MONITORING AND OBSERVATION OF FÖHN WIND IN HONG KONG USING A MULTI-CHANNEL, GROUND-BASED MICROWAVE RADIOMETER

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Abstract: The performance and application of a multi-channel, ground-based microwave radiometer in the monitoring of Föhn wind was studied in an experiment conducted in Hong Kong in 2004. Three scanning modes (zenith, elevation and 15-degree elevation) were tried out for the radiometer to monitor the low-level temperature inversions upwind of the hills. Thermodynamic profiles retrieved from the zenith mode compared the best with the radiosonde measurements. For inversions associated with low clouds, an empirical method based on saturation temperature appeared to improve temperature retrieval. When placed downwind of the hills, the radiometer captured very well the warming and drying of the boundary layer as a result of Föhn wind. The frequency spectrum of the brightness temperature from the radiometer was found to follow a -5/3 law. A quantity dervied from the spectrum turned out to vary in a manner similar to the intensity of air turbulence in a strong Föhn wind case.

***Keywords** – microwave radiometer, Föhn wind, turbulence, windshear*

1. INTRODUCTION

Föhn wind occurs at the Hong Kong International Airport (Figure 1) after strong southeasterly winds climb over the mountainous Lantau Island (with peaks of about 1 km AMSL) south of the airport in a stably stratified boundary layer. It is known to be associated with the occurrence of windshear and turbulence at the airport (Shun et al. 2003). Whilst the upper-air dynamics of the Föhn wind is continuously monitored by a wind profiler network in Hong Kong and a Doppler Light Detection and Ranging system at the airport, the thermodynamic profile is only available from the twice-daily radiosonde measurements at King's Park (Figure 1), located at about 25 km east of the airport.

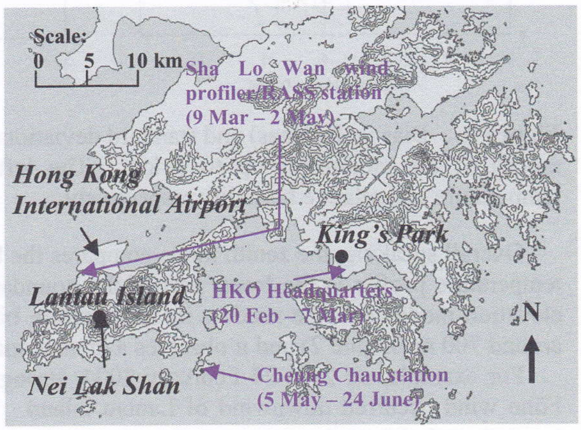

Figure 1. Map of Hong Kong (height contours: 100 m). The radiometer was set up at three locations (names in purple) for the periods indicated in parentheses in 2004.

In 2004, an experiment was conducted in Hong Kong to study the performance and application of a ground-based, multi-channel microwave radiometer in a subtropical coastal area. The radiometer provided temperature and humidity profiles at a vertical resolution of 100 m in the first 1 km and 250 m between 1 and 10 km. It demonstrated usefulness in rain nowcasting (Chan and Tam 2005). This paper focuses on its application in Föhn wind, mainly to address the following questions:

(a) Upstream of Lantau, could it resolve the temperature inversion within the boundary layer?

(b) Downstream of Lantau, what does the radiometer observe about the temporal changes of the temperature and humidity in the boundary layer?

The first question will be discussed in Section 2. The second question will be studied in two ways, namely, reviewing the retrieved thermodynamic profile output from the radiometer (Section 3) and analyzing its "raw" brightness temperature data (Section 4). Conclusions of this paper are given in Section 5.

2. MONITORING OF UPSTREAM TEMPERATURE PROFILE

During the experiment, the radiometer was configured to scan in three modes: besides the more conventional zenith mode (pointing to the zenith) and elevation mode (scanning at 7 elevation angles in sequence, from 15 degrees above horizon to 165 degrees in the opposite direction), a new mode was introduced with the radiometer measuring at the fixed elevation angle of 15 degrees. On one hand, this 15-degree mode observes a longer optical path in the lower troposphere in comparison to the zenith mode, aiming to resolve the thermodynamic profile in greater detail. On the other hand, compared with the elevation scan, it has a faster data update rate (by 7 times), though the spatial resolution is reduced. Neural network files for the three scan modes were trained by using high-resolution (0.5 Hz) radiosonde data from King's Park for one whole year. The radiometer had the "rapid scan" capability and provided brightness temperature measurements every 10 seconds.

