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OBSERVATION OF TERRAIN-INDUCED WINDSHEAR AROUND HONG KONG INTERNATIONAL AIRPORT UNDER STABLY STRATIFIED CONDITIONS

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1. INTRODUCTION

The new Hong Kong International Airport (HKIA) at Chek Lap Kok (CLK) came into operation on 6 July 1998. The airport has two parallel northeast-southwest oriented runways designated as RWY 07L/25R and RWY 07R/25L. As part of a comprehensive set of meteorological systems implemented to support the HKIA, the Hong Kong Observatory (HKO) installed a Terminal Doppler Weather Radar (TDWR) for detecting microbursts and windshear associated with convective storms (see Shun and Johnson 1995; Johnson et al. 1997).

Lantau Island, immediately south of the HKIA, is quite mountainous. Figure 1 illustrates the complex terrain of Lantau Island and location of the HKIA. The northeast-southwest oriented island has a width of about 5 km and length of about 20 km. In the middle of Lantau, Nei Lak Shan (NLS), Lantau Peak (LP) and Sunset Peak form a U-shape ridge. These peaks rise to between 700 and 950 m above mean sea level (amsl) with valleys as low as 350 to 450 m amsl separating these peaks. To the southwest of this U-shape ridge, a northeast-southwest oriented ridge rises to between 400 and 500 m amsl at many locations along the ridge line.

Study in 1994 using research aircraft had 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 attributed as the main causes of such terrain-induced turbulence.

Pilot reports received since opening of the HKIA indicated that, apart from terrain-induced turbulence, significant terrain-induced windshear could also occur downwind of Lantau in both deep uniform flow and stably stratified conditions. An account of the former phenomenon during the passage of a tropical cyclone based on observations of the TDWR was given in Shun (1999).

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

This paper gives an account of the windshear encountered by several aircraft on 8 March 1999, a typical case of terrain-induced windshear under stably stratified conditions, and the observations made by the TDWR and other meteorological equipment specially installed around the HKIA.

2. SYNOPTIC SITUATION AND PILOT REPORTS

A cold front crossed the south China coast early on 8 March 1999. On the surface, a ridge of high pressure extended from east China to the south China coastal areas behind the front (Figure 2). As a result, fresh to strong surface easterlies and apart from some rain recorded in the early hours cloudy weather affected CLK the whole day.

The surface easterlies gradually veered with height to become southeasterlies at 925

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hPa and southwesterlies at 850 hPa. The 12Z (20H local time) radiosonde ascent on 8 March 1999 at King's Park, around 25 km east of CLK, revealed shallow low-level inversions at around 750 m (0.2°C) and 1,940 m (1.0°C) (Figure 3) which corresponded to the respective local maxima of N^2, N being the Brunt-Väisälä frequency.

