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1. INTRODUCTION

The Hong Kong International Airport (HKIA) at Chek Lap Kok (CLK) came into operation on 6 July 1998. It is located to the north of Lantau Island, a mountainous island with peaks rising to between 700 and 950 m above mean sea level (amsl) and saddle-like valleys with mountain passes as low as 350 to 450 m amsl (Figure 1).

When the prevailing wind is from east through southwest, HKIA lies downwind of Lantau Island. Numerous studies, including physical and numerical modeling studies, had been conducted before airport opening to study the effects of such flow on airport operation.

Physical modeling using water tank study in early 1980's suggested non-linear topographic waves occurring over a large range of conditions and having large vertical excursions. In the atmosphere, this would correspond to downflows with wind speed of the order of 10 ms^{-1} over a relatively short horizontal distance of a kilometer (Baines and Manins 1989).

Study in 1994 using research aircraft suggested the occurrence of terrain-induced turbulence in association with airflow over Lantau (Neilley et al. 1995). Two distinct mechanisms, gravity wave - critical level flow interaction and mechanically generated turbulence under deep uniform flow, were considered as the main causes for such terrain-induced turbulence.

Since airport opening, observational studies revealed complex low-level atmospheric flow downwind of Lantau, including shear lines, streaks of low-speed and high-speed flows, reverse flows, small-scale vortices, signatures of gravity wave as well as descending high-speed flows from mountain cols. This indicates that it is possible for significant terrain-induced windshear to occur downwind of Lantau in both deep uniform flow (Shun and Lau, 2000) and

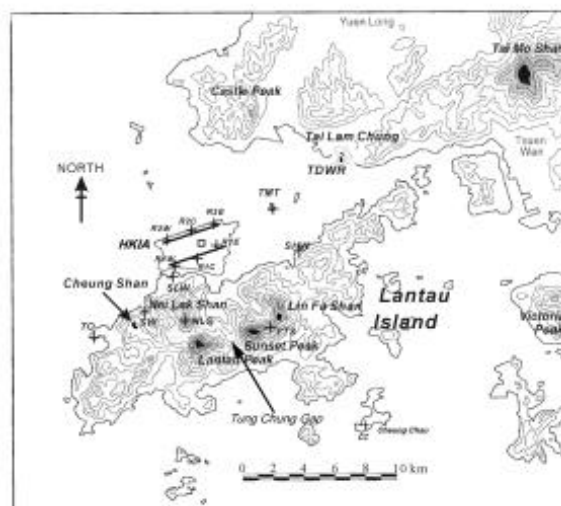


Figure 1 Map of HKIA and its surrounding areas. Terrain contours are in 100 m intervals.

stably stratified conditions (Lau and Shun, 2000).

This paper presents the TDWR observations obtained in deep-uniform flow during the passage of Typhoon Utor and compares them against the on-board data from an aircraft which had to conduct a go-around as a result of windshear and turbulence.

2. SYNOPTIC SITUATION

Typhoon Utor made landfall to east of Hong Kong in the morning of 6 July 2001 and soon weakened into a severe tropical storm (Figure 2). After landfall, it continued to move northwestward and passed about 100 km to the north of Hong Kong at 02 UTC (10 a.m. local time). As it departed, the gale force winds near its center also moved away from Hong Kong.

In the evening when Utor was well inland Guangdong about 200 km from Hong Kong, one of its outer rain bands and the associated gale force southerly winds started to affect HKIA. At the height of the episode, winds with 1-minute mean speed reaching 25 ms^{-1} and 1-minute gusts reaching 33 ms^{-1} were recorded at the airfield.

Figure 3 shows the vertical profile of wind and temperature at 12 UTC 6 July 2001 taken at King's Park Meteorological Station,

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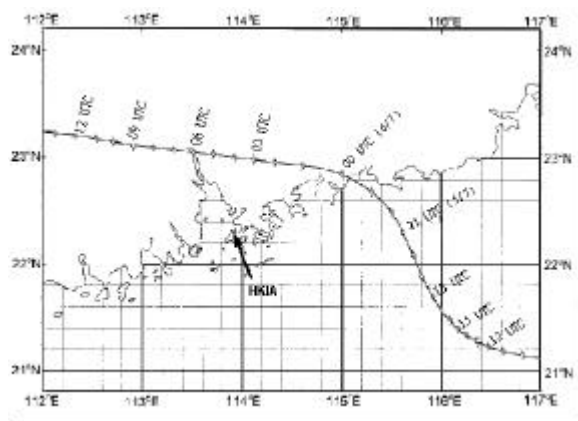


Figure 2 Track of Typhoon Utor.
(local time = UTC + 8h; 00UTC
means 8 a.m. local time)

about 25 km east of HKIA. It indicated southerlies extending all the way from surface to around 10 km. No low-level temperature inversion can be identified. The average Brunt-Väisälä frequency (N) is estimated to be about 0.135.

