Observations of lee waves and rotors downwind of the Pennines.

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1. Introduction

A field experiment was conducted in the Pennines, UK, between November 2003 and April 2005. The aims of the experiment were to study lee waves and rotors forming downwind of the Pennines in order to better understand and predict turbulence and flow variability associated with these types of flow. This is of particular importance due to the high density of airfields and associated air traffic in the area. Measurements of the near-surface flow and pressure perturbations up- and downstream allowed the effects of the pressure field associated with lee waves to be observed. Vosper *et al.*, in an accompanying talk, and journal article (2006), discuss idealised 2-D simulations in which the normalised pressure perturbation amplitude, $\Delta p/u_*^2$, controls the fractional deceleration, Δs, beneath a wave crest. A value of Δs less than -1 indicates reversal of the near-surface flow resulting in the formation of a rotor. The quantity $\Delta p/u_*^2$ represents the trade off between the size of the adverse pressure gradient induced by the waves, and the velocity scale of the background flow near the surface. The measurements discussed here allow the illumination of how real flows respond to the lee-wave induced pressure field.

2. Description of experiment

The orography of the Pennines in northern England is shown in Figure 1. A network of automated weather stations (AWS), each measuring 2 m horizontal wind, and incorporating a sensitive microbarograph, was placed in the Vale of York, to the east of the Pennine ridge which runs down the centre of the figure, in order to measure the downstream near-surface flow in westerly conditions. Pressure perturbation amplitudes were taken as the largest difference in recorded perturbation pressure across the array. A single AWS was located to the west of the Pennines at Lancaster. Sonic anemometers mounted on instrumented 20 m turbulence masts at Lancaster and three locations in the Vale allowed the friction velocity, u_*, to be accurately measured. The experiment was supported by daily radiosonde releases from Lancaster, and flights by the FAAM BAe 146 aircraft. Additionally, a sky camera ('skycam'), located at Leeming airfield in the Vale of York, recorded cloud motions at 30 second intervals. During a number of intesive observation periods (IOPs) radiosondes were released roughly hourly for a day.

3. Results

A large number of westerly lee wave events were observed during the 1.5 year term of the experiment, some of which contained evidence of rotor activity. Radiosonde data for two examples, which will be termed cases 1 and 2, of wave events are shown in Figure 2(a) and 2(b) respectively (both correspond to IOP dates). In addition to a significant cross-barrier flow, both sondes recorded curvature in the theta profile, and variation of the wind profile, such that the Scorer parameter decreases with height. This situation is conducive to

