later on that day. The trend of wind speed (Figure 14b) was generally satisfactory. For temperature (Figure 14c), the model could simulate the set-in of Foehn at around 04 UTC of the day, but the temperature remained at around high level for the rest of the day. On the other hand, the actual temperature showed variability with the rise and fall of the temperature following the set-in and retreat of the Foehn wind. Such micro-scale variability still could not be captured by the LES. The RH (Figure 14d) was in general simulated quite well despite, once again, the micro-scale variability.

Finally comparison was made for an island station, sha chau (SC) (location in Figure 1). Only wind speed and direction were available. The comparison results are shown in Figure 15. In general, the comparison appeared to be quite satisfactory.

![Graph showing SC one minute mean wind direction and speed](image)

**FIGURE 15** Same as Figure 12a, b but for SC station. (a) SC wind direction. (b) SC wind speed
For more direction comparison of the observed and the simulated results, the scatter plots of some of the meteorological parameters to be compared are given in Figure 16. In general, the comparison is not bad, but the best-fit straight line may not pass the origin and the correlation coefficient could be on the rather low side.

**Figure 16** Scatter plot (density plot) for comparison between model simulation (y-axis) and actual observation (x-axis) for R2C wind speed (upper) and TFA wind speed (lower). The best-fit equation and correlation coefficient are shown in the upper parts of the plots.
WINDSHEAR ALERTING

The simulated headwind profiles over the runway corridors have also been analysed, especially in the application for low-level windshear alerting. An example of the headwind profiles to the west of the two runways is shown in Figure 17a. For 07LA (arriving corridor to the west of the north runway), in the actual LIDAR observations, the headwind was generally smaller from 4 to 3 nautical miles, and then rose up at around 3 nautical miles and remained there up to the touchdown point. For 07RA (arriving corridor to the west of the south runway), the headwind remained at around certain level from 4 to 1 nautical mile, rose up at around 1 nautical mile and then fluctuated around higher values between 1 nautical mile and the touchdown point. These patterns are generally consistent with the location of the mountain wakes (occurrence of tiny vortices) as discussed in Figure 3. Similar headwind profiles could be reproduced in the computer simulation, Figure 17b for 07LA and Figure 17c for 07RA.

Moreover, the computer-simulated headwind profiles were input into the LIDAR windshear alerting algorithm to highlight areas of significant headwind changes, that is, locations of significant low-level windshear. The highlighted areas in Figure 17b,c are generally consistent with the real LIDAR alerting ranges in Figure 17a.

For departure corridor, an example is shown in Figure 18. An actual headwind change over 07RD (departure corridor to the east of the south runway) is shown in Figure 18a. The change of headwind mostly occurred at about the runway end (as distance 0 from the runway end). The pattern of the headwind profile and the headwind changes was reproduced reasonably well in the computer simulation in Figure 18c. The magnitudes of headwind changes were also similar.

For more in-depth analysis of the headwind profile in the disturbed airflow, a schematic diagram is shown in Figure 19. It refers to background easterly at the surface with wind direction veering with height, becoming southerly at a height of about 500 m. As such the headwind is decreasing with the distance away from the runway threshold (location 0 at the right hand side). Two Rankine vortices are embedded in the background flow, and the resulting wind field is smoothed by Barnes analysis. The headwind profile at a location of the north 500 m and at a location of the south 500 m is given in Figure 19b,c respectively. It could be seen that the headwind profile in Figure 19c is similar to the 07LA headwind profile in Figure 17.

