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Monitoring of aviation turbulence using a tropospheric profiler - case studies

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सार - विमानन सुरक्षा में सावधानी बरतने के लिए प्रक्षोभ की निगरानी उपयोगी होगी। हालांकि, एयरोस्पेस में प्रक्षोभ डेटा ना के बराबर ही उपलब्ध है, जैसे कि टर्मिनल क्षेत्र में और विमान के रास्ते के आकाश में। इस शोधपत्र में ऊपरितन वायु प्रक्षोभ का पता लगाने हेतु क्षोभमंडलीय प्रोफाइलर द्वारा मापी गई भंवर ह्रास दर का उपयोग प्रस्तुत किया गया है। प्रक्षोभ के दो विशेष विषयों का इस शोधपत्र में अध्ययन किया गया है अर्थात् उपोषणीय चंडवात लाइनों से जुड़ा तीव्र संवहनी मौसम, और ऊपरी वायु गर्त / जेट धारा से जुड़े प्रक्षोभ। इन विषयों के अध्ययन में यह देखा जा सकता है कि पायलट को जब मध्यम या प्रचंड प्रक्षोभ की सूचना मिलती है तो उस समय प्रक्षोभ में बढ़ोतरी के स्पष्ट लक्षण दिखाई देते हैं। क्षोभमंडलीय प्रोफाइलर क्षोभमंडल के अंदर उपरितन वायु प्रक्षोभ के विकसित होने के समय ऊंचाई का अभूतपूर्व दृश्य दिखाता है। सीमित विषयों में प्रोफाइलर की भंवर ह्रास दर के आंकड़े हवाई अड्डे के टर्मिनल क्षेत्र में प्रक्षोभ की निगरानी और समय रहते चौकन्ना करना और विमान के रास्ते की अवस्थाओं में उपयोगी साबित होते हैं।

ABSTRACT. Monitoring of turbulence would be useful for the assurance of aviation safety. However, turbulence data are only scarcely available in the aerospace, e.g., in the terminal area and en-route space of the aircraft. This paper documents the use of eddy dissipation rate as measured by a tropospheric profiler in the detection of upper air turbulence. Two typical cases of turbulence are considered in this paper, namely, intense convective weather associated with subtropical squall lines and turbulence associated with upper air trough / jet stream. Through these case studies, it could be seen that there is signature of enhanced turbulence at times when moderate or severe turbulence is reported by the pilots. The tropospheric profiler provides unprecedented view of the height-time evolution of upper air turbulence inside the troposphere. From a limited number of cases, the eddy dissipation rate data from the profiler is demonstrated to be useful in the monitoring and timely alerting of turbulence in the terminal area of the airport and en-route phase of the aircraft.

Key words – Turbulence, Eddy Dissipation Rate (EDR), Tropospheric profiler, Squall lines, Jet streams, Vertical velocity.

1. Introduction

Turbulence, *i.e.*, short-term irregular motion of the air, may be hazardous to the aircraft. In severe turbulence, the pilot may lose control of the aircraft for a short period of time. In international civil aviation (ICAO, 2013), turbulence is quantified in terms of the cube root of eddy dissipation rate ($EDR^{1/3}$), which is the rate at which the turbulent kinetic energy decays. The commonly used thresholds for light, moderate and severe turbulence are 0.1 $m^{2/3}s^{-1}$, 0.4 $m^{2/3}s^{-1}$ and 0.7 $m^{2/3}s^{-1}$ respectively. However, based on studies of the pilot reports of turbulence encounter, there are some suggestions that the thresholds may be lower. For instance, in Sharman *et al.*, (2014), the thresholds are considered to be as low as 0.014 $m^{2/3}s^{-1}$, 0.125 $m^{2/3}s^{-1}$ and 0.35 $m^{2/3}s^{-1}$.

Low level turbulence, which is mostly turbulence occurring at the aerodrome, may be monitored by ground-based anemometers and remote-sensing meteorological instruments such as Doppler Light Detection and Ranging (LIDAR) system (Chan, 2011). It becomes more difficult to monitor turbulence in the wider regions of the terminal area and the en-route phase. The turbulence may be derived from the spectrum width data obtained from the Doppler weather radar (DWR) [Suresh (2009); Chan *et al*. (2016)].

In Li *et al*. (2015), the turbulence and vertical velocity in a land-falling tropical cyclone are documented using the measurements from a tropospheric profiler. The turbulence data are also available in other weather conditions, e.g., in subtropical squall lines and turbulence associated with upper air troughs or jet streams. This short