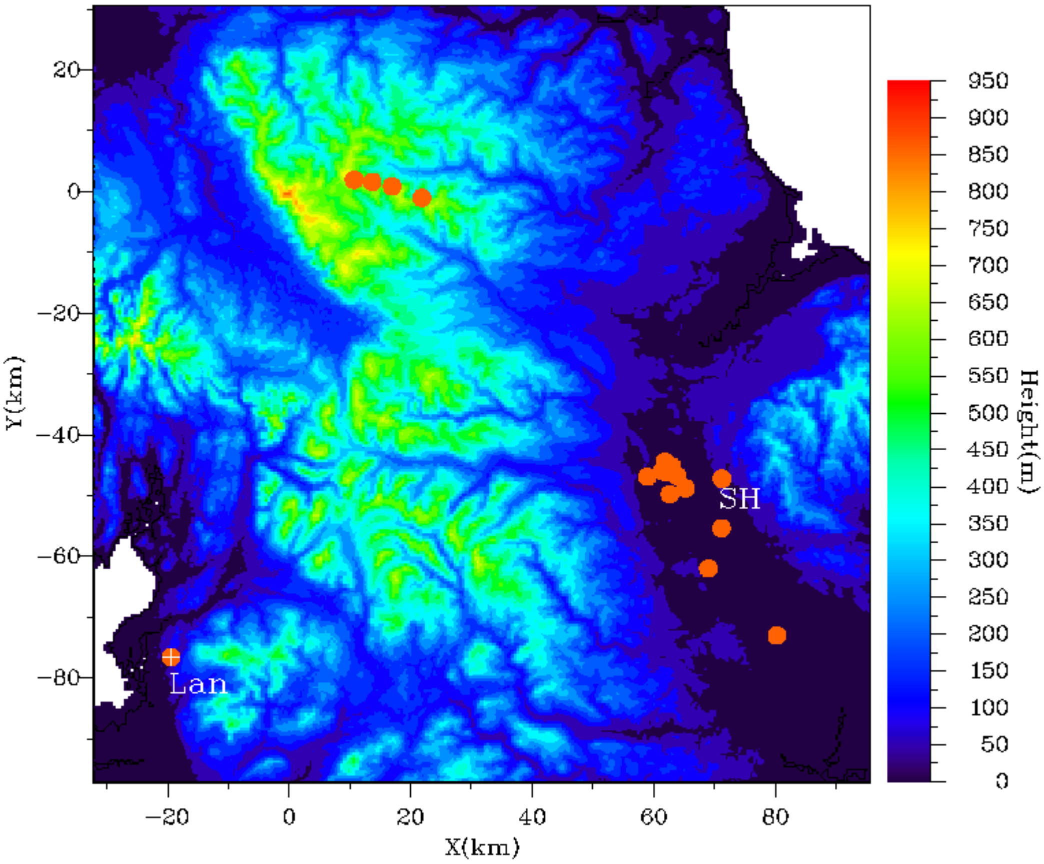
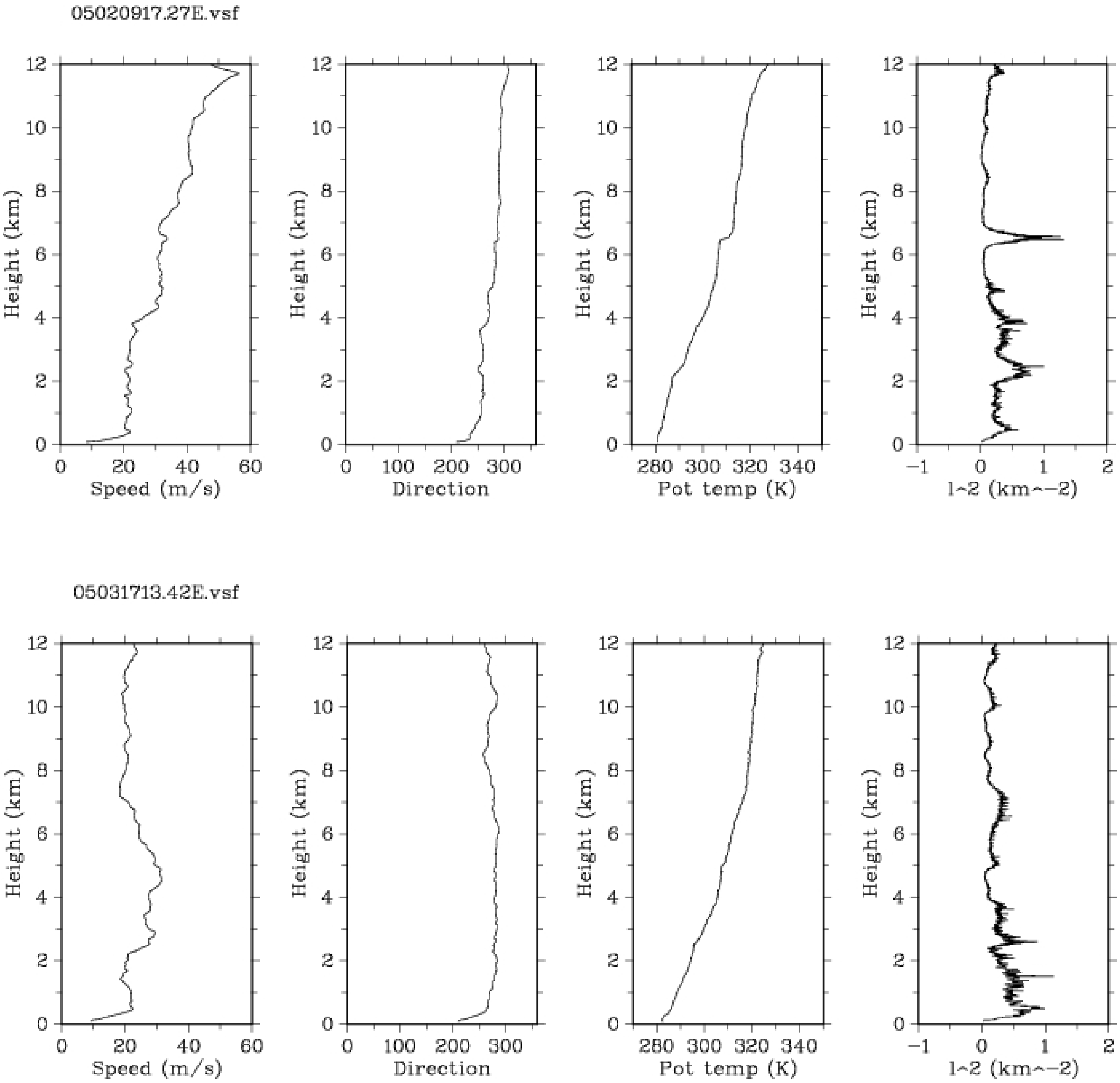


Figure 1: The orography of the Pennines (terrain heights shown in metres) with locations of all automatic weather stations marked as red dots.

the formation of trapped lee waves (Scorer 1949). Although the radiosonde profiles are ostensibly similar in each case, rotors were only observed in case 2. This is evident from the timeseries of winds shown in Figure 3, where that for case 2 indicates a particularly high level of variability, including intermittent reversal of the wind direction with respect to that upstream at Lancaster, unlike for case 1.