Temperature and humidity profiles obtained from the three scan modes are compared against the radiosonde measurements. The results are shown in Figure 2. To eliminate the Föhn effect by Lantau Island, only the radiometer data collected at the Hong Kong Observatory (HKO) headquarters and Cheung Chau station (Figure 1) are used in the comparison. The followings are observed:

(a) Concerning the temperature, the three modes have comparable bias below 1.4 km or so. Above this height, the bias of the 15-degree mode is the smallest and does not seem to be systematic. On the other hand, the zenith mode has the lowest standard deviation at all altitudes.

(b) Concerning the relative humidity, the zenith and 15-degree modes have smaller bias below 1.4 km or so. Above this height, the 15-degree mode has the smallest bias. Once again, the zenith mode gives the lowest standard deviation at all heights.

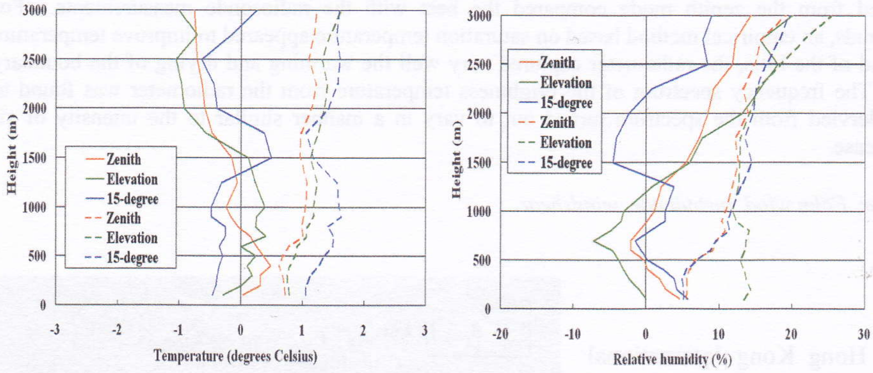

Figure 2. Bias (solid lines) and standard deviations (broken lines) for the three modes of the radiometer up to 3 km. The left and right panels refer to temperature and relative humidity respectively.

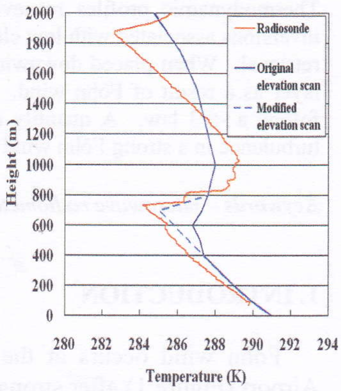

Figure 3. Temperature profile at 00 UTC, 24 February 2004

Overall speaking, the zenith mode compares the best with the radiosonde measurements. However, when the temperature profile in the lower part of the boundary layer is considered in the monitoring of Föhn wind, the elevation mode could be used as its temperature bias is generally smaller than that of the zenith mode below around 700 m (Figure 2) and it observes a greater spatial volume in retrieving the temperature profile.

For example, on 23 – 24 February 2004, strong east to southeasterly wind prevailed over Hong Kong and Föhn wind occurred downwind of Lantau Island. Temperature difference between Cheung Chau (upwind of Lantau) and the stations around the airport (downwind of Lantau) reached as high as 4°C. Temperature inversion in the boundary layer coupled with the strong cross-mountain wind resulted in disturbed airflow over the airport. Between 14 UTC of 23 February and 05 UTC of 24 February, 12 aircraft landing at the airport from the west reported the encounter of windshear and turbulence.

Located upstream of Lantau, the radiosonde launched at King's Park showed a more or less isothermal layer between 400 and 1000 m at 12 UTC of 23 February (not shown). Elevation mode measurements from the radiometer captured this isothermal layer very well.

At around 00 UTC of 24 February, the cloud base lowered, falling below 500 m occasionally. The radiosonde gave a temperature inversion of 5 K between around 500 and 1000 m (Figure 3). The radiometer also indicated a temperature inversion, though the magnitude was just 1.2 K. It appears to have difficulty in resolving the inversion associated with clouds. To overcome this difficulty, the radiometer's temperature profile is modified following an empirical method that has been tested in Payerne, Switzerland (Ware, private communication). Firstly, the cloud top is identified. This is found to be 700 m based on the liquid water measurement from the radiometer and signal-to-noise ratio data provided by the 1299-MHz wind profiler at Cheung Chau (not shown). The temperature at this height is then taken to be the average of the retrieved temperature from the radiometer and the saturation temperature of the air based on the radiometer's water vapour measurement. Finally, the temperatures between the cloud top and the cloud base are determined by linear interpolation. The resulting modified temperature profile is shown in Figure 3 (green dotted line). It is closer to the radiosonde measurement, with a temperature inversion of 3.5 K between 500 and 1000 m. While this simple empirical algorithm improves depiction of low-level inversion, it requires further adjustments using a larger dataset. Nonetheless, the present example illustrates the need of combining several sensors (radiometer and wind profiler) to accurately retrieve the temperature profile in the presence of low clouds. For Föhn wind cases in spring-time in Hong Kong, low clouds occur quite frequently as the cooler air (of continental origin) near the surface undercuts the warmer and moister air aloft (of maritime origin).