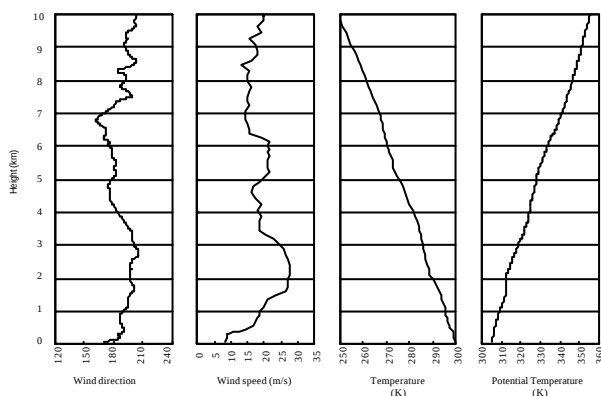


Figure 3 King's Park radiosonde ascent at 12 UTC
6 July 2001: (a) wind direction (degrees); (b) wind
speed (ms^{-1}); (c) temperature (K); and (d) potential
temperature (K).

As Utor moved away, local pressure gradually rose. However, on top of this rising trend, rapid fluctuations in the surface pressure were observed at SLW (see Figure 1 for location) resulting in pressure difference of more than 1 hPa between SLW and HKIA at times. Such a pressure difference could not be simply explained by the pressure gradient due to Utor considering the short distance between the two locations. Spectral analysis of the pressure difference between these two locations gives a periodicity of around 8 min, closely matching the period for buoyance-driven oscillation given by $2\delta/N$ of 465 s, or 7.8 min, suggesting that such fluctuations might be associated with gravity waves.

3. TERMINAL DOPPLER WEATHER RADAR (TDWR) OBSERVATIONS

As part of a suite of meteorological systems implemented to support the HKIA, the Hong Kong Observatory (HKO) installed a TDWR at Tai Lam Chung, about 12 km northeast of HKIA, for detecting microbursts and windshear associated with convective storms (Shun and Johnson 1995; Johnson et al. 1997).

Figure 4 shows the 2.4° elevation radial winds at 1341 UTC. Regions of positive (outbound) radial velocities can be clearly seen just downwind of the peaks. Further downwind, a streak of weak inbound radial wind (around 6 ms^{-1}) over the coast of Lantau can be clearly identified. Meanwhile, winds of up to 30 ms^{-1} were seen to emanate from the U-shape ridge over Lantau (streak-I associated with flow around the eastern flank of Lin Fa Shan (766 m), streak-II with Tung Chung Gap and streak-III with flow around the western flank of Lantau Peak (934 m) or Nei Lak Shan (751 m)) resulting in NNE-SSW oriented alternating streaks of low- and high-speed inbound radial velocities over the HKIA and its eastern approach. These streaks displayed wavy characteristics and were rather narrow with typical width of about 1-2 km (equivalent to 13-25 s of flight time assuming an approach speed of 80 ms^{-1}).

Similar low- and high-speed streaks were observed in the TDWR 0.6° (Figure 5) and 1.0° scans (not shown). However, the high wind streaks were much weaker at these lower elevations. The low and high-speed streaks at different elevations are fairly well aligned in the vertical. Take streak-II (associated with Tung Chung Gap) as an example. The 0.6° radar beam cut the streak (located around 6 km from the TDWR over the north runway) at a height of around 120 m amsl, lower than the height of Tung Chung Gap (~ 340 m). These relatively high winds at lower elevations must have been transported downward from aloft or drawn in from the sides.

To better understand the vertical structure and periodicity of these pockets, Hovmuller diagrams of radial velocity at location A (see Figure 4 for location) downwind of Sunset Peak (869 m) were constructed and are given in Figure 6. At location A, the most prominent feature is the jet core at around 1 km and the resulting strong vertical shear below it. The jet extended downwards at a period of around 8 min. This is consistent with the period derived from pressure difference between SLW and HKIA and

also the period of buoyance-driven oscillations. From the Hovmuller diagram, these waves only occurred below the jet core, suggesting that they might be trapped gravity waves. The jet subsequently lifted and broadened at around 1430UTC.