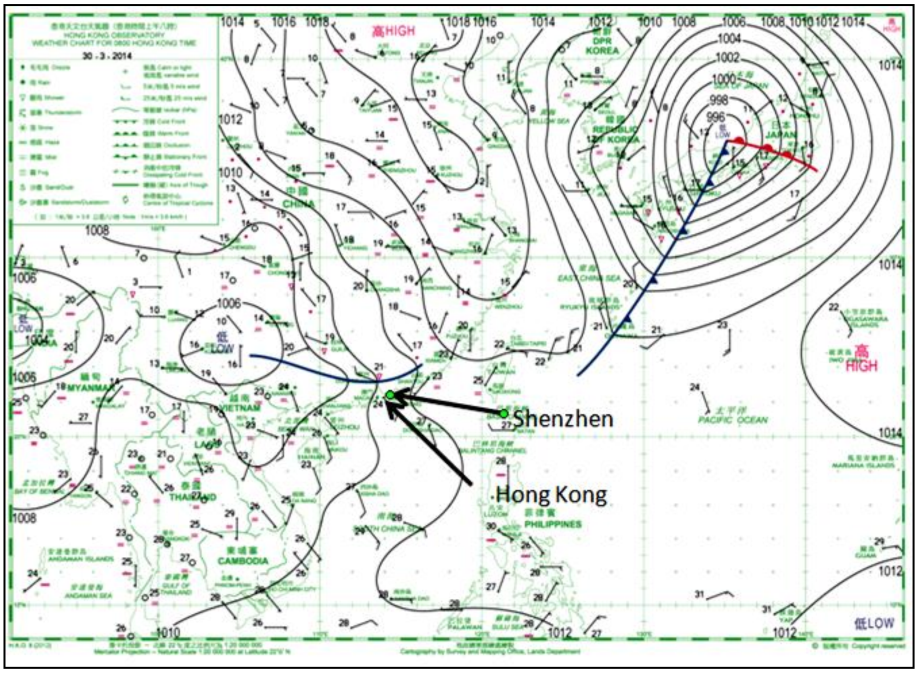


Fig. 1. Surface isobaric chart at 0000 UTC, 30 March, 2014

paper documents the $EDR^{1/3}$ observations of the tropospheric profiler in Shenzhen, China (location in Fig. 1) in these two kinds of weather conditions. Comparison with aircraft data / pilot reports is made and possible limitation of the turbulence measurement would also be discussed.

The tropospheric profiler at Shenzhen, China operates with a frequency of 51 MHz. It measures the winds up to 12 km above ground using a four-beam configuration, namely, to the fore, rear, left and right of the phased array antenna. The outputs include horizontal as well as vertical wind velocities and the turbulence intensity based on the spectrum width of the radar signal return. The latter is determined from the National Center for Atmospheric Research (NCAR) Improved Moments Algorithm (NIMA, Morse *et al*., 2002, for technical details).

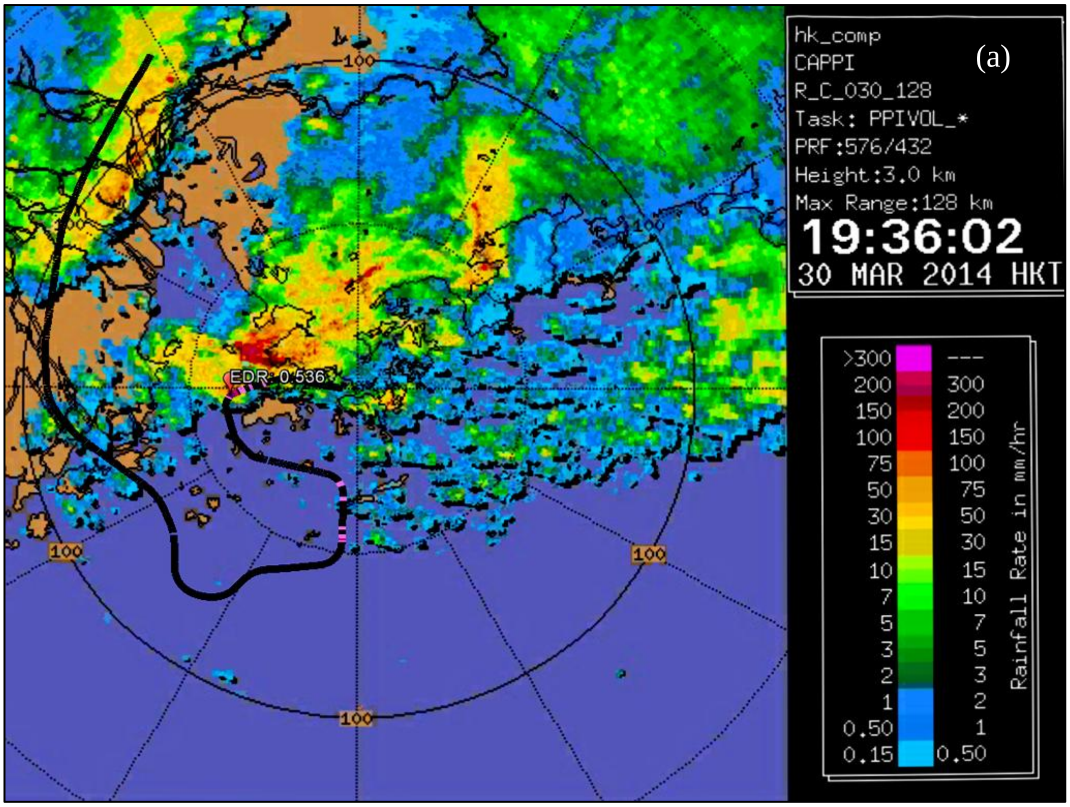
In the rainy case in the summer, the tropospheric profile up to 12 km is considered due to deep convection and the availability of moisture higher up in the troposphere. However, in the stable air case in the autumn/ spring time, the upper tropospheric wind profiles are questionable as the atmosphere would be rather dry over there. Only the part of the profile up to 8 km is considered, even though NIMA is still able to output data up to 12 km.