3. OBSERVATIONS OF FÖHN WIND

For two months in the experiment, the radiometer was placed at Sha Lo Wan (Figure 1) to observe the temperature and humidity changes associated with Föhn wind within the boundary layer. An example occurred on 18 March 2004. Between 11 and 14 UTC on that night (i.e. 7 and 10 p.m. in Hong Kong time, 8 hours ahead of UTC), southeasterly winds picked up in Hong Kong, reaching gale force at Nei Lak Shan (Figure 1). Zenith measurements from the radiometer showed warming and drying of the air below 1 km as a result of the Föhn wind (not shown). Comparison with the radiosonde measurement at King's Park at 12 UTC revealed that, after the wind climbed over Lantau Island, temperature rose by about 5 K between 100 and 500 m, and the relative humidity dropped by 20% between 100 m and 1 km. The corresponding changes at the surface were smaller: a temperature rise by 1 – 2 degrees and a drop of relative humidity by about 10%, as indicated by data from the surface weather stations and the radiometer.

In some Föhn wind cases, the southeasterly wind picked up in the form of "pulses", each lasting for a few hours. The radiometer data indicated the warming and drying of the boundary layer associated with these pulses. For instance, between 05 UTC of 24 March and 05 UTC of 25 March 2004, eight events of the warming and drying of the boundary layer were observed by the radiometer (Figure 4). The weather was cloudy with some rain patches in Hong Kong on those two days, and these events do not appear to be related to solar heating. The cloud base measured by the radiometer was above 500 m during these events and the problem of temperature retrieval in the presence of low clouds (Section 2) should not have great impact.

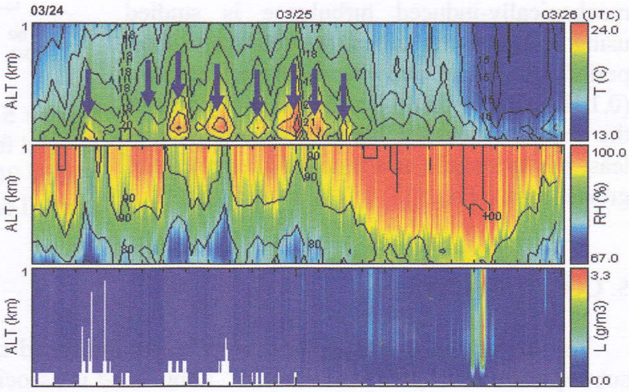

Figure 4. The radiometer measurement of temperature (upper panel), relative humidity (middle panel) and liquid water (lower panel) on 24 – 26 March 2004 (in UTC). Scales of the quantities are shown on the right hand side. Time marks are given on the upper axis of each panel and each mark interval refers to 2 hours. The warming and drying events are indicated by arrows. (The figure is generated by the software Vizmet bundled with the radiometer.)

4. SPECTRAL ANALYSIS OF BRIGHTNESS TEMPERATURE

Fluctuation of the air temperature is known to follow the -5/3 law at high frequencies (in the inertial subrange) and the temperature structure function could be calculated from the frequency spectrum. Brightness temperature in the oxygen channels, such as around 60 GHz, is an integrated temperature (Vyazankin et al. 2003):

$$\delta T_b(\upsilon,\theta) = \frac{1}{\cos\theta}\int_0^\infty \delta T(h)\gamma_\upsilon(h)\exp[-\frac{1}{\cos\theta}\int_0^h \gamma_\upsilon(h')dh']dh \quad (1)$$

where T_b is the brightness temperature, T the air temperature, δ the fluctuation quantity, υ the frequency, θ the elevation angle, γ_v the absorption coefficient of molecular oxygen at frequency υ and h the measurement path. The fluctuation of the brightness temperature at the 58.8 GHz channel of the radiometer is studied here to see if it also follows a -5/3 law in a certain frequency range and if it has any relation with the airflow disturbance at the airport area in Föhn wind.

