P.10 Performance of Eddy Dissipation Rate Estimates from Wind Profilers in Turbulence Detection

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1. INTRODUCTION

Since the opening of the Hong Kong International Airport (HKIA) in July 1998, about one in 2000 flights reported significant turbulence. HKIA is located on reclaimed land to the north of the mountainous Lantau Island (Figure 1), which has peaks rising to nearly 1000 m adjacent to valleys as low as 400 m. The land-sea interaction and the hilly terrain often produce complex wind patterns in and around the airport. Turbulent airflow mostly occurs when strong winds are disrupted by the hills surrounding HKIA in the spring and during the passage of tropical cyclones (Chan and Mok, 2004). Thunderstorms and sea breeze can also lead to turbulence.

The Hong Kong Observatory (HKO) operates a number of meteorological equipment to monitor the weather conditions at HKIA (Figure 1) and provides turbulence alerting service for arriving and departing aircraft using the Windshear and Turbulence Warning System (WTWS). The alerts are based on the same intensity thresholds as those adopted for automatic aircraft turbulence reporting by the International Civil Aviation Organization (ICAO, 2001). They are classified into two levels according to eddy dissipation rate (EDR) with the unit of $m^{2/3}s^{-1}$, namely, moderate turbulence for EDR ranging between 0.3 and 0.5, and severe turbulence for EDR of 0.5 or above. Moderate and severe turbulence are considered to be significant for alerting purpose.

This paper focuses on the use of the two wind profilers near HKIA, namely, the Sha Lo Wan and Siu Ho Wan profilers (Figure 1) to monitor turbulence at the airport by estimating EDR from the width of the spectral peak. The quality of this EDR estimate is studied by comparing with EDR estimates from the WTWS as well as turbulence reports from aircraft. The usefulness of the profiler-based EDR in turbulence alerting for the airport will also be discussed.

2. EDR FROM WIND PROFILER

The Sha Lo Wan and Siu Ho Wan wind profilers measure wind in the boundary layer using radio waves with a central frequency of 1299 MHz. To monitor the wind near the glide paths of the airport, they are configured to measure up to about 1.6 km above ground with a vertical resolution of 60 m. Data are updated every 10 minutes.

The width of the spectral peak in the wind profiler measurement is related to peak-broadening effect arising from turbulent eddies in the measurement volume of the radar beam. It can be used to produce an estimate of the turbulence of the airflow provided that spectral peaks with artificial origins, such as clutter and radio interference, are effectively removed. In the present study, spectral data from the wind profilers are processed by the NCAR Improved Moments Algorithm (NIMA) to remove these artificial peaks, determine the peak of the atmospheric return signal and provide an estimate of EDR (Morse et al., 2002).

Besides turbulence-induced broadening, the spectral width is also influenced by non-turbulent effects. This is summarized in the following equation (Shaw and LeMone, 2003):

$$s_t^2 = s_s^2 + s_a^2 + s_{11}^2 \qquad (1)$$

where s_t^2 is the total velocity variance measured in the Doppler spectral peak, s_s^2 is the contribution from wind shear across the radar beam, s_a^2 is a contribution depending on antenna properties (which is significant only for scanning radars but not for wind profilers), and s_{11}^2 is the radial velocity variance (the turbulence term) which is the main interest of this study. NIMA includes algorithms to remove the wind shear term, but the resulting spectral width becomes negative at times. This is related to the difficulty of accurately determining the horizontal wind velocity at all range gates in a cluttered environment and thus calculating the wind shear across the radar beam. Wind shear correction is therefore not considered here and its application calls for a separate study.

