4.6 **COMPARISON OF DOPPLER LIDAR OBSERVATIONS OF SEVERE TURBULENCE AND AIRCRAFT DATA**

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1. INTRODUCTION

The Hong Kong International Airport (HKIA) is located on reclaimed land to the north of Lantau Island, which has peaks rising up to around 1000 m. (Figure 1). Disruption of airflow by terrain, especially during the passage of tropical cyclones, can result in wind shear (horizontal scales of approximately 400 to 4000 m, according to Proctor et al. 2000) and turbulence (horizontal scales less than 400 m) which affect aircraft flying in and out of the airport. Such wind shear and turbulence are usually associated with high- and low-speed air streaks, and vortices shed from the lee slopes of mountain peaks of Lantau Island and the descent of high-speed flow through mountain cols as the airflow crossed Lantau Island (Shun et al. 2003b).

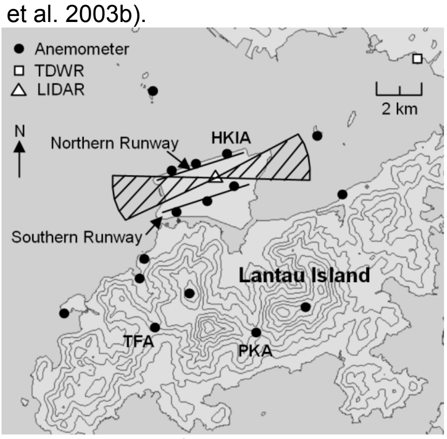

Figure 1. Location of HKIA and its approach and departure corridors. Terrain contours are given in 100 m intervals. The hatched regions indicate the selected regions for which the standard deviation of LIDAR radial speeds and mean spectrum width are calculated.

During the passage of Typhoon Imbudo (0307) on 24 July 2003, a total of 31 aircraft reported encountering significant turbulence at HKIA. Of these, 15 were severe or moderate to severe turbulence reports (collectively referred to as severe turbulence reports hereafter). It was a day with the largest number of severe turbulence reports from aircraft since the opening of HKIA in 1998. On the same day, there were also 66 aircraft reports of significant wind shear (a change of 15 kt (7.7 ms^{-1}) or more in headwind/tailwind). 14 of these also contained reports of turbulence.

This turbulence episode can be attributed to strong winds blowing across the hills over Lantau. In this study the relevant meteorological observations were analysed, including wind data collected by anemometers in and around HKIA, data from the Terminal Doppler Weather Radar (TDWR) at Tai Lam Chung and the LIght Detection And Ranging (LIDAR) system on the aerodrome, as well as flight deck data recorded by commercial flights. The feasibility of using the LIDAR for turbulence detection in an operational setting was examined.

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2. BACKGROUND

Imbudo developed into a tropical depression over the western Pacific near 730 km southwest of Guam on 17 July 2003. It intensified into a typhoon on 20 July and entered the South China Sea on 22 July, heading towards the south China coast. In the morning of 24 July, Imbudo landed over western Guangdong at about 300 km west-southwest of Hong Kong. Figure 2 shows the track of Imbudo near Hong Kong.

Winds in Hong Kong gradually veered from east to southeast and picked up as Imbudo approached the south China coast. Imbudo was closest to Hong Kong at around 05 HKT (HKT = UTC + 8 h) on 24 July 2003 when generally strong to gale force southeasterly winds prevailed locally. HKIA was situated in between spiral rainbands of Imbudo most of the time, with a daily total rainfall of just 4.2 mm. As the prevailing winds were east to southeasterly, all of the arriving flights landed from the west using the northern runway, whereas all the departing flights took off from the southern runway towards the east.

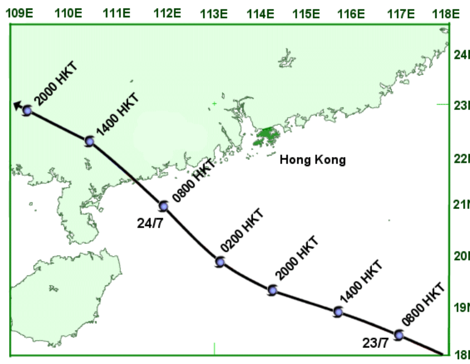

Figure 2. Track of Typhoon Imbudo (0307).