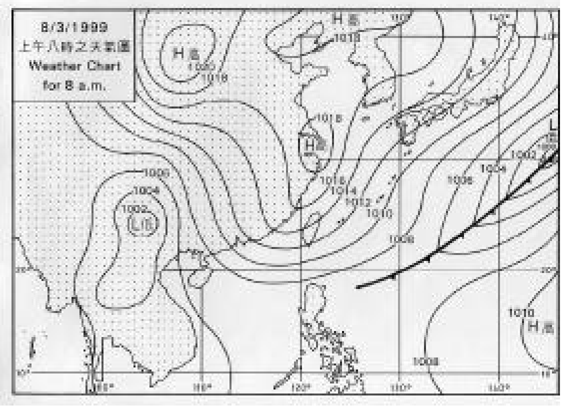


Figure 2 Surface synoptic map valid at 00Z 8 March 1999

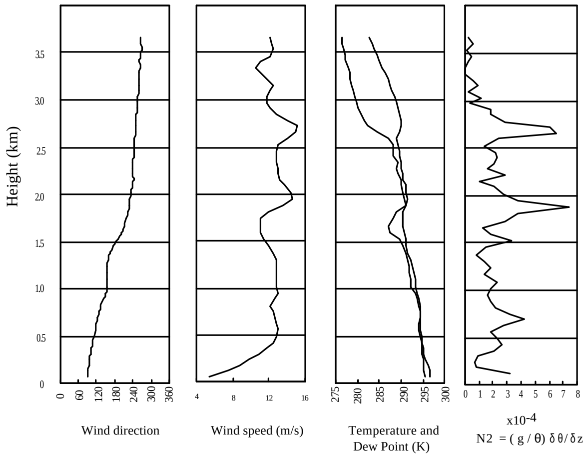


Figure 3 Variation of wind direction, speed, temperature, dew point and N^2 based on the King's Park radiosonde ascent valid at 12Z 8 March 1999

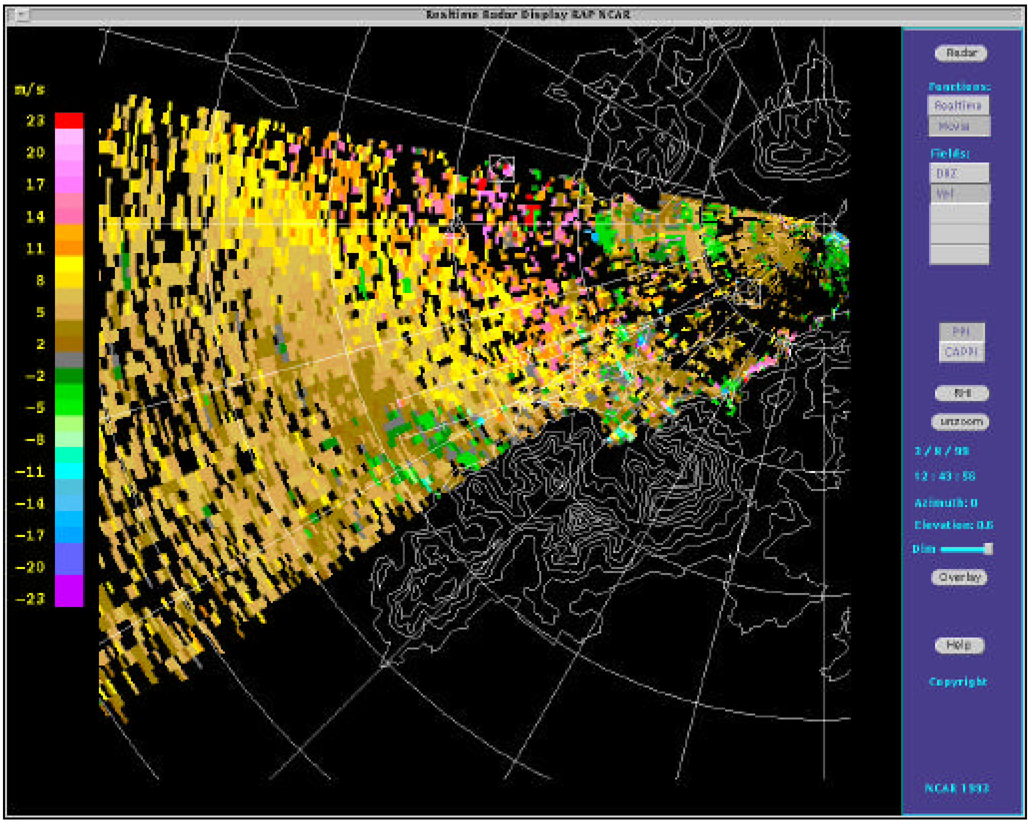
A number of pilots of aircraft landing at HKIA reported encountering windshear after 12Z on this day. In particular, at around 1230Z, a pilot reported +20 kt and then –20 kt windshear on approach to RWY 07R (i.e. approach from the west-southwest) and conducted a go-around. The plane finally landed at around 1243Z. The following aircraft, first attempted to land at 1232Z, finally diverted to Macau after encountering up to 20 kt windshear on final approach.