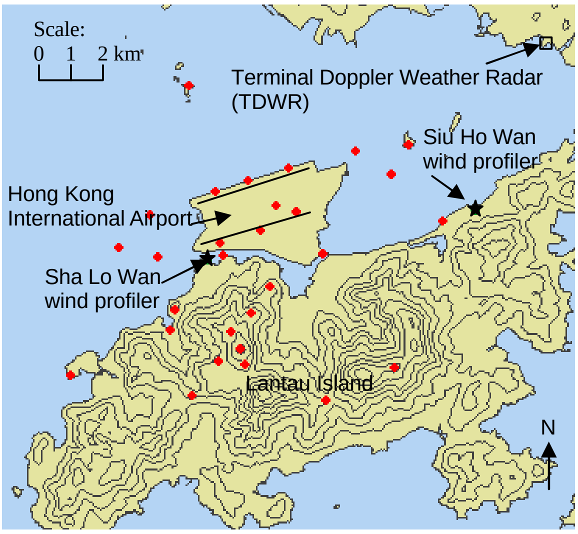

Figure 1 Map of the Hong Kong International Airport and the meteorological equipment for aviation weather services. Red dots are the anemometer stations. The two runways of the airport (black lines) are oriented in 070-250 direction. Height contours are in 100 m.

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3. EDR FROM WTWS

WTWS makes use of two independent means for determining the level of turbulence along the approach and departure corridors of HKIA. The first algorithm is based on observations from the Terminal Doppler Weather Radar (TDWR, see Figure 1 for its location) and the second algorithm is based on wind measurements from a network of anemometers around HKIA (Figure 1). A field experiment conducted in 1994 revealed good correlation between the levels of turbulence measured by a research King Air aircraft and the wind and gust measurements at various anemometer stations (Neilley et al. 1995). In view of this demonstrated performance of anemometer-based measurements, turbulence contribution from the anemometer algorithm has been assigned a heavy weight of 0.8 (compared with 0.2 for the TDWR-based algorithm) since the operation of WTWS.

The anemometer-based turbulence detection algorithm applies the principle of multi-linear regression to diagnose the level of turbulence along the approach and departure corridors. Separate regression equations are used for each corridor as well as for different wind directions. A set of regression equations was developed using temporally-averaged wind speed and gust measurements from various anemometer stations as predictors and the King Air aircraft measured eddy dissipation rates as predictants. Since at least 20 independent wind speed and gust measurements were made available to the WTWS, the regression was over-determined. To provide a measure of quality-assurance, the algorithm computes a set of turbulence estimates from each pair of speed and gust measurements, rejects the highest and lowest of those estimates, and then computes a weighted average of the remaining estimates as the final turbulence estimates. This allows the algorithm to continue to estimate turbulence intensities when certain input data from the anemometers are not available.

4. EDR DATA COMPARISON

For the wind profiler, an estimate of EDR is available from the Doppler spectrum of each range gate. An average EDR is calculated for the wind profiler by taking the arithmetic mean of the EDR estimates from 120 m (the lowest range gate) up to 520 m MSL, which is about the maximum height at which wind shear warnings are to be issued for the aircraft according to ICAO requirements.

The EDR at each range gate of the profiler is assigned a confidence level by NIMA (Morse et al., 2002). Several schemes of selecting EDR data for the averaging based on the confidence levels have been tried out (e.g. all confidence levels have to exceed a certain threshold), but they do not seem to have significant impact on the results of this study.

For WTWS, an EDR estimate is available for each of the four flight corridors of HKIA (ends of the two runways) and updated every minute. To align with the measurement cycle of the wind profiler, the 1-minute WTWS EDR data for each runway corridor are first averaged to give a 10-minute value. The10-minute EDR values of the two flight corridors on one side of HKIA are averaged further and then compared with the range gate-averaged EDR estimate from the wind profiler nearby these corridors. The Sha Lo Wan and Siu Ho Wan wind profilers are considered for the western and eastern corridors respectively.