When installed at Sha Lo Wan, the radiometer measurements in the 15-degree mode provided brightness temperature at nearly 0.1 Hz. Construction of the time series of the brightness temperature obtained from this mode and its Fourier transform (based on measurements in an hour) are calculated in a manner basically identical to the analysis of air turbulence using a mini-sodar (Chan 2004). The frequency spectrum is found to follow a -5/3 law in the range from 0.03 to 0.003 Hz most of the time, which spans one order of magnitude in the frequency space. Let b be the y-intercept of the least square linear fit to the frequency spectrum in this "inertial subrange". Similar to the study of air turbulence (Chan 2004), the quantity 10^b is taken to represent the magnitude of the fluctuation or "turbulence" of the brightness temperature.

As an example, the fluctuation of the 58.8 GHz brightness temperature is analyzed here for the Föhn wind case on 24 – 25 March 2004 (discussed in Section 3). This frequency channel has an effective measurement range of about 300 m (Vyazankin et al. 2003). For comparison, the average eddy dissipation rate (EDR) up to this height is obtained from the Sha Lo Wan wind profiler using the NCAR improved moments algorithm (NIMA). It is found to vary in a manner similar to the quantity 10^b (Figure 5). During the occurrence of Föhn wind, both EDR and 10^b remain at higher values. For the 14 reports of significant turbulence by aircraft landing at the airport from the west (including one severe turbulence report), the 10^b value was at 0.0028 or above for 79% of the reports. Fluctuation of brightness temperature has been investigated before for coherent structure in a convective boundary layer using wavelet transform (Vyazankin et al. 2003). To the knowledge of the author, this is the first time that mechanically-induced turbulence is studied using a radiometer albeit the relatively short period of dataset and slow data update rate (0.1 Hz). To further examine the robustness of the results discussed here, the radiometer at least has to sample at a much higher rate (e.g. greater than 1 Hz).

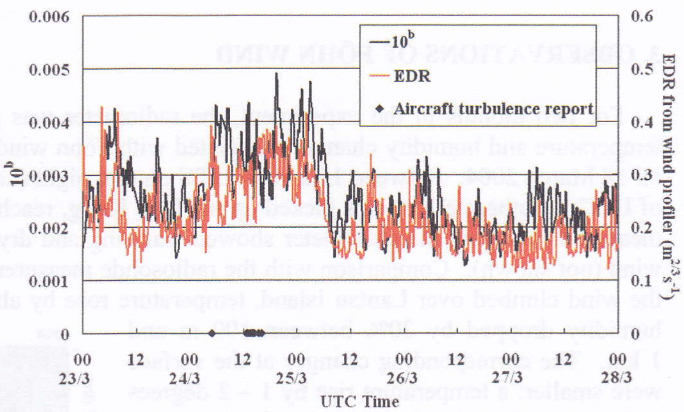

Figure 5. Time series of 10^b from the radiometer and EDR derived from Sha Lo Wan wind profiler for the period 23 to 28 March 2004. Aircraft reports of significant turbulence are marked on the time axis.

5. CONCLUSIONS

The performance and application of a ground-based microwave radiometer in monitoring Föhn wind in a subtropical coastal area was studied. Föhn wind is associated with the occurrence of temperature inversion in the boundary layer. Three scanning modes of the radiometer were compared in the resolution of the inversion. Overall speaking, thermodynamic profiles obtained from the zenith mode compared the best with the radiosonde measurements. The 15-degree mode had the smallest bias for both temperature and humidity measurements between 1.4 and 3 km. For resolving temperature inversions within the boundary layer, the elevation scan could be used as it had the lowest bias for temperature below about 700 m. A multi-sensor approach (such as combination of the radiometer and a boundary layer wind profiler) appeared to be a possible way to get both the vertical extent and the magnitude of such inversions more accurately in the presence of low clouds.

Placed in a downwind location of the hills on Lantau Island, the radiometer observed the warming and drying of the boundary layer associated with the Föhn wind, in the form of wind speed pulses. The temperature and humidity differences across Lantau Island reached 5 K and 20% respectively. The brightness temperature at 58.8 GHz channel appeared to follow a -5/3 law in the frequency range of 0.03 to 0.003 Hz. A quantity based on the y-intercept of the least square linear fit to the frequency spectrum in this "inertial subrange" was constructed to represent the magnitude of the brightness temperature fluctuation. In a Föhn wind case with rather frequent aircraft reports of significant turbulence at the airport, it was found to vary in a manner similar to the eddy dissipation rate. Both the raw brightness temperature measurements and the retrieved temperature and humidity profiles from the radiometer are found to reveal some interesting features about the thermodynamic fluctuations in the boundary layer associated with the Föhn wind.

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