4. DATA ON-BOARD AIRCRAFT

Figure 7(a) and (b) show the wind direction and speed as measured on-board a B777 aircraft that penetrated the streaks on approach to northern runway from the east. As the plane exited streak-I at about 300 m, the wind speed dropped dramatically from 28 ms^{-1} to 16 ms^{-1} in 22 seconds. This resulted in 11 ms^{-1} loss in head wind and the plane soon had to conduct a go-around at 1344 UTC due to wind shear. As it pulled up, it encountered streak-II at around 600 m and the wind speed picked up rapidly to 32 ms^{-1} . The radial component derived from the on-board data agreed reasonably well with the TDWR observation.

It is of interest to note that the wind speed of 32 ms^{-1} recorded on-board the aircraft was higher than the wind speed upstream (around 25 ms^{-1} based on the winds recorded at Cheung Chau, see Figure 1 for location). This suggested that as a result of the constriction of the Tung Chung Gap, the flow might have transited from subcritical to supercritical.

To better understand the three-dimensional structure of the streaks, the vertical winds (Figure 7c) were estimated from the flight parameters (computed airspeed, pitch angle, roll angle and lateral acceleration) recorded on-board. The most striking feature is the rapid fluctuations in the vertical wind as the plane entered the wake of Lantau Island. Based on the estimated vertical wind, the downflow was indeed fairly strong in the low-speed streaks (with peak downdrafts up to 7 ms^{-1} and 10 ms^{-1} for the low-speed streaks associated with Sunset Peak and Lantau Peak respectively). While the atmosphere was near-neutral, the magnitude of the downflow encountered agreed fairly well with result from the water tank experiments (Baines and Manins, 1989). This suggests that the strong vertical motion might be associated with the downward motion of the trapped gravity wave.

6. DISCUSSION

Observations from the TDWR, aircraft and surface observation indicate that the flows downwind of the Lantau terrain are highly complex and three-dimensional.

From the TDWR analysis and the winds measured on-board the aircraft, the winds associated with the high-speed streaks were higher than upstream suggesting that the high-speed streaks had resulted from gap flows.

Hovmuller analysis of the radial velocity immediate downwind of the hills and spectral analysis of the surface pressure show clear periodicity in the radial velocity fluctuations. The period agrees fairly well with that estimated from buoyance calculation.

Although the atmosphere was near-neutral on this occasion, the similarity of the phenomena observed with the theoretical framework based on shallow-water theory suggested that further numerical studies using shallow-water model may be able to shed more light on the cause of the phenomena observed.

ACKNOWLEDGEMENTS

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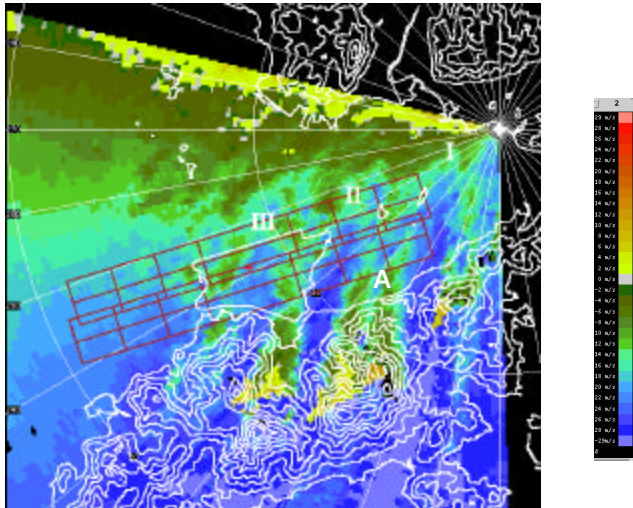


Figure 4 TDWR radial velocity display at 2.4° elevation at 1341 UTC 6 July 2001. Regions of positive (in yellow) radial velocities suggestive of return flow can be seen immediately downwind of the peaks. Further downwind, a streak with weak inbound radial wind (in green) can be identified. Meanwhile, high wind streaks (I, II and III) can be seen emanating from the U-shape ridge.