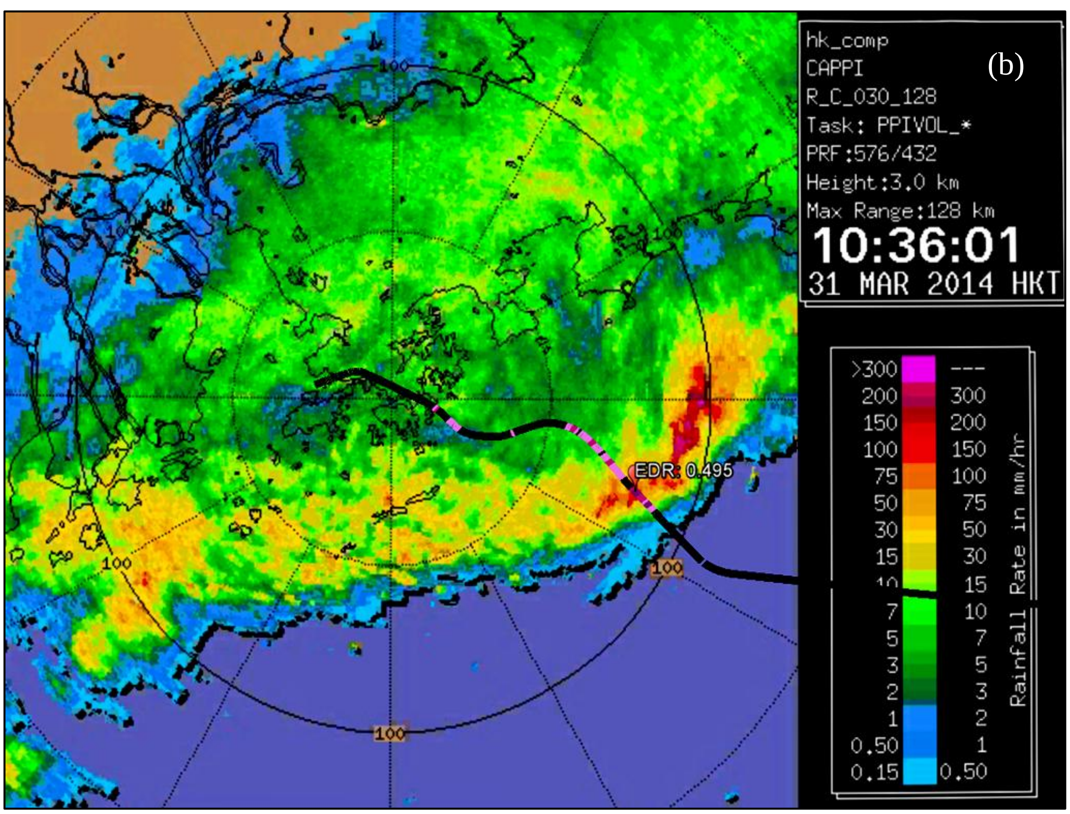
In the analysis below for the stable weather condition, outputs of a meso-scale numerical weather prediction model have been considered. This is the 10 km resolution model used in the Hong Kong Observatory for public weather service and aviation weather service. Details of the model could be found in Saito *et al*. (2006). The standard model level output that is closest to the height of turbulence report from the pilot is considered.