3. EVIDENCE FOR COMPLEX MOUNTAIN WAKE FLOW BRINGING WINDSHEAR TO AIRCRAFT

The TDWR is strategically located at Tai Lam Chung, about 12 km northeast of CLK so that it has a clear view of the runways, airport approach and departure areas. To avoid beam blockage by nearby ships, the antenna of the TDWR was installed at about 60 m amsl. The TDWR has a half-power beamwidth of 0.55° and operates a highly stable klystron based amplifier which allows clutter suppression of up to 55 dB. Although the TDWR was designed to detect microbursts and windshear associated with convective storms, it is highly sensitive and can provide high-resolution data under certain favourable clear air conditions. Clear air data from the TDWR were examined for the possible cause of the pilot reported windshear.

At 1137Z, the Doppler radial winds from the TDWR 0.6° Plan Position Indicator (PPI) scan (the lowest elevation scan) over the HKIA and its western approach were generally away from the radar (positive radial velocity – in warm colours on TDWR display) consistent with the low-level east-southeasterly flow. However, at about 3 nm (nautical miles) from the RWY 07R threshold, the radial winds away from the radar were apparently weaker. This area of weaker positive radial winds became more prominent gradually and streaks of radial winds *towards* the radar (negative radial velocity – in cold colours on TDWR display) were seen downwind of NLS and Cheung Shan (CS) from time to time (see Figure 4 for the TDWR 0.6° PPI scan Doppler radial winds valid at 1243Z 8 March 1999 and Figure 1 for locations of NLS and CS). These streaks were rather narrow with typical width of about 1 km (equivalent to 13 seconds of flight time assuming an approach speed of 150 kt), but at times, they joined together to form a larger area of radial winds *towards* the radar. Similar features were detected by the TDWR 1.0° PPI scan (the second lowest elevation scan, not shown).

The 2.4° PPI scans of the TDWR during the same period revealed a general veering of winds with height, similar to the radiosonde profile at King's Park. However, a streak of radial winds *towards* the radar could be seen downwind of NLS and LP in the background of radial winds away from the radar (Figure 5). This streak of negative radial velocity displayed unsteady wave-like behaviour in animation sequence of the 2.4° PPI scans at 5-minute update rate. Previous studies have shown that non-dimensional ridge height, Nh/u, is a good



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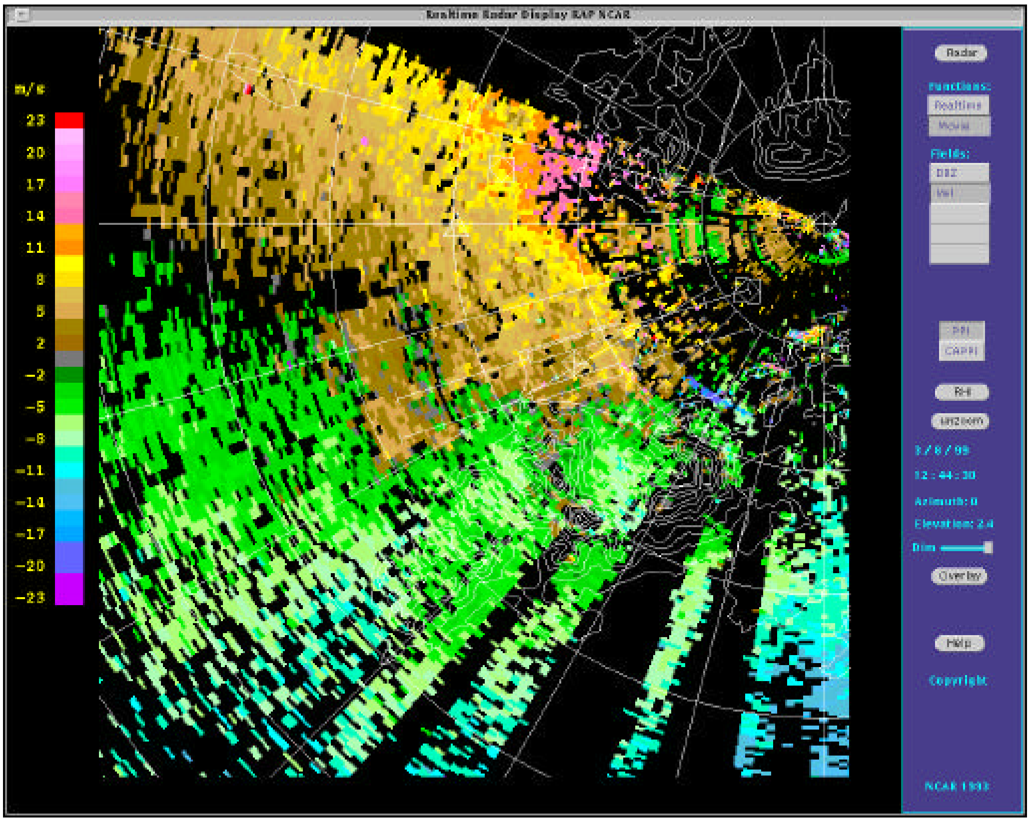
12 : 43 : 58