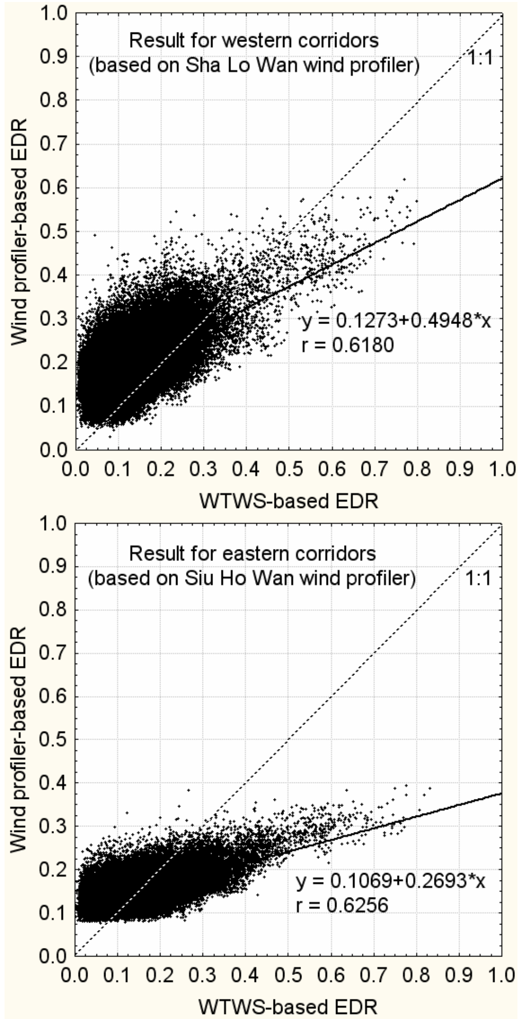


Figure 2 Scatter plots of the EDR determined from WTWS and the wind profilers. Solid lines are the least square linear fits of the data points. Dotted lines are the 1:1 lines.

Data of 2002 and 2003 are used in this study. Results of comparison of the wind profiler-based EDR and WTWS-based EDR are presented in Figure 2. The two EDR estimates are found to correlate quite well, with a correlation coefficient of around 0.62 for both corridors. The scattering of the data points in these comparison graphs suggests that the two EDR estimates may have different skills in certain weather conditions.

From Figure 2, it is apparent that there is a lower limit of the profiler-based EDR, namely, the EDR values from Sha Lo Wan and Siu Ho Wan profilers in general do not get below 0.05 and 0.075 respectively. This is probably due to the fact that wind shear correction has not been applied in the determination of the spectral width. Since turbulence alerting at the airport is mainly concerned with significant turbulence (i.e. moderate and severe turbulence with EDR = 0.3), the existence of these rather small lower limits of EDR should not have large impact on the practical usage of the profiler-based EDR.

5. COMPARISON WITH AIRCRAFT REPORTS

For turbulence alerting at HKIA, an EDR threshold of 0.3 is adopted in WTWS following ICAO (2001). There are two possible choices for the corresponding threshold of the profiler-based EDR:

(a) using 0.3 as well, based on the assumption that the wind profiler measures EDR accurately;

(b) determining the profiler-based EDR value that corresponds to 0.3 of WTWS-based EDR from the best-fit straight line in the scatter plot of the two EDR datasets (Figure 2) – the thresholds are found to be 0.28 and 0.2 for Sha Lo Wan and Siu Ho Wan wind profilers respectively.

In the following discussion, the threshold value x is indicated inside the parenthesis following the abbreviated name of the system that produces the EDR data, namely, SLW (x) [for Sha Lo Wan wind profiler] and SHW (x) [for Siu Ho Wan wind profiler].

The performance of the EDR estimates in turbulence alerting is studied by using the turbulence reports from aircraft as reference. Aircraft reports of 2002 and 2003 are included in this study. Firstly we have to define the meaning of turbulence and no-turbulence cases:

(a) a turbulence (turb) case refers to an aircraft report of light-moderate turbulence, moderate turbulence, moderate-severe turbulence or severe turbulence;

(b) a no-turbulence (no turb) case refers to an aircraft report of (i) no turbulence and wind shear less than 15 knots (including no wind shear), or (ii) light turbulence.

