11.2 LIDAR OBSERVATIONS OF WIND SHEAR INDUCED BY MOUNTAIN LEE WAVES

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1. INTRODUCTION

Shun et al (2003a) documented weather radar observations of periodic shedding of vortices, velocity streaks and gap-related descent of high-speed flow caused by the complex terrain of Lantau Island to the south of the Hong Kong International Airport (HKIA) during the passage of tropical cyclones. Shun et al (2003b) reported LIDAR (LIght Detection And Ranging) observations of suspected cases of hydraulic jump and complex wind flow in clear-air wind shear conditions. In this paper we present recent Doppler LIDAR observations of standing lee waves induced by the Lantau terrain which could result in wind shear to departing aircraft flying through them. In particular, both the Doppler radial velocity and backscatter returns at 4.5 degrees elevation reveal an interesting zig-zag pattern (refer to the right hand side of Figures 1 and 2) attributed to the lee waves. The wind flows revealed by the LIDAR at the lower elevation angles of 1.0 degree (Figure 3) and 0.0 degree (Figure 4) are however rather different due to the complexity of the Lantau terrain. Figure 5 shows the location of HKIA relative to the nearby terrain and the weather sensors in the area.

Hong Kong implemented a LIDAR at HKIA in mid-2002 to enhance the detection and warning of wind shear under clear-air conditions. Making use of azimuthal scans at three different elevation angles, the three-dimensional structure of the complex flow resulting in the zig-zag pattern will be analysed and diagnosed in this paper. We will also compare this case with a previous one on 17 March 2000 in which

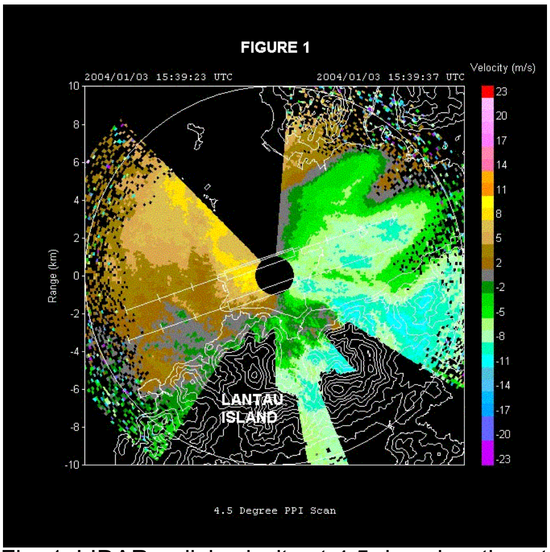

Fig. 1. LIDAR radial velocity at 4.5 deg elevation at 15:40 UTC on 3 Jan 2004.

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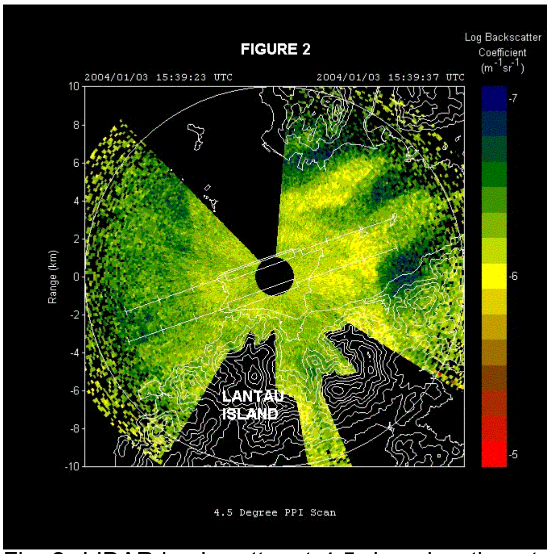

Fig. 2. LIDAR backscatter at 4.5 deg elevation at 15:40 UTC on 3 Jan 2004.