3. WIND ANALYSIS

The anemometer station at Tai Fung Au (TFA) on Lantau Island (see Figure 1) registered a rapid increase in 1-minute mean wind from 10 m/s to 30 m/s with gusts reaching up to 50 m/s between 02 HKT and 06 HKT on 24 July (Figure 3). The wind direction also saw rapid changes during the early hours, veering from east to southeast at 04 HKT. It became rather steady for the rest of the day. At around 04 HKT, an arriving aircraft reported severe turbulence at 1 nautical mile (1.85 km) west of HKIA. It was the first pilot report of significant turbulence received on that day.

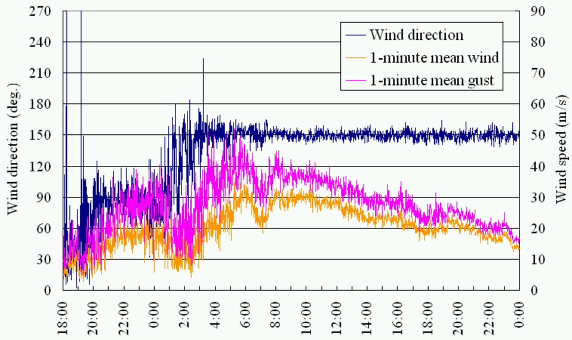

Figure 3. Winds recorded at Tai Fung Au (TFA) from 18 HKT 23 July 2003 to 00 HKT 25 July 2003.

The anemometer at TFA is located in a gap over Lantau, which lies in a southeast-northwest direction. The acceleration of winds is apparently gap-related. Similar wind conditions were observed at the Pak Kung Au (PKA) anemometer station, which is located in another gap to the east of TFA on Lantau (see Figure 1). The severe turbulence reported by aircraft was probably induced by the interaction of the gap-accelerated southeasterlies with the prevailing easterlies over the approach corridors (Figure 4).

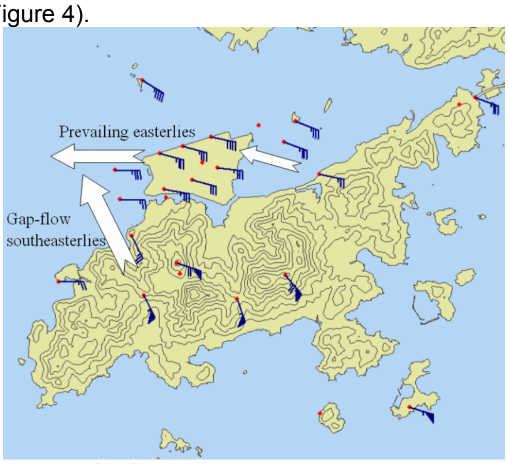

Figure 4. Surface wind observations at 0400 HKT 24 July 2003.

4. ANALYSIS OF TDWR DATA

A TDWR was installed at 12 km northeast of HKIA (see Figure 1) for detecting microburst and wind shear associated with convective storms (Shun and Johnson 1995; Johnson et al. 1997). Azimuthal scans at elevation angles ranging from 0.6 degrees to 60 degrees are made with re-visit times ranging between 1 and 5 minutes.

Figure 5 shows the radial velocity data at 0.6-degree elevation at 0400 HKT on 24 July. It reveals marked radial speed fluctuations over the flight corridor west of the northern runway, varying from as low as about 8 m/s (15 kt) to a maximum of about 20 m/s (39 kt). This is indicative of the presence of wind shear and/or turbulence. However, the TDWR did not consistently provide good clear-air returns as HKIA was not covered by the rainbands of Typhoon Imbudo. A more detailed analysis of TDWR data was therefore difficult and not made.