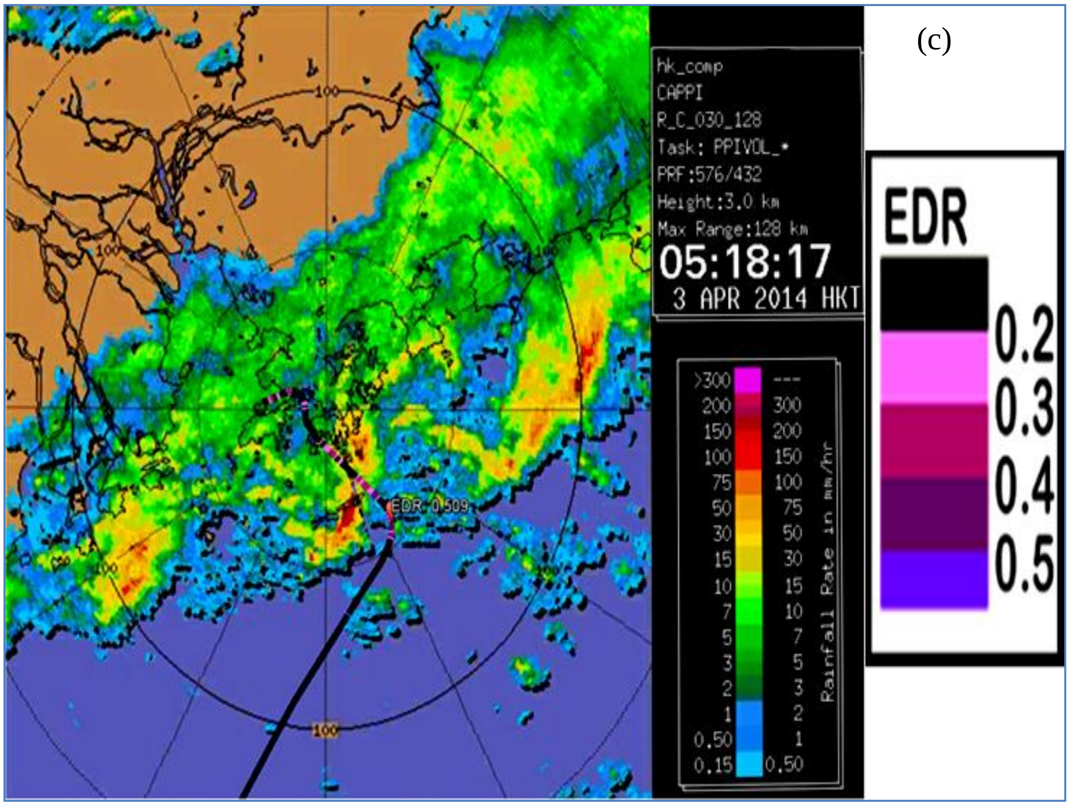
2. Observation of subtropical squall lines

In late March and early April of 2014, a trough of low pressure was bringing unsettled weather to the south China coast. A typical surface isobaric chart in that period is shown in Fig. 1. Along the surface trough, bands of heavy rain developed and moved to the east in the form of subtropical squall lines. The typical weather radar pictures in the period could be found in Figs. 2(a-c).

The aircraft departing from Hong Kong International Airport has to move across the unsettled weather associated with the surface trough in order to get to the en-route phase and move away from Hong Kong. A number of aircraft encountered severe turbulence in the terminal area. The time series of $EDR^{1/3}$ from some aircraft is overlaid on the weather radar imageries and are shown in Figs. 2(a-c). It may be mentioned here that the $EDR^{1/3}$ values are not directly available from the aircraft. It is calculated from the parameters measured by the aircraft, e.g., vertical and longitudinal accelerations using the method as described in Haverdings and Chan (2010). It could be seen that moderate turbulence up to 0.5 $m^{2/3}s^{-1}$ is


hk_comp
CAPPI
R_C_030_128
Task: PPIVOL_*
PRF:576/432
Height:3.0 km
Max Range:128 km
19:36:02
30 MAR 2014 HKT
(a)
EDR: 0.536
100
>300 ---
200 300
150 200
100 150
75 100
50 75
30 50
15 30
10 15
7 10
5 7
3 5
2 3
1 2
0.50 1
0.15 0.50
Rainfall Rate in mm/hr


hk_comp
CAPPI
R_C_030_128
Task: PPIVOL_*
PRF:576/432
Height:3.0 km
Max Range:128 km
10:36:01
31 MAR 2014 HKT
(b)
EDR: 0.495
100
>300 ---
200 300
150 200
100 150
75 100
50 75
30 50
15 30
7 10
5 7
3 5
2 3
1 2
0.50 1
0.15 0.50
Rainfall Rate in mm/hr



Figs. 2(a-c). Weather radar imageries at 3 km above sea level for the three cases of severe turbulence encountered by the aircraft. The flight route of the aircraft is shown, together with the EDR$^{1/3}$ as determined from the aircraft data