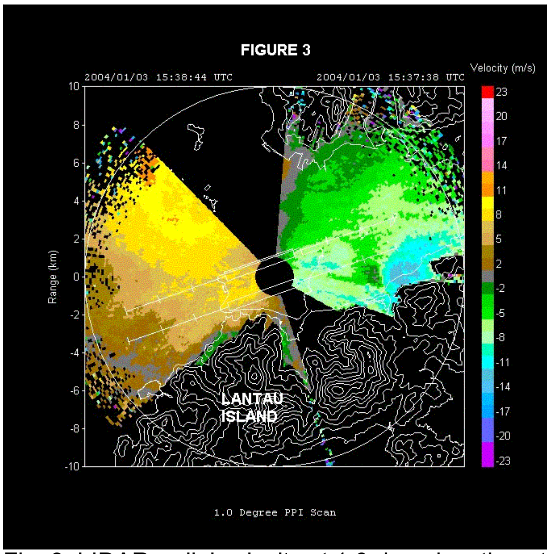

Fig. 3. LIDAR radial velocity at 1.0 deg elevation at 15:39 UTC on 3 Jan 2004.

a similar zig-zag pattern was depicted by a weather radar. On that day, numerous wind shear reports with magnitudes of up to +35 kt (18 ms^{-1}) headwind change were received from aircraft. In the following sections, we will try to relate the observed phenomena with the presence of low-level inversion and characteristics of the vertical wind profiles. Aircraft data from commercial flights for these cases, where available, will be analyzed.

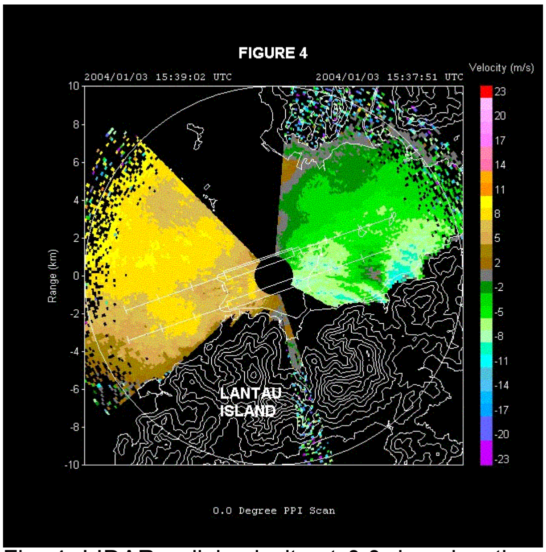

Fig. 4. LIDAR radial velocity at 0.0 deg elevation at 15:39 UTC on 3 Jan 2004.

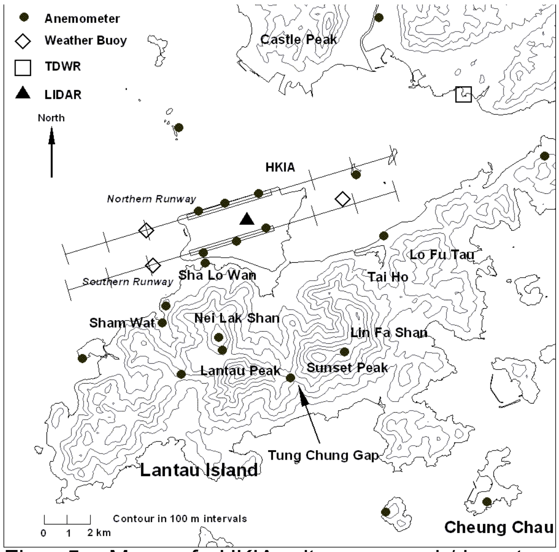

Fig. 5. Map of HKIA, its approach/departure corridors and surrounding areas. Terrain contours are given in 100 m intervals.

2. LEE WAVES OBSERVED ON RADAR

On 17 March 2000, strong easterly winds prevailed over HKIA and the surface winds veered with height to southeasterlies over the hilltops of Lantau (Figure 6). A strong inversion of about 3 °C and a low-level jet of 15 ms^{-1} could be identified just below 1000 m from the 00 UTC radiosonde ascent at the King's Park Meteorological Station, some 25 km east of HKIA. This is known to be a typical wind shear conducive situation in springtime and indeed a total of 48 wind shear reports were received from aircraft on that day. From the on-board flight data of an aircraft that reported wind shear a few minutes after the time of Figure 6, we found that the headwind decreased by around 30 kt between 1500 ft (460 m) and 3400 ft (1040 m). This headwind decrease corresponded well with the simultaneous abrupt veering of wind direction, decrease of wind speed and increase of temperature at around 2000 ft (610 m) and again at just above 3000 ft (910 m) (Figure 7). Furthermore, a zig-zag pattern with horizontal wavelength of around 3 km, similar to that observed in Figure 1, was intermittently (due to lack of clear-air return) observed by the Terminal Doppler Weather Radar (TDWR) within the same region east of the airport on the same day (refer to the upper right hand side of Figure 8). The zig-zag pattern was attributed to a lee-wave train induced by the Lantau terrain, notably the small 465 m hill named Lo Fu Tau (see Figure 5 for its location). A schematic drawing illustrating the concept of a lee-wave train as observed by the TDWR is given in Figure 9. The concept was that at the lee-wave trough position, airstream from aloft the inversion with higher potential temperature and more southerly component (thus bringing crosswind or even tailwind to the aircraft) was brought downward to a lower altitude where airstream with lower potential temperature and more easterly component (thus bringing headwind to the aircraft) still prevailed at the lee-wave ridge position. This would create a horizontal shear for aircraft traversing the lee wave. The temperature inversion just below 1000 m as noted earlier from the radiosonde ascent was relevant to the generation of