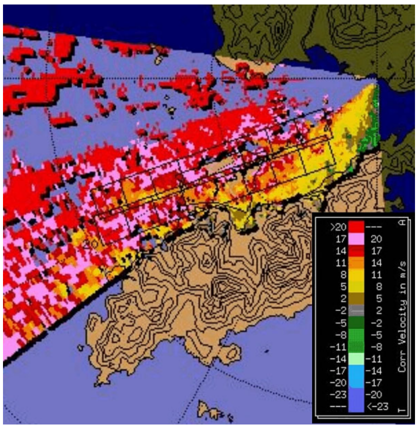
Figure 5. TDWR radial velocity at 0.6 deg elevation at 0400 HKT on 24 Jul 2003.

5. ANALYSIS OF LIDAR DATA

The LIDAR proves to be particularly useful in this occasion. The system, which is a pulsed Doppler LIDAR operating at 2 micron wavelength, with a range resolution of about 100 m and an azimuthal resolution of about 1 degree, was installed at the roof-top of the Air Traffic Control Complex in mid-2002 (see Figure 1). It supplements the TDWR in monitoring the wind flow around HKIA in clear-air conditions. Shun et al. 2003a described interesting terrain-induced phenomena including, among others, disrupted flow during the passage of tropical cyclones.

On 23 and 24 July, the scanning patterns employed for the LIDAR included Plan Position Indicator (PPI) scans at 1.0- and 4.5-degree elevation angles for monitoring the wind flow affecting the approach and departure corridors respectively; and also Range-Height Indicator (RHI) scans pointing at a number of azimuths for monitoring the vertical cross-section of the wind field above both runways.

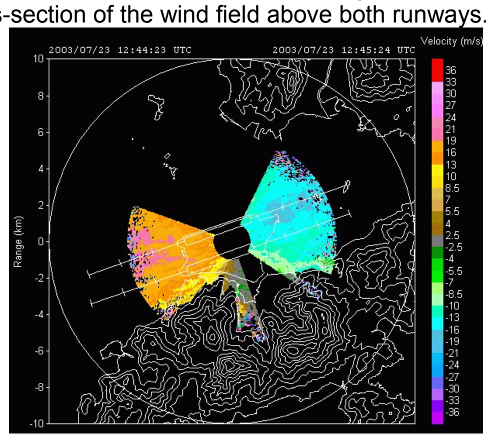

Figure 6. LIDAR radial velocity at 1.0 deg elevation at 2045 HKT on 23 Jul 2003. (Note: The LIDAR was operated with a reduced range in "wide bandwidth" mode at that time to avoid velocity aliasing.)

At 2047 HKT on 23 July, an aircraft approached HKIA and the landing was reported to be uneventful. The LIDAR radial velocity at 1.0 degree elevation near the time (Figure 6) indicates a generally smooth wind field over the approach corridor. The mean and standard deviation of the radial speed data over the two selected regions (the hatched regions in Figure 1) respectively on the approach corridors (based on 1.0-degree elevation PPI) and departure corridors (based on 4.5-degree elevation PPI) are computed to assess the likelihood of turbulence occurrence at the airport. The mean radial wind speed in the approach region was determined to be 15.9 m/s (30.9 kt) and the standard deviation is 1.2 m/s (2.3 kt).

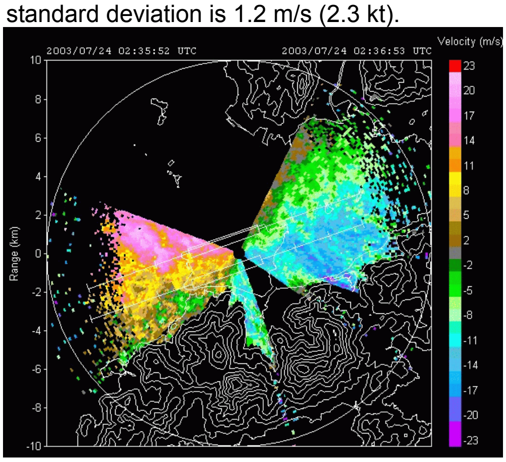

Figure 7. LIDAR radial velocity at 1.0 deg elevation at 1036 HKT on 24 Jul 2003.