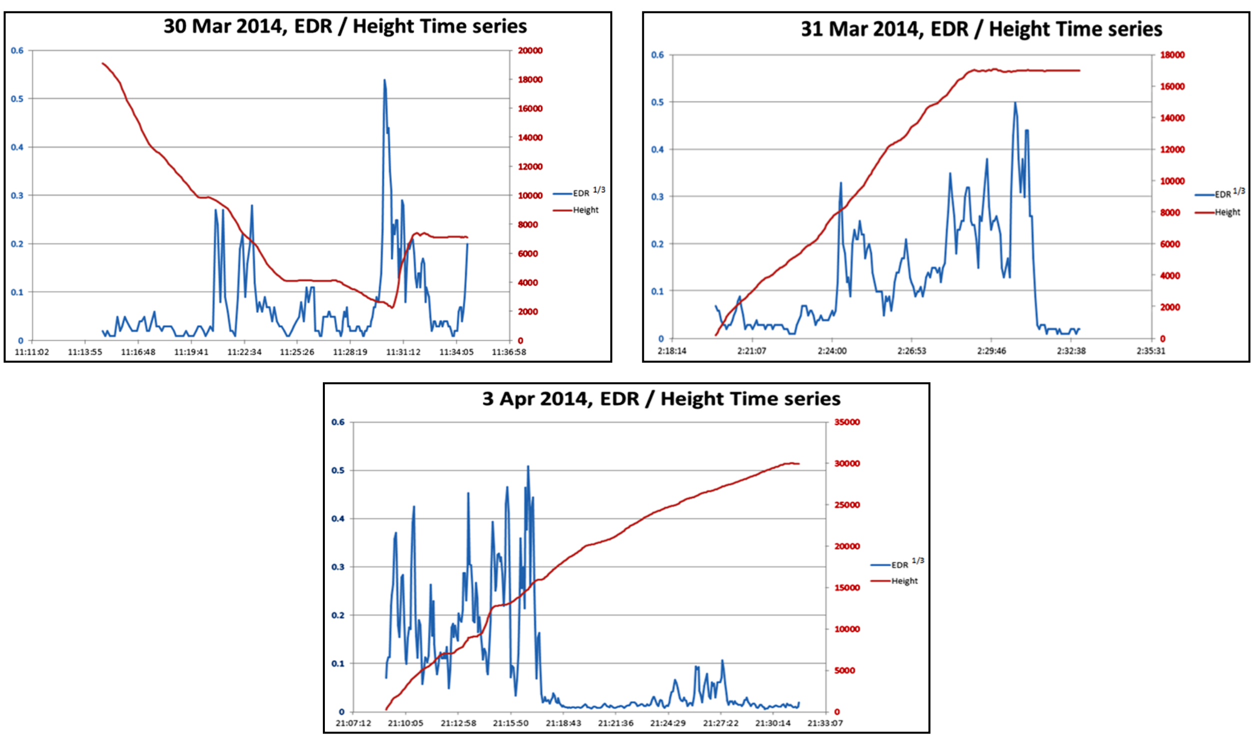
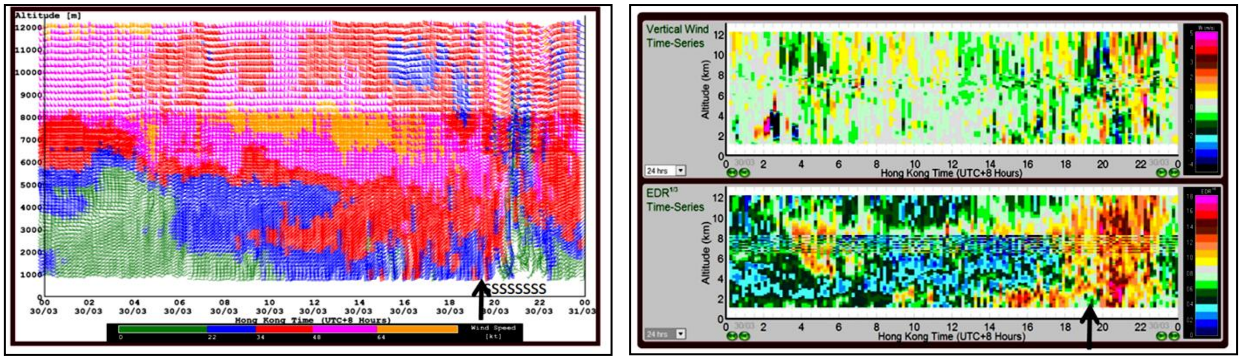
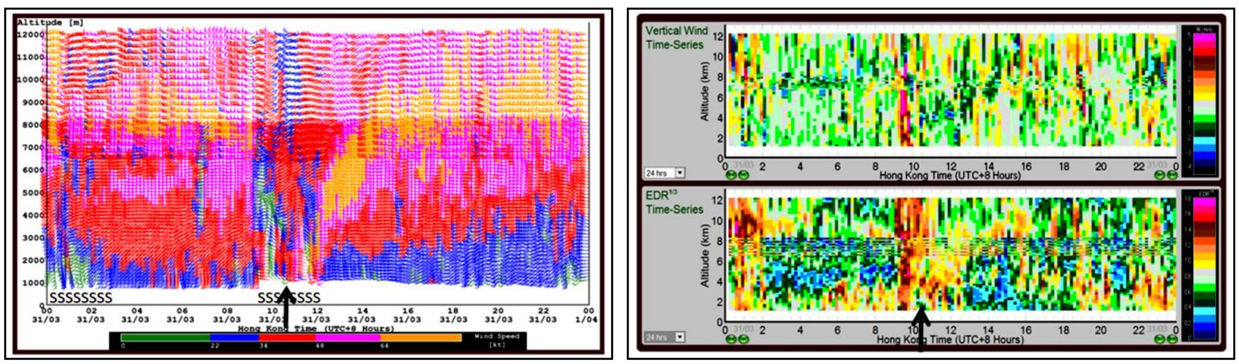