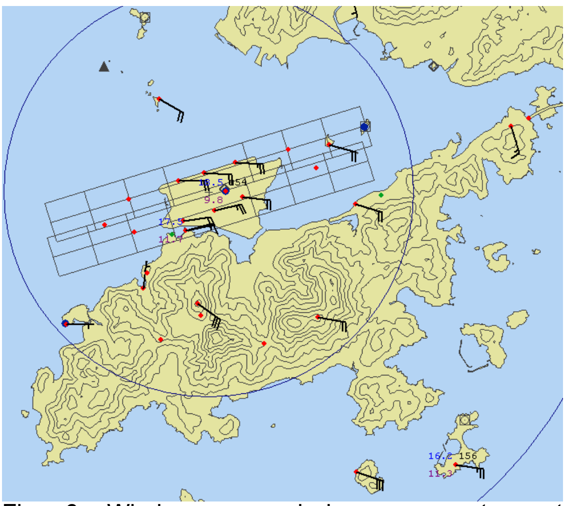

Fig. 6. Winds measured by anemometers at 02:30 UTC on 17 Mar 2000.

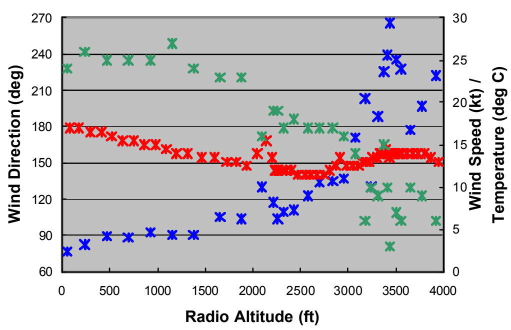

Fig. 7. Wind direction (blue), wind speed (green) and temperature (red) profiles measured by a flight departing on the southern runway at 02:31 UTC on 17 Mar 2000.

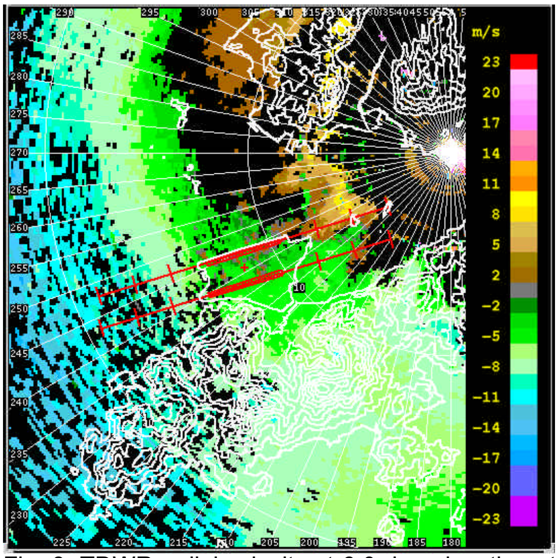

Fig. 8. TDWR radial velocity at 6.0 deg elevation at 07:14 UTC on 17 Mar 2000.

the lee waves. Following the classic theory of Scorer (1949), lee-wave trapping was possible considering a decrease of Scorer's parameter with height between 650 m and 1100 m. See Section 4 on further discussion on wave trapping.