At 1035 HKT on 24 July, an arriving flight reported severe turbulence during landing. The radial velocity map at 1.0 degree elevation (Figure 7) revealed a strong wind zone over the approach corridor. In the midst of the strong wind zone there were irregularly-arranged regions of comparatively lower speeds. From the RHI radial velocity at 258 degree azimuth cutting across a plane closest to the approach path, radial speed difference reaching 25 m/s (48.6 kt) could be seen within a distance of less than 300 m across (circled region in Figure 8), a scale and magnitude suggestive of turbulence. The mean wind speed in the approach region was 11.1 m/s (21.6 kt) and standard deviation was 3.3 m/s (6.4 kt) at this time.

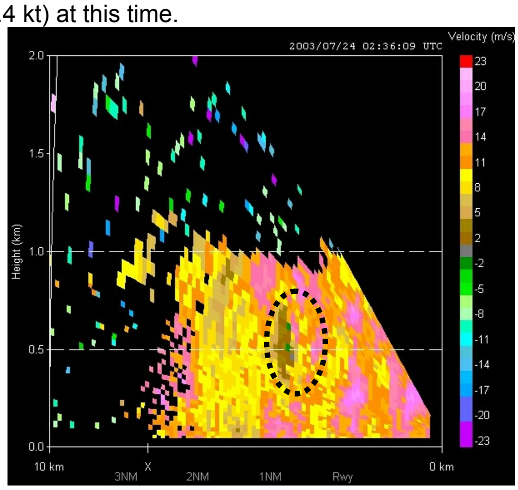

Figure 8. LIDAR RHI radial velocity at 258 deg azimuth at 1036 HKT on 24 Jul 2003.

Winds at the airport gradually moderated in the afternoon and the strong wind zone revealed by the LIDAR diminished gradually, coupled with a fall in the standard deviation of winds over the approach corridors. No more arriving aircraft reported turbulence except one at 2006 HKT that night. The decrease in the number of turbulence reports corroborated with the falling trend in the standard deviation of the radial winds over the approach region.

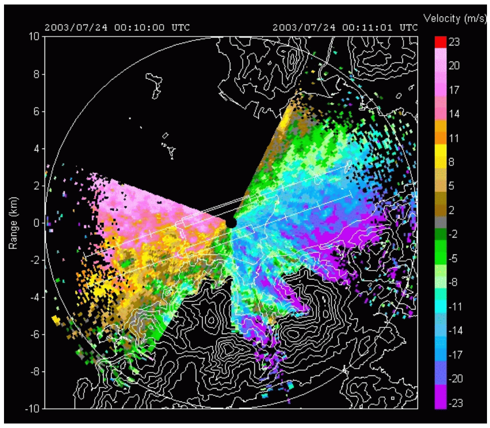

Figure 9. LIDAR radial velocity at 4.5 deg elevation at 0811 HKT on 24 Jul 2003.

For departures, only two flights which departed around 08 HKT on 24 July and another three which departed at around 23 HKT reported severe turbulence. All other reports were moderate turbulence. At 0811 HKT, the 4.5-degree elevation scan (Figure 9) revealed the existence of large spatial variation of radial speeds over the departure corridor (southern runway, towards the east). The mean radial speed was found to be 13.9 m/s (27.0 kt) and standard deviation was 3.2 m/s (6.2 kt).

The standard deviation of the radial speeds over the approach and departure regions for all 31 turbulence reports and 4 other null reports (reports of nil or light turbulence) received on 23 and 24 July are shown in Figure 10. The standard deviation values in general increase with the intensity of the turbulence reported.

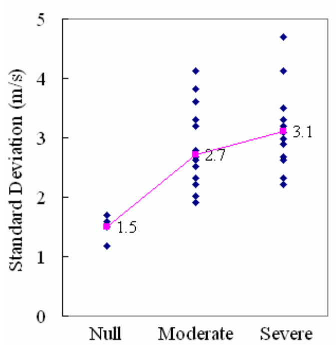

Figure 10. A plot of the standard deviation of LIDAR radial speeds at times of the pilot reports of turbulence. The figures indicate the average standard deviation values for each turbulence intensity.

6. ANALYSIS OF FLIGHT DECK DATA

The International Civil Aviation Organization (ICAO, 1996) and World Meteorological Organization (WMO, 1998) classify conditions which cause a change in vertical acceleration greater than 1.0 g at the aircraft's centre of gravity as severe turbulence, and those which cause a change of 0.5 g to 1.0 g as moderate turbulence. Based on these thresholds, a total of 82 sets of flight data collected between 23 and 25 July were analysed.