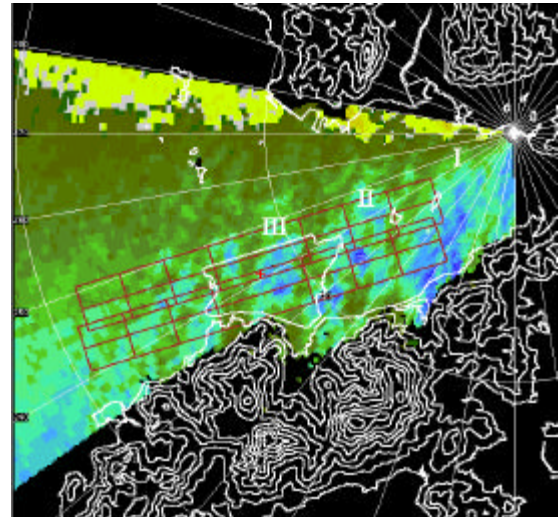


Figure 5 TDWR radial velocity display at 0.6° elevation at 1344 UTC 6 July 2001. Similar to its counterpart at 0.6° elevation, high-speed streaks can be seen to emanate from the U-shape ridge but were much weaker.

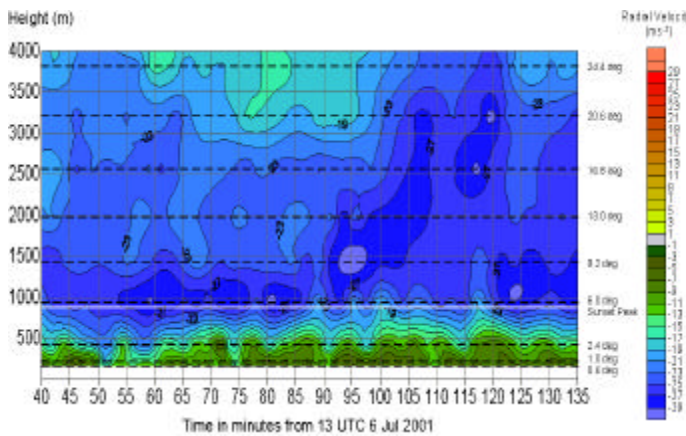


Figure 6 Hovmuller diagram of TDWR radial velocity at location A between 1340 – 1535 UTC 6 July 2001. The jet core occurred at around 1 km. Wave-like fluctuations with a period of around 8 min can be clearly identified below the core. The jet lifted and broadened at around 1430 UTC but then descended again at around 1500 UTC.

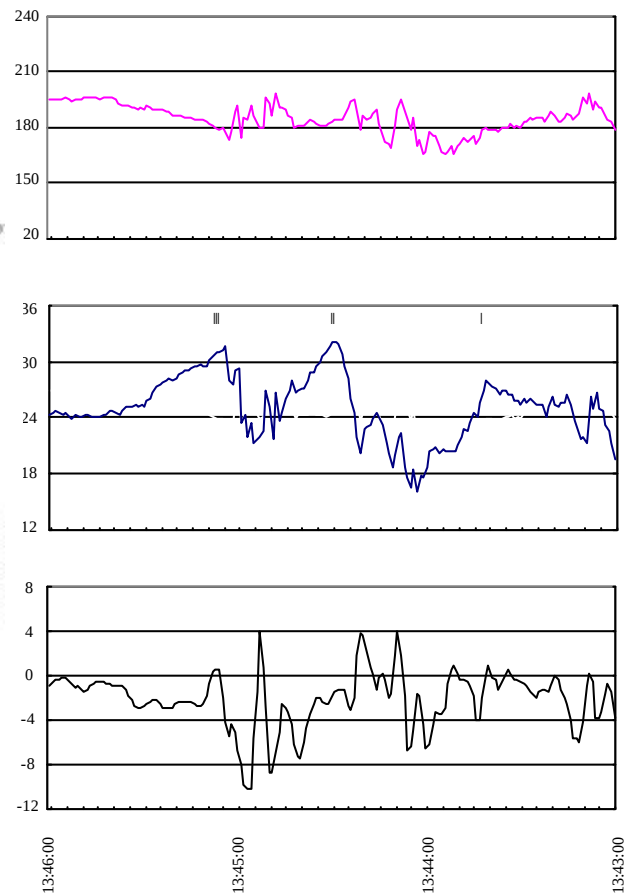


Figure 7 Aircraft data as it penetrated the streaks (marked I, II, III in Figure 4) on approach to HKIA. (a) wind direction (degrees) (b) wind speed (ms^{-1}) (c) 3-second averaged vertical wind (ms^{-1}).