3. LEE WAVES OBSERVED ON LIDAR

With the installation of the Doppler LIDAR at HKIA in mid-2002 and its continuous operation since then, more data in clear air has become available for better understanding of the complex terrain-induced flow in the vicinity of the airport, especially during the wind shear peak season in spring. At 15:09 UTC on 3 January 2004, a 15-knot headwind loss shear was reported at a height of 600 ft (180 m) by a flight departing on the southern runway. Surface winds were moderate easterly veering to southeasterly at hilltops of Lantau. Review of the LIDAR Doppler radial velocity imageries at 4.5 degrees elevation around the time of the event revealed the presence of an almost stationary zig-zag pattern from 15 UTC to 17 UTC (see Figure 1). This zig-zag pattern, which closely resembles that observed by radar on 17 Mar 2000 (Figure 8), was apparently located downwind of Lo Fu Tau and the adjacent ridge to its northeast. At

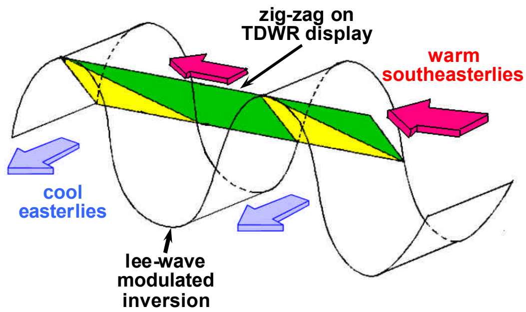

Fig. 9. Schematic drawing showing the lee-wave train as observed by the TDWR as a zig-zag pattern in Fig. 8.

the same time, the LIDAR backscatter (a measure of the aerosol concentration in the atmosphere) at 4.5 degrees elevation (see Figure 2) showed the same zig-zag pattern. The King's Park radiosonde ascent at 12 UTC revealed that there were two weak temperature inversions of 0.5 / 0.3 °C at about 1600 ft (490 m) / 2100 ft (640 m) and the surface visibility at HKIA was 6-7 km, suggesting the trapping of aerosols which brought the reduced visibility under the inversions. The LIDAR backscatter imageries strongly indicate that "cleaner" air with less aerosol concentration above the inversion was brought downward at the lee-wave troughs causing the same zig-zag pattern as revealed by the LIDAR radial velocity imageries. This corroborates the conceptual model in Figure 9.

Figures 10 and 11 show the temperature and wind direction profiles measured by six flights departing on the southern runway between 14:53 UTC and 17:05 UTC on 3 Jan 2004. Considering the typical 6-degree glide path for departure flights towards east-northeast (070 degrees) and the zig-zag pattern in Figure 1, these aircraft would intercept the lee-wave train at horizontal distances of several kilometres (and at altitudes of several hundred metres) after take-off. Measurements of the radiosonde ascent at 12 UTC are indicated in red in Figures 10 and 11 for comparison. The flights consistently measured marked temperature increases of 2-3 °C and simultaneous veering of the wind direction from 110

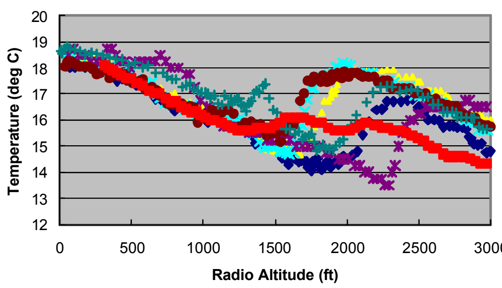

Fig. 10. Temperature profiles measured by six departure flights between 14:53 UTC and 17:05 UTC on 3 Jan 2004. Measurements by the radiosonde ascent at 12 UTC are indicated in red.

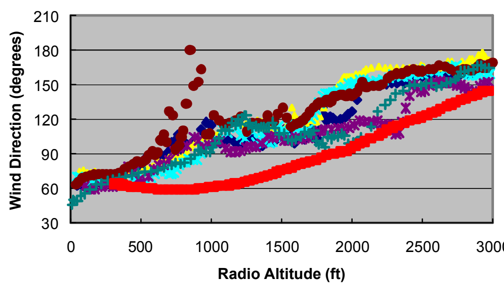

Fig. 11. Wind direction profiles measured by six departure flights between 14:53 UTC and 17:05 UTC on 3 Jan 2004. Measurements by the radiosonde ascent at 12 UTC are indicated in red.