Azimuth: 0

Elevation: 0.6

Figure 4 TDWR 0.6◦ PPI scan Doppler radial winds valid at 1243Z 8 March 1999



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12 : 44 : 30

Azimuth: 0

Elevation: 2.4

Figure 5 TDWR 2.4◦ PPI scan Doppler radial winds valid at 1244Z 8 March 1999 indicator of the characteristics of the wake. Using the height of NLS (h=750m) and LP (h=900m), the average Brunt-Väisälä frequency from surface to the height of LP (N=0.014) and a cross-mountain component of 10 ms^{-1} - averaged cross-mountain component between 400 to 900m, the non-dimensional ridge height so calculated ranges between 1.05 to 1.26. Baines (1995) noted asymmetric obstacles were often observed to have unsteady, periodic vortex-street-type wakes when Nh/U > 1, containing eddies shed alternately from lines of separation on each side of the obstacle. As the mountains over Lantau are highly asymmetric, the wakes so generated should be unsteady.

More prominent streaks that displayed similar unsteady wave-like behaviour downwind of the Lantau terrain were also identified in studying the 2.4° PPI scans of the TDWR during the passage of a tropical cyclone (Shun, 1999). In that study, TDWR data with higher update rates (approximately 2.5 minutes for 2.4° PPI scans and 1 minute for 0.6° PPI scans) were available in the TDWR "Hazardous Weather" mode and the strong southwesterly flow associated with the tropical cyclone contributed a much larger radial wind component to the TDWR Doppler observations, allowing a more detailed examination of the behaviour of the streaks. It was suggested that these streaks might be von Kármán vortex streets resulting from vortex shedding in the wake of the Lantau terrain. This suggestion was supported by observations of very strong gap flows emanating from the valleys between the peaks of Lantau and significant reverse flows just on the lee side of the Lantau peaks in the same data set. We believe that the streak of radial winds *towards* the radar observed downwind of NLS and LP in the present case is similar to those described in Shun (1999) but the lower TDWR data update rate (essentially 5 minutes for all scans) in the TDWR "Monitor" mode and the weaker southeasterly flow contributing less radial wind component to the TDWR Doppler observations in this case precluded more detailed analysis.

As on-board aircraft data from the two flights that conducted go-arounds were not available to the HKO, the current study made use of data from a later flight arriving at 1252Z. The aircraft observed winds were basically southeasterlies as the flight descended from 2,300 ft to 1,350 ft amsl (7 to 4 nm from touchdown) (Figure 6). The wind direction then varied significantly, veering to southwest and then northwest as the wind speed dropped markedly to below 5 kt. As the plane continued its descent, the wind direction again changed significantly to northeast at about 800 ft amsl (2.5 nm from touchdown) before veering to