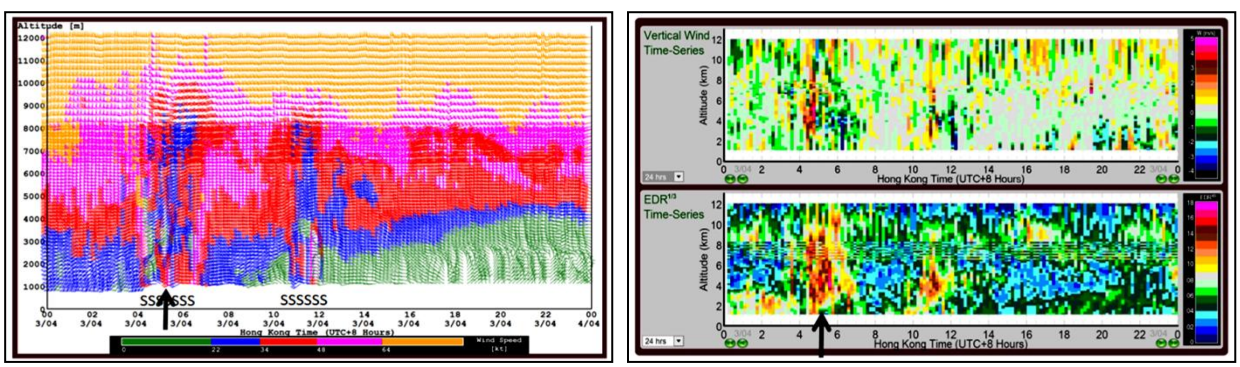
Fig. 3. Time series of the EDR$^{1/3}$ (in $m^{2/3}s^{-1}$) and the height (in feet) of the three aircraft encountering severe turbulence in rain. Horizontal axis is UTC time



(a) 30 March 2014 - the height of severe turbulence encounter is about 2000 feet, or 606 m



(b) 31 March 2014 - the height of severe turbulence encounter is about 17500 feet, or 5303 m



(c) 3 April 2014- the height of severe turbulence encounter is about 15000 feet, or 4545 m

Figs. 4(a-c). The height-time evolution of horizontal wind, vertical wind and $EDR^{1/3}$ from the tropospheric profiler on (a) 30 March, 2014, (b) 31 March, 2014 and (c) 3 April, 2014. The time and the height of the severe turbulence encountered by the aircraft are highlighted. The periods in which squall lines passed through the profiler site are marked by strings of "S". Hong Kong time = UTC + 8 hours

recorded on the aircraft within and around the intense radar reflectivity cores. In order to display the turbulence clearly, the $EDR^{1/3}$ time series is redrawn in Fig. 3.

The tropospheric profiler observations of vertical velocity and $EDR^{1/3}$ on three days corresponding to the three flights in Figs. 2(a-c) are shown in Figs. 4(a-c). There are a number of observations:

(*i*) For the vertical velocity, the values are higher and fluctuating more rapidly at times when the squall lines passed through the profiler, which corresponded to the times when there were changes in the horizontal winds from the prevailing southwesterly, e.g., from north-westerly or becoming southeasterly. The wind fluctuations occurred up to the upper troposphere, e.g., from ground up to 8 km. Corresponding to such changes, the vertical

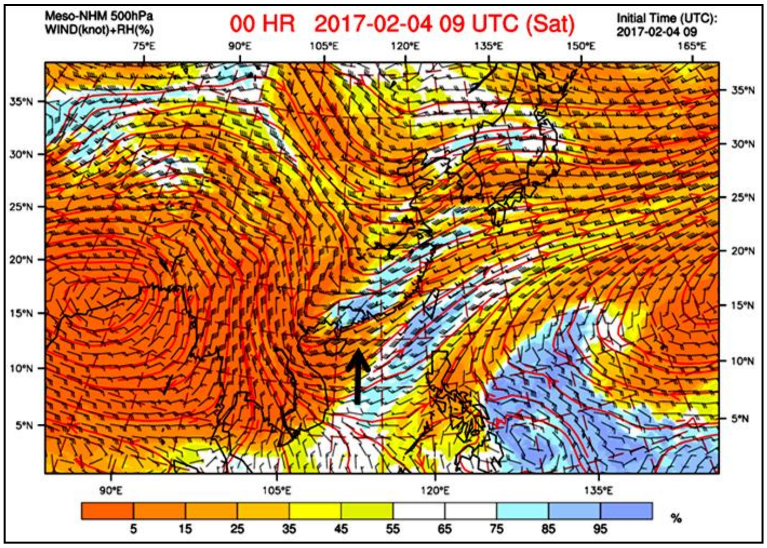


Fig. 5. 500 hPa humidity and wind field at 0900 UTC, 4 February, 2017. The approximate location of the severe turbulence is indicated by an arrow

velocity might reach +/- 5 m/s. Please note that the measurements are 10 minute averages and thus the vertical velocity might appear low for severe convection in the present case. However, there is no vertical beam in the tropospheric profiler to provide instantaneous value of the vertical velocity directly.

(*ii*) The $EDR^{1/3}$ values are generally larger during the passage of the squall lines across the profiler site. They are found to reach as high as 0.18 $m^{2/3}s^{-1}$. These values, however, are still lower than the maximum values recorded on the aircraft [Figs. (2&3)]. There may be rather large spatial variability of the $EDR^{1/3}$ in intense convection.