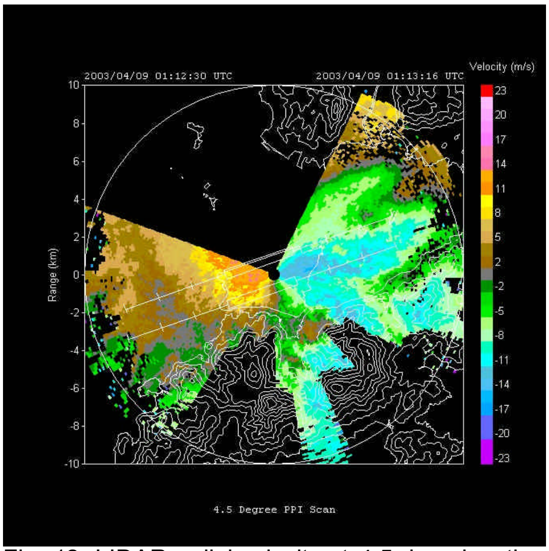

Fig. 12. LIDAR radial velocity at 4.5 deg elevation at 01:13 UTC on 9 Apr 2003.

degrees to 160 degrees between 1700 ft (520 m) and 2600 ft (790 m), again corroborating the conceptual model in Figure 9. The temperature increases are apparently larger than those associated with the temperature inversions measured by the radiosonde ascent, strongly suggesting enhancement associated with the lee-wave train. The marked wind direction veering between 520 m (1700 ft) and 790 m (2600 ft) is in good agreement with the LIDAR radial velocity pattern at 4.5 degrees elevation (Figure 1) and could cause headwind loss of 15 kt or more to departing aircraft if the wind speed was strong enough. For example, considering the flight direction of 070 degrees, a 20 kt wind at 110 degrees veering to a 20 kt wind at 160 degrees would cause the headwind to drop from 15 kt to zero. Indeed a review of past wind shear cases reported over the same departure corridor on 9 April 2003 identified a very similar zig-zag pattern on the LIDAR (Figure 12). A departing aircraft reported a headwind loss of 15 kt between 900 ft (270 m) and 2000 ft (610 m) 4 minutes after the time of Figure 12, with 20-kt winds veering from 90 to 140 degrees and temperatures increasing from 17 to 21 °C.

In Figure 11, one of the flight profiles (coloured in brown) shows a large veering of wind direction to 180 degrees below 1000 ft (300 m). This was probably due to a transient wind disturbance downwind of Lin Fa Shan (see its location in Figure 5) but a detailed analysis of this feature is beyond the scope of the present paper.

Due to the complexity of the terrain, the LIDAR radial velocity imageries at the lower elevation angles (see Figures 3 and 4) reveal quite different patterns compared with that at 4.5 degrees (Figure 1). Both the 1.0 and 0.0 degree elevation imageries indicate the presence of relatively strong easterly flow downwind (i.e. to the northwest) of Lo Fu Tau with an area of weak reverse flow in between. This appears rather similar to a jump feature with reverse flow downwind of Lo Fu Tau previously discussed by Shun et al (2003b). In the present case of 3 January 2004, the Froude number (Fr) = $U_0 / (g'D)^{½}$ is estimated at 0.8 taking $U_0 \approx 6$ ms^{-1}, $g' = g\Delta\theta/\theta = 0.1$ ms^{-2} with θ = 292 K, and D ≈ 530 m. Together with the dimensionless mountain height M = h/D ≈ 0.9 for Lo Fu Tau, this Fr value falls into Regime IIb of Schär and Smith (1993), viz. wake regime associated with the formation of a hydraulic jump including reverse flows in the wake. We note further for the adjacent ridge northeast of Lo Fu Tau, h < 300 m and thus M < 0.57. The Fr value of 0.8 therefore just falls into Regime IIa of Schär and Smith (1993), viz. wake regime associated with the formation of a hydraulic jump with no reverse flow, consistent with the fact that reverse flow could not be identified in Figures 3 and 4 downwind (i.e. to the northwest) of that ridge.

4. WAVE TRAPPING

To better understand why wave trapping occurred in the weather conditions on 3 January 2004, we attempt to estimate the Scorer's parameter (l) given by (Scorer, 1949):

$$l^2 = (N(z) / U(z))^2 - U_{zz} / U \qquad (1)$$

where N = Brunt-Väisälä frequency
U(z) = cross-mountain wind speed profile
U_{zz} = second derivative of U with height z

Chan and Tam (1996) had previously applied Scorer's parameter in a study of trapped lee waves and Foehn effect over Lantau Island to explain temperature differences observed at surface stations up- and downwind of Lantau. In the present case, we note from the radiosonde ascent at 12 UTC that the wind speed only increased gradually between 4 and 7 ms^{-1} in the lowest 1000 m and so the second term in (1) may be ignored. To represent the upstream profile for Lantau Island, we construct an idealized wind profile taking into consideration the radiosonde ascent data, surface and hilltop anemometer data (see Figure 13) and aircraft data. The idealized profile assumes that the wind speed was uniform (≈ 6 ms^{-1}) and the wind direction veered linearly from 90 to 160 degrees below 1000 m. N is computed from the potential temperature profile from the radiosonde ascent. The cross-mountain component is relative to the direction of 145 degrees considering the orientation of Lo Fu Tau together with the adjacent ridge to its northeast (see Figure 5).