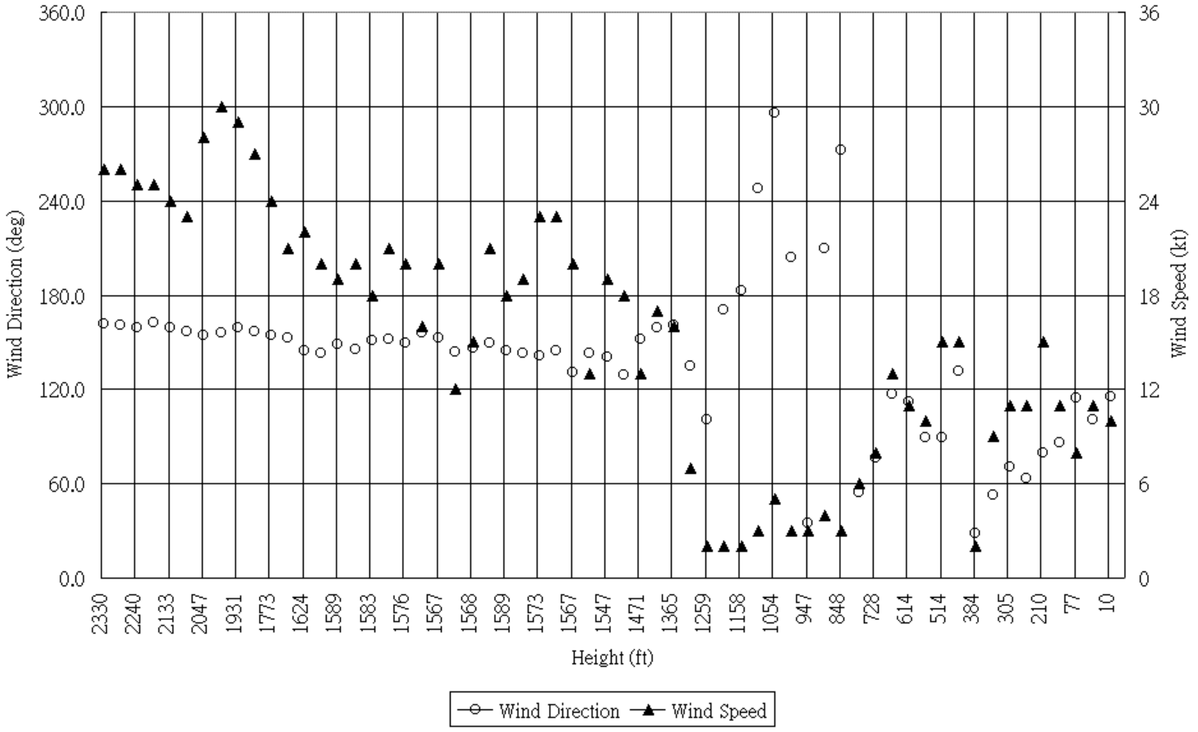

Figure 6 On-board aircraft observed wind direction and speed against the radio height. Data were available every 4 seconds.

southeast as the wind speed increased to 10 to 15 kt.

The aircraft data thus confirmed the existence of mountain wake with reverse flow (albeit weak) downwind of the northeast-southwest oriented ridge southwest of NLS. Although this ridge is not as high as the major peaks of the U-shape ridge, it reaches 400 m (1,300 ft) amsl at many locations along the ridge line and is therefore sheltering the flight path from the prevailing southeasterlies within 4 nm from touchdown. So the scenario may be as follows. Before the aircraft came within this wake region, it was exposed to the prevailing strong southeasterlies aloft which brought significant cross-wind and some head wind to the aircraft. As the aircraft came within this wake region, the aircraft experienced a loss of head wind as the wind subsided and the wind direction fluctuated significantly. Although the wind direction made a full 360° cycle when the aircraft was about 1,000 ft amsl, detailed analysis of aircraft data (not shown) indicates that the aircraft had probably traversed several small-scale weak vortices rather than a large one. The above is consistent with what was observed on the TDWR 0.6° PPI scans.