The tropospheric profiler's $EDR^{1/3}$ profiles, though only corresponds to a column of air above the profiler's location, could still be useful for monitoring the turbulence in this intense convection weather condition. They may be monitored closely for the periods when the values are generally higher (e.g., above 0.1 $m^{2/3}s^{-1}$), which may indicate higher chance of the occurrence of light turbulence in the terminal area of Hong Kong airport. However, there are no EDR measurements directly at the flight paths to substantiate that the wind profiler based EDR is comparable with that measured by the aircraft.

3. Upper air troughing flow (UATF) cases

Two cases of UATF are presented in this paper. One occurred in the afternoon of 4 February, 2017. An A320 aircraft at the location in Fig. 5 encountered severe turbulence. Unfortunately, aircraft data are not available in this case. The pilot report was severe turbulence at 21.39° N, 113.42° E, flight level 130 (*i.e.*, height of 13000 feet or 3939 m) at 1010 UTC, 4 February. From the upper air analysis at that time (Fig. 5), the turbulence occurred ahead of an upper-level trough. The strong core of wind of about 50 knot ahead of the trough may bring about the turbulence in this case.

The tropospheric profiler observation in this case is given in Fig. 6. Around the time of the severe turbulence (between 0900 and 1100 UTC), there is passage of the stronger wind between 3 and 4 km above ground, namely, from gale to strong southwesterly winds, to strong southwesterly winds. Incidentally, the $EDR^{1/3}$ around that height also became larger, though the maximum value of $EDR^{1/3}$ is not particularly large, just 0.15 $m^{2/3}s^{-1}$ which corresponds to light to moderate turbulence. Of course, as discussed in the Introduction, there may be uncertainty about the $EDR^{1/3}$ value for the pilot report of severe turbulence. In any case, the occurrence of higher $EDR^{1/3}$ may hint the possible occurrence of moderate or severe turbulence though the measured turbulence level by the wind profiler is just light to moderate. The tropospheric profiler provides unprecedented observation of the height-time evolution of the higher level of turbulence for the aircraft and such information could be useful for the monitoring of turbulence.

Another UATF case occurred on 5 December, 2015. The pilot report was moderate turbulence at 22.15° N, 114.18° E (location in Fig. 7) at flight level 110 (*i.e.*, 11000 feet or 3333 m) at 0713 UTC, 5 December,

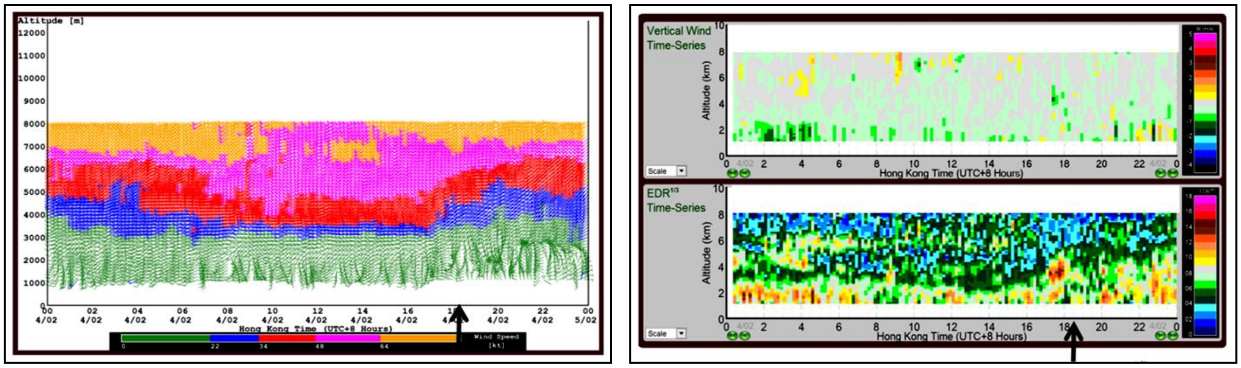


Fig. 6. Height-time plot of horizontal wind, vertical velocity and $EDR^{1/3}$ for the severe turbulence case of 4 February, 2017. The time of the event is indicated by an arrow. The height of the event is 3939 m, *i.e.*, around 4 km

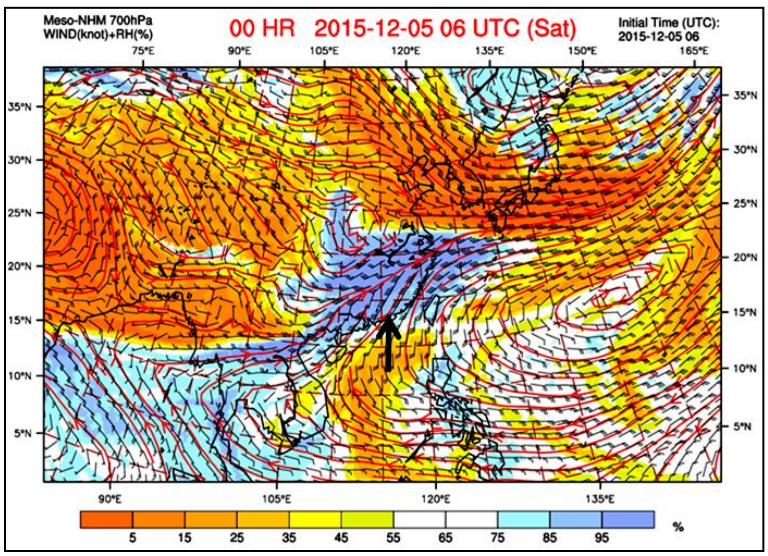


Fig. 7. 700 hPa humidity and wind field at 0600 UTC, 5 December 2015. The approximate location of the moderate turbulence is indicated by an arrow