Aircraft reports of no turbulence and wind shear = 15 knots are not included here because it is not certain whether there is no turbulence at all, or turbulence is taken to be wind shear.

The performance of the profiler-based EDR in alerting significant turbulence is assessed by considering probability of detection (POD), false alarm rate (FAR) and critical success index (CSI). Scores for the western and eastern flight corridors of HKIA are summarized in Tables 1 and 2.

Methods (thresholds in brackets)	POD, total turb cases: 138	FAR, total no turb cases: 213	CSI
SLW (0.3)	59%	25%	0.49
SLW (0.28)	69%	31%	0.53

Table 1 Performance of the various EDR estimates in turbulence detection for western flight corridors of HKIA in 2002 and 2003.

Methods (thresholds in brackets)	POD, total turb cases: 111	FAR, total no turb cases: 132	CSI
SHW (0.3)	5%	0%	0.05
SHW (0.2)	64%	25%	0.53

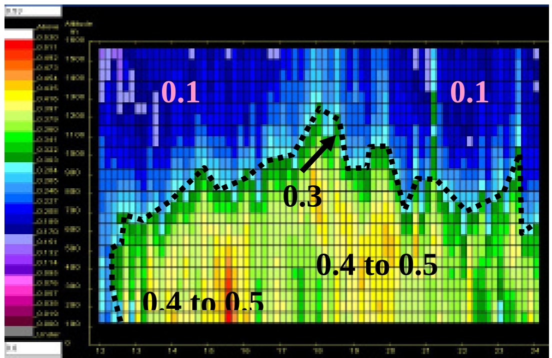
Table 2 Similar to Table 1, but for eastern flight corridors of HKIA.

For both wind profilers, the use of a threshold derived from the least-square linear fit in Figure 2 performs better than the straightforward adoption of a threshold of 0.3. The improvement is more significant for Siu Ho Wan wind profiler, though the reason is not certain and further studies are required.

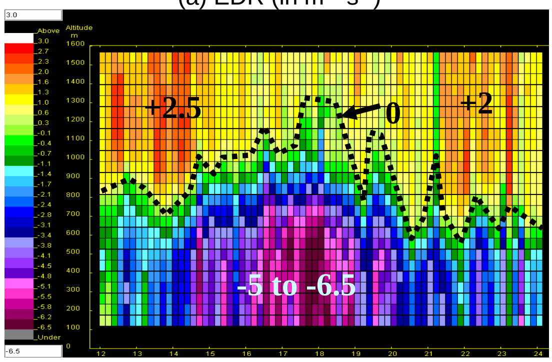
6. EXAMPLES OF VERTICAL PROFILES OF PROFILER-BASED EDR

Only the range gate-averaged EDR from the wind profiler is considered so far in this paper. A study of the vertical profile of the EDR at various range gates also helps to reveal the complexity of the airflow in windy weather and should be useful for the monitoring of turbulence at the airport. Two examples are discussed here.

The airflow at HKIA becomes rather turbulent in springtime when strong southeasterly wind is disrupted by the hills on Lantau Island in the presence of a significant temperature inversion within the boundary layer. On 4 March 2003, south to southeasterly winds up to 40 knots prevailed over Hong Kong from the ground to about 1.5 km. There were three aircraft reports of moderate turbulence over the western flight corridors of HKIA on that day, including one missed approach. From the radiosonde ascent data (not shown) at 8 p.m. (Hong Kong time, which is eight hours ahead of UTC), there was a temperature inversion of about 3 degrees between 660 and 870 m, just below the peaks of Lantau Island. As measured by Sha Lo Wan wind profiler (Figure 3a), the airflow in the boundary layer



(a) EDR (in $m^{2/3}s^{-1}$)



(b) vertical velocity (in m/s)
(+ means upwards, - means downwards)