Figure 14 shows the estimated vertical profile of the first term of Scorer's parameter (l) which reveals two sharp interfaces with transitions of l from large to small values: (i) from l_1 (0.0053 m^{-1}) at 470 m to l_2 (0.0017 m^{-1}) at 570 m; and (ii) from l_3 (0.0044 m^{-1}) at 640 m to l_4 (near zero) around 800 m. These suggest that, following Scorer (1949) and Baines (1995), lee waves with wavelengths between $2\pi/l_1$ (1200 m) and $2\pi/l_2$ (3700 m) would be trapped by the first interface whereas all wavelengths would be trapped by the second interface (l_4 being near zero). In other words, the lee-wave train revealed by the LIDAR, having a wavelength of around 4 km, would be trapped below 800 m but not below 570 m. This is consistent with the LIDAR and aircraft observations presented in Section 3. We further note that the

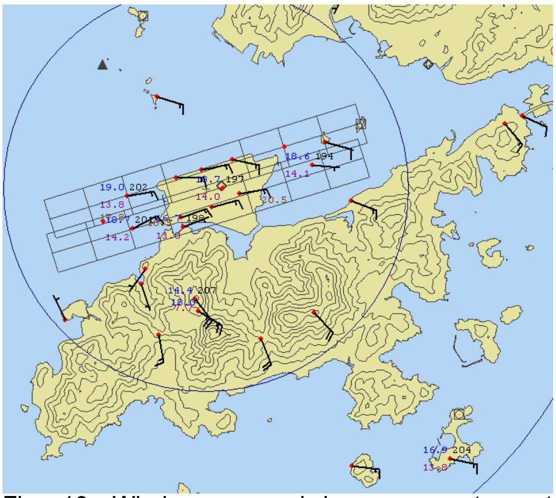

Fig. 13. Winds measured by anemometers at 15:40 UTC on 3 Jan 2004.

relationship for wave occurrence in the 2-layer model of Scorer (1949):

$$L_1^2 - L_2^2 > \pi / 4h^2 \qquad (2)$$

is satisfied with $L_1 \approx 0.0026\ m^{-1}$ (mean Scorer's parameter below 800 m), $L_2 = l_4 \approx 0$ at $h \approx 800$ m and ignoring the variations above 800 m (see the 2-layer L profile marked in red in Figure 14). Similar profiles of Scorer's parameter (i.e. with sharp decreases with height to near zero values) are found near or below 1000 m for both the 17 March 2000 and 9 April 2003 cases. Further studies are however required to explain the apparent difference in the observed wavelengths in the 17 March 2000 case (3 km) and in the 3 January 2004 and 9 April 2003 cases (4 km) and to ascertain whether the observed wavelengths could be quantitatively obtained from the Scorer's parameter profiles.

5. CONCLUSIONS

With the above analysis, we found that the theory of trapped lee waves was able to explain the zig-zag patterns revealed by LIDAR and TDWR data. We showed that these trapped lee waves could cause wind shear to aircraft departing from HKIA in typical springtime easterly situations, in addition to other terrain-induced flow mechanisms that have already been identified (notably gap-related flow, vortex shedding, and hydraulic jump). Using only the first term of Scorer's parameter, we suggest that the temperature inversion was the primary mechanism for the lee-wave trapping. Further studies are however required to quantitatively explain the observed wavelengths.

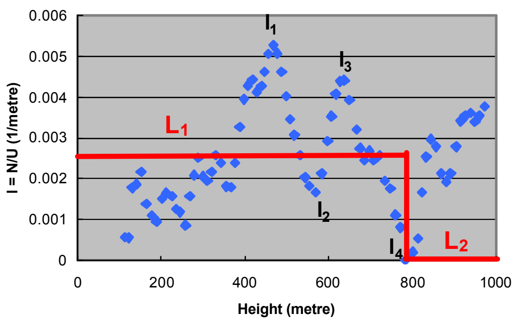

Fig. 14. Estimated vertical profile of the first term of Scorer's parameter (l). Red lines show the simplified 2-layer model discussed in Section 4.

6. ACKNOWLEGMENTS

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