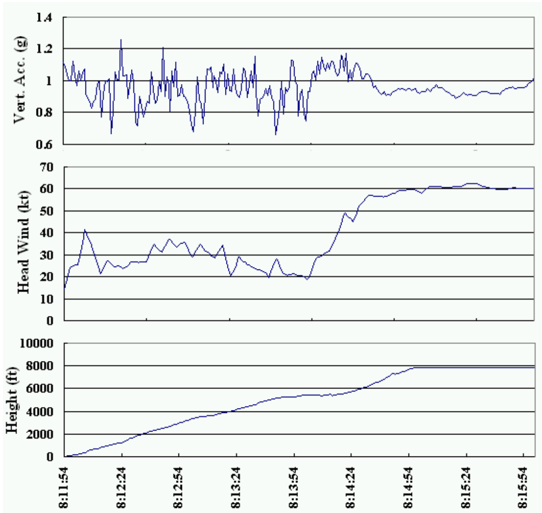

Figure 11. A plot of vertical acceleration, head wind and radio altitude recorded by an aircraft departed at 0811 HKO on 24 July 2003.

As an example, the aircraft which departed at 0811 HKT on 24 July and reported severe turbulence (see Section 5 above) recorded large amplitude vertical acceleration fluctuations with high frequency (Figure 11). The deviation of the vertical acceleration from gravity reached a maximum of 0.3 g. At 0827 HKT on the same day, another aircraft encountered severe turbulence during approach. Again large amplitude fluctuations in vertical acceleration were recorded by the aircraft and the peak deviation from gravity was around 0.6 g.

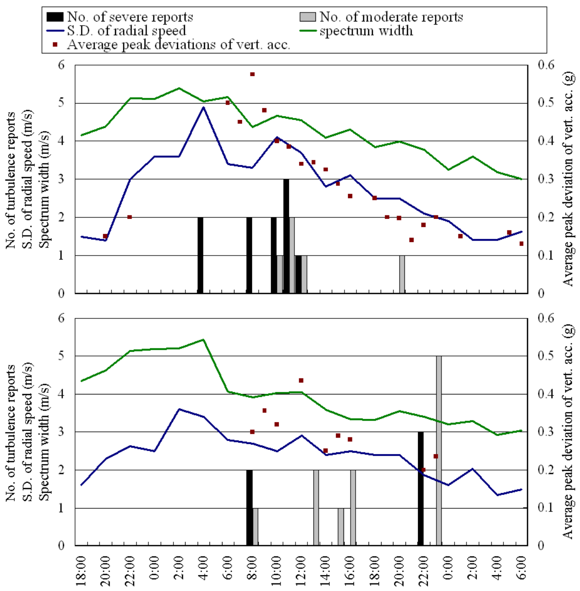

Figure 12. Combined plots of average peak vertical acceleration deviation, standard deviation of LIDAR radial speeds and mean spectrum width from 18 HKT 23 July 2003 to 06 HKT 25 July 2003. The number of pilot reports which reported turbulence is also indicated. The upper chart is for arrivals and the lower for departures.

Similar observations were extracted from flight data from the other aircraft that provided turbulence reports. In summary, aircraft reporting severe turbulence recorded deviations of vertical acceleration from gravity by 0.3 g to 0.6 g, whereas aircraft reporting moderate turbulence recorded deviations of 0.2 g to 0.25 g. These deviations are less than the respective thresholds for moderate and severe turbulence defined by ICAO/WMO.

For the 63 sets of flight deck data from arrivals and 19 sets from departures during 23-25 July 2003, the hourly average of the peak deviations of vertical acceleration from gravity is calculated. Figure 12 shows a comparison of these values with the standard deviation of the LIDAR radial speeds and the mean spectrum width in the corresponding regions (hatched regions in Figure 1). Figure 13 shows the corresponding scatter plots. All three times series reached their maxima in the early hours of 24 July. All severe turbulence reports from arrivals were received when the standard deviation and mean spectrum width exceeded 3 m/s and 4 m/s respectively. For departures, despite the gradual falling trend of all parameters during the day of 24 July, 3 more severe turbulence reports and 5 more moderate turbulence reports were received in the evening. The corresponding flight deck data shows that the average peak deviation of the vertical acceleration was below 0.25 g, suggesting only light turbulence (following the ICAO and WMO criteria). The pilots concerned might have over-estimated the intensity of the turbulence encountered.