In the period 00 UTC to 14 UTC of 5 March 2015, there were 48 reports of significant low-level windshear from the pilots over 07LA. The ‘alerts’ from the simulated LIDAR headwind profiles were compared with
the actual reports. Following the method of Shun and Chan (2008), an alert from the simulated headwind profile was considered to be a hit if it occurred within $T$ to $T-3$ min from the pilot report at time $T$. An allowance of 3 min was taken as the time required for the aircraft to prepare for landing/departing. For every alert, the alerting duration was considered to be 10 s (in the present study, the model outputs were updated every 10 s). The total alert duration was expressed in terms of a fraction of the total time period under consideration.
The resulting relative operating characteristics (ROC) curve of hit rate versus the alert duration is shown in Figure 20. This is a plot of the hit rate versus the alert duration. For the best-behaving windshear alerting algorithm, the hit rate should be as high as possible (close to 100%) and the alert duration should be minimized in order to get this hit rate (close to 0% as far as possible). As such, the algorithm’s result should get to the upper left corner. The algorithm’s performance could be represented by an ROC curve by changing, for example, the windshear alerting threshold. It is found to have skills if the ROC curve is above the diagonal of the plot. It could be seen that the curve was above the diagonal line, which indicated that the computer-simulated windshear alerts had skills. The optimal alerting threshold, namely, the points closest to the upper left corner of the diagram, was in the order of 13–14 kn, which was consistent with the alerting threshold adopted (14 kn) for the real LIDAR windshear alerting system.
FIGURE 19  Schematic diagram of headwind profile of background veering winds with two vortices embedded. This is based on the constructed velocity field with two vortices embedded in a background velocity field veering with height, with the headwind extracted along the flight path. The background wind speed is 5 m/s. The background wind direction is veering with height, with surface easterly veering to southerly at a height of about 500 m. Two Rankine vortices are embedded, with a radius of the vortex with maximum velocity of 200 m. The west and the east vortices have maximum speed of 18 and 20 m/s, respectively. The wind field is smoothed using Barnes analysis. (a) Is the surface wind field. (b) Is the headwind profile at a location of north 500 m. (c) Is the headwind profile at a location of south 500 m.
7 | CONCLUSIONS

A rather large model simulation domain with high spatial resolution (40 m) was adopted in this study to examine a case of severe low-level windshear due to terrain-disrupted airflow. It contained the major mountains and valleys of Lantau Island, covering the airport island as well as the windshear alerting regions (up to 3 nautical miles to the runway ends). According to the authors, this kind of attempt had not been made before in the existing literature, although large-scale large eddy simulation (LES) exists in the literature (e.g., Gronemeier et al., 2017; Smith & Skyllingstad, 2009).

Snapshots of LES simulation are compared with the actual Doppler light detection and ranging (LIDAR) observations, and it is found that many interesting flow features in the LIDAR data could be reproduced, for example, the tiny vortices. A statistical analysis of the wind flow has also been considered, and the model and LIDAR data compare well. More statistical analysis would be conducted in future study, for example, structure function calculations.

The LES appeared to have high enough spatial resolution to resolve the tiny vortices associated with the convergent airflow, as shown in the tiny reverse flow features in the Doppler LIDAR velocity imageries. A number of interesting patterns also showed up in the computer simulation of temperature, RH and vertical velocity.

The simulation results were inspected in detail by comparing with the actual observations, such as Doppler LIDAR velocity imageries and observations from the surface stations/buoys. Apart from the limitation of the boundary condition of the model (too fast veering to southeasterly in the global model), in general, the actual observations and the computer simulations had good comparison results.

The application of LES modeling for low-level windshear alerting was studied for the first time using pilot windshear reports as the sky truth. The model appeared to have skills in capturing the windshear from the relevant relative operating characteristics (ROC) curve. However, this was just one case, although the sample of windshear reports was not small, and more extensive investigation would be required to justify the use of such high spatial resolution numerical modeling for windshear alerting purpose. The computational requirement for the LES was really very high. With the computer resources available for the authors, it took about 2 weeks for completing the 14-h computer simulation.

The simulation provided useful data for studying this severe windshear case in more detail. Further study would be conducted in the low-level turbulence, namely, calculation of structure function, generation of eddy dissipation rate map and investigation of the sensitivity to the turbulence parameterization schemes. All these would be presented in the second paper of the series. In particular, the choice of Smagorinsky (1963) scheme would be considered. However, this scheme appears to be computationally less effective as compared with Deardorff (1980) scheme, and a much longer computation time would be required. As such the results are not yet available for reporting in the present paper. The results would be reported in the second paper of the series.

Though the Deardorff (1980) scheme has quite a long history, the present results support the study of Gibbs and Fedorovich (2016), which is quite effective in resolving turbulent flow. The comparison with actual observations, for example, LIDAR and ground weather station/buoy data, appears very well. More cases of turbulent airflow at Hong Kong International Airport would be considered to study the robustness of the scheme in different turbulent flow conditions.

In conclusion, the paper’s results generally indicate that the board features of the terrain-induced airflow as observed from the Doppler LIDAR have been reproduced in the LES model simulation. This opens up the possibility of implementing real-time LES run for modeling and alerting low-level windshear to be encountered by the aircraft for terrain-disrupted airflow. More case studies would be conducted to examine the technical feasibility and performance of LES simulation for windshear alerting.
AUTHOR CONTRIBUTIONS
Pak Wai Chan: Formal analysis (lead); writing – original draft (lead); writing – review and editing (lead). K.K. Lai: Software (lead). Q.S. Li: Supervision (lead).

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