At about 650 ft amsl, there was a sudden increase of the aircraft observed winds from the east and southeast. This increase of the winds from the east and southeast brought a gain in head wind to the aircraft. The previous loss of head wind and this gain of head wind by the aircraft apparently marked the beginning and end of the wake of the ridge southwest of NLS. Although it is unclear where exactly this east to southeasterly flow originated from, judging from the fact that the aircraft was downwind of the valley at Sham Wat between NLS and CS at this location, it is reasonable to suggest that it was related to the complex flows around NLS and CS.

As the aircraft further descended to about 450 ft amsl, the aircraft observed winds subsided momentarily, backed to the northeast and then strengthened from the east-southeast again shortly before the aircraft landed. This consecutive decrease and increase of winds brought another pair of head wind loss and gain to the aircraft, apparently resulting from the effects of another mountain wake region. In view of the small horizontal scale traversed by the aircraft (estimated to be about 1.5 km or less) and the fact that the aircraft was downwind of NLS during this period, it is likely that this second wake was associated with NLS or its finer scale structures.

Apart from the streaks of complex flow associated with the different wake regions of the complex terrain over Lantau observed by the TDWR and aircraft, strong updraughts of up to 3 ms^{-1} between 2,800 and 3,500 ft amsl around the time of the reported windshear events were detected by a wind profiler at Sha Lo Wan (Figure 7), located just to the south of the threshold of RWY 07R. Further studies are required to determine whether these updraughts are also observed in similar windshear events and how they are related to the flows associated with the wake regions of the Lantau terrain.

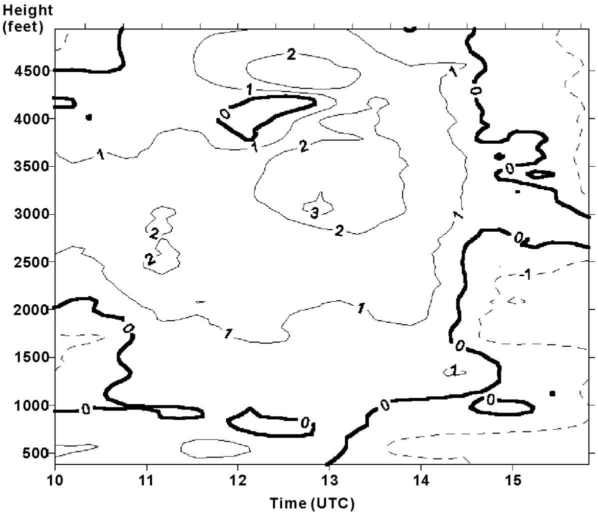

Figure 7 Vertical winds detected by Sha Lo Wan profiler between 10-15Z 8 March 1999. Updraughts (in ms^{-1}) are positive.

Although there were numerical and observational studies of mountain wake of isolated islands, such as the wake of St. Vincent (Smith et al., 1997), Hawaii's wake (Smith and Grubisic, 1993), vortices downwind of Hawaii (Nickerson and Dias, 1981) and flow structure around Ailsa Craig (Jenkins et al., 1981), few had the benefit of having high resolution information (in both space and time) from ground based remote sensing equipment such as the TDWR and wind profiler. The availability of on-board data from commercial aircraft served to confirm the existence of the wake and reverse flow and further our understanding of the flow downstream of the complex Lantau terrain.

4. CONCLUSION

Observations from the TDWR, aircraft and wind profiler indicate that the flows associated with the wake regions of the Lantau terrain are highly complex, three-dimensional with interactions on different scales. The wakes of the individual peaks of Lantau probably interacted with each other and manifested themselves in the form of unsteady streaks or even vortex shedding as suggested by the TDWR data.

The availability of dense network of meteorological equipment around the HKIA and data from commercial aircraft offered a suitable platform for systematic observation of mountain generated wakes.

Ongoing studies are being conducted to better understand the cause, interactions and behaviour of these wakes with the view to further improve the existing windshear and turbulence warning facilities and services for the HKIA.

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