Figure 3 Sha Lo Wan wind profiler measurements between noon of 4 March and midnight of 5 March 2003. Horizontal axis is the time axis with a marking every hour. Vertical axis is the height axis (up to 1600 m) with a marking every 100 m. Representative values of EDR and vertical velocity are also shown on these height-time plots.

was very turbulent, with a maximum EDR of about 0.5. Moderate turbulence (EDR between 0.3 and 0.5) occurred at an altitude up to about 1.25 km at 6 p.m., which was higher than the top of the temperature inversion. The EDR varied more or less in phase with the vertical velocity (Figure 3b), which has a maximum downward velocity of around 6.5 m/s below 700 m at 6 p.m. The turbulent airflow seems to be associated with strong vertical motion in this case.

Turbulent airflow also occurs around HKIA during the passage of tropical cyclones. In the morning of 25 August 2003, Typhoon Krovanh crossed the northern part of the South China Sea and landed on Leizhou Peninsula (Figure 4). From the radiosonde ascent data at 8 a.m. (not shown), gale to storm force southeasterly winds prevailed in Hong Kong up to about 6.5 km. There were altogether 13 aircraft reports of moderate to severe turbulence over the eastern flight corridors of HKIA on that day. As measured by Siu Ho Wan wind profiler (Figure 5), there seems to be a layer of turbulent air with EDR ranging between 0.3 and 0.4 below 450 m or so up to about 2 p.m. This turbulent layer may be related to the boundary layer of the typhoon (Knupp et al., 2000) and airflow disruption by Lantau terrain.

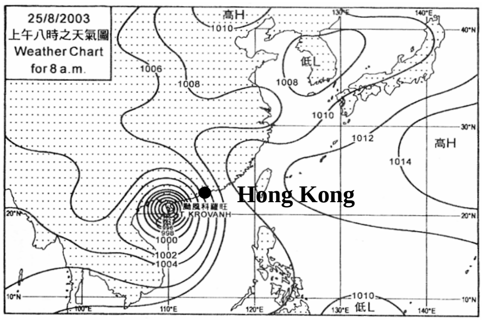


Figure 4 Surface isobaric chart at 8 a.m., 25 August 2003.

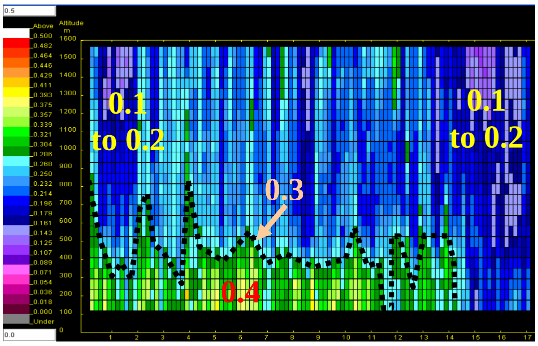


Figure 5 Similar to Figure 3(a), but for Siu Ho Wan wind profiler measurements between midnight and 5 p.m. on 25 August 2003.

7. CONCLUSION

EDR is derived from the width of spectral peak of the two wind profilers in the vicinity of HKIA by applying the NIMA algorithm. It is available at each range gate of the profiler once every 10 minutes, and an average EDR from 120 m (lowest gate height) up to 520 m MSL is calculated to represent the turbulence intensity of the runway corridors on either side of the airport. This average EDR was found to correlate reasonably well with the temporally and spatially averaged values provided by WTWS, with a correlation coefficient of around 0.62.

The profiler-based EDR was compared with turbulence reports from aircraft in a two-year period (2002 – 2003) in order to assess its usefulness in turbulence alerting for the airport. By using an alerting threshold derived from the least-square linear fit in Figure 2, the profiler-based EDR is found to have a critical success index of 0.53. The vertical profiles of EDR were also available from the wind profilers at HKIA. They were found to be useful in the monitoring of turbulence, such as airflow disruptions by the hilly terrain near HKIA in springtime and during the passage of tropical cyclones.

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