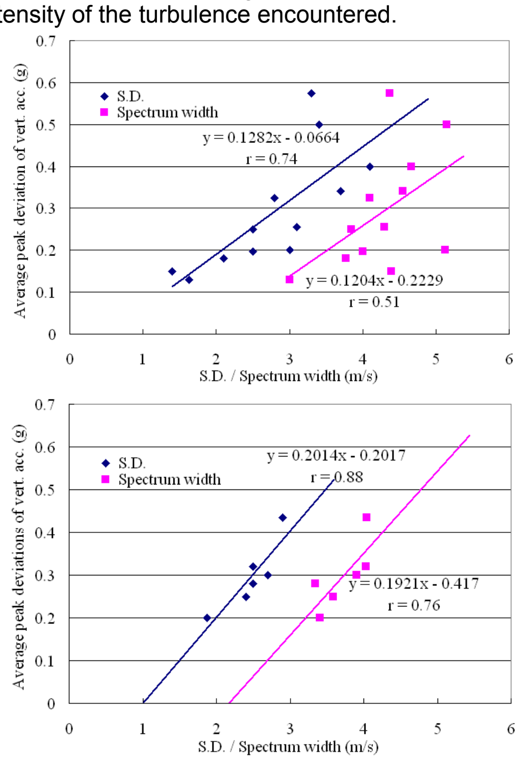

Figure 13. Scatter plots of average peak vertical acceleration deviation versus standard deviation of LIDAR radial speeds and mean spectrum width. The upper chart is for arrivals and the lower for departures.

The least square linear fits in Figure 13 have non-zero x-intercepts. This could be attributed to the presence of non-zero gradient in the radial velocities (i.e. wind shear) and the broadening effect of the linear wind field on the second moments of the LIDAR velocity field (Doviak and Zrnic, 1993). Despite these, the figures exhibit high correlation among the parameters. In particular, compared with the mean spectrum width, the standard deviation displays stronger correlation with the peak vertical acceleration deviation recorded by aircraft.

It is also noted that the slopes of the lines (unit in s^{-1}) fitted for arriving aircraft (~0.12) are quite different from those for departing aircraft (~0.2). The reason may be related to the use of PPI at different elevations over the approach corridors (1.0 degree) and the departure corridors (4.5-degree) in deriving the parameters, and is subject to further study.

7. SUMMARY AND DISCUSSIONS

The turbulence episode during the approach of Typhoon Imbudo on 24 July 2003 was terrain-induced. In particular, significant turbulence was first reported when winds at TFA and PKA on Lantau Island turned to gale-force southeasterlies. This is indicative of the important role played by the accelerated gap-flow.

Turbulence estimates were obtained from two different moments of the Doppler LIDAR velocity field, namely the standard deviation of the radial speeds and the mean spectrum width. The estimates obtained from the standard deviation method were found to correlate strongly with the aircraft-recorded fluctuations in vertical acceleration. While the standard deviation method gave estimates for turbulence eddies with characteristic sizes larger than the LIDAR pulse volume (range resolution ~100 m and azimuthal resolution ~1 degree), the spectrum width method gave information on small-scale eddies. Compared with the standard deviation method, the mean spectrum width correlates less well with the vertical acceleration deviations. This can possibly be explained by the fact that the characteristics sizes of the turbulent flow encountered by the aircraft (typically 300 m or less) were larger than the pulse volume of the LIDAR. The above results suggest that the LIDAR could be useful for turbulence detection. The standard deviation method appears to be more promising.

Aircraft reports collected in this case showed that the pilots might sometimes over-estimate the intensity of turbulence encountered with respect to the objective criteria promulgated by ICAO and WMO. This should be taken into account in the development of new alerting techniques based on LIDAR data in the future.

Acknowledgement

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