from a B773 aircraft. Aircraft data are also not available for this case. From the upper air analysis at that time (Fig. 7), the location of moderate turbulence occurred in between an upper air trough and northwestern flank of the subtropical ridge. The confluence of the airflow from these two weather systems may bring about turbulence in this case.

The tropospheric profiler observations in this case are given in Fig. 8. Around the time of the turbulence (between 0700 and 0900 UTC), there was a change of southwesterly flow to more southerly flow between the ground up to about 3 km above ground. This is consistent with the competing airflow between the upper air trough and sub-tropical ridge. The $EDR^{1/3}$ was also slightly larger, up to about 0.14 $m^{2/3}s^{-1}$. Though the $EDR^{1/3}$ did not seem to be particularly high (only light to moderate level), the occurrence of higher level of turbulence may still be useful for the timely alerting of aviation weather forecaster of the occurrence of moderate or severe turbulence around the Hong Kong airport.

There are also some observations of the behaviour of higher values of $EDR^{1/3}$ in the tropospheric profiler in the stable air situation [Figs. (6&8)] compared with the convective weather conditions in summer [Figs. 4(a-c)]. In the former case, the $EDR^{1/3}$ values within the boundary layer appear to be generally higher than the upper air values. There are also some banded shapes of areas of higher $EDR^{1/3}$ in the stable conditions, which may be associated with shear lines, e.g., between 1200 and 1600 UTC, 4 February, 2017, at a height of about 3 km (Fig. 6). On the other hand, the higher value of $EDR^{1/3}$ within the boundary layer may not occur at times in convective weather conditions [Figs. 4(a-c)], but the turbulence intensity may become rather high in the middle to the upper troposphere in the convective weather (in the order

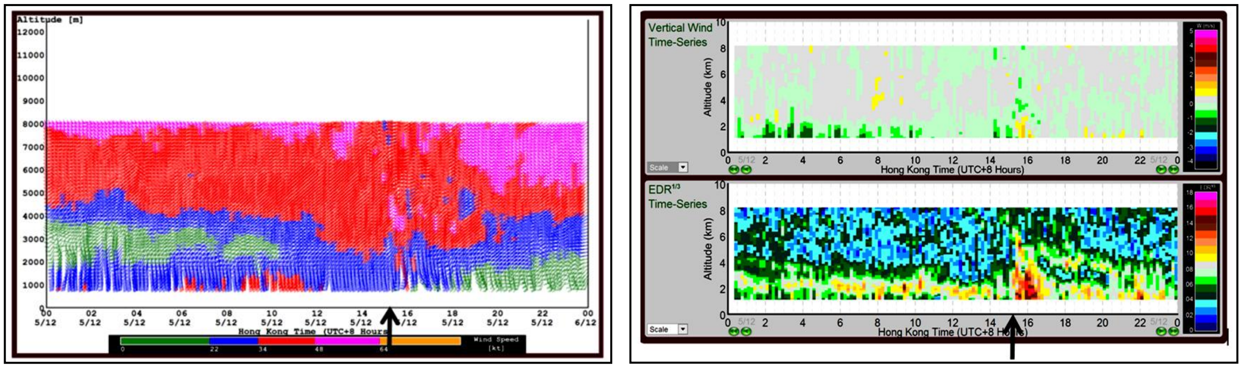


Fig. 8. Same as Fig. 6 but for the moderate turbulence case of 5th December, 2015. The time of the event is indicated by an arrow. The height of the event is 3333 m, *i.e.*, around 3 km

of 0.1 to 0.12 $m^{2/3}s^{-1}$). As pilot's report is rather subjective and qualitative, their turbulence level may not be compared with the light turbulence of $EDR^{1/3}$ in the region of 0.1 to 0.3 $m^{2/3}s^{-1}$, which is specified in ICAO Annexure 3, as measured by the wind profiler.

4. Conclusions

This short paper documents the turbulence observations of a tropospheric profiler in two types of conditions, namely, intense convective weather and UATF associated with upper air trough / jet stream. Though the absolute magnitude of $EDR^{1/3}$ from the profiler does not appear to be particularly large, the occurrence of higher levels of $EDR^{1/3}$ is still useful for monitoring the occurrence of moderate or greater turbulence to be encountered by the aircraft in the terminal area and en-route phase. There are only limited number of pilot reports of turbulence in the Hong Kong flight information region so that the usefulness of the tropospheric profiler observations could only be studied with the accumulation of more cases. However, based on the limited cases so far, the $EDR^{1/3}$ profile so obtained is found to have the potential for monitoring upper level turbulence.

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