The time series of pressure perturbations measured at the same stations is also shown in Figure 3. It is clear that the variation of the winds downstream of the Pennines is linked to the size of the pressure perturbations during the lee wave events – a stronger wind at a given downstream station corresponds with a lower pressure perturbation.

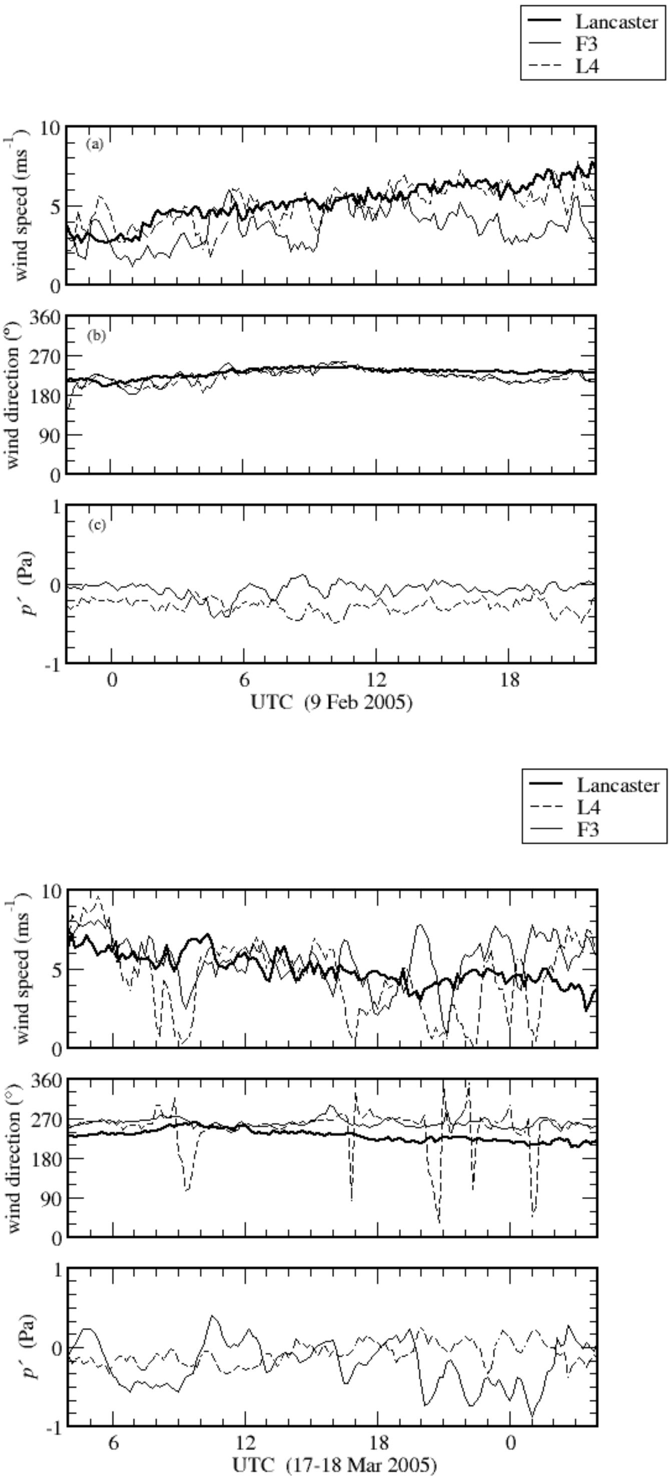
A number of factors can affect the pressure amplitude induced at the surface by lee waves. As indicated above, the profile of Scorer parameter is crucial in defining the structure of the wave field, determining if the wave energy is trapped close to the surface. For a given Scorer parameter profile, however, the wave amplitude additionally depends on the upstream orography, and the speed of the wind passing over the mountain, plus any non-linear effects. Vosper *et al.* further emphasise the importance of the near-surface wind scale, represented by u_*, in the formation of rotors. A further plot showing the pressure amplitude normalised by u_*^2 is shown in Figure 4 for each case. Clearly, while $\Delta p/u_*^2$ barely reaches 100 during case 1, it attains significantly higher values, frequently above 150 in case 2, explaining the occurrence of flow reversal.



(a)

(b)

Figure 2: Profiles of wind speed and direction, potential temperature and Scorer parameter obtained from radiosonde ascents on (a) 9 February 2005 at 17:27 UTC and (b) 17 March 2005 at 13:42 UTC.



(a)

(b)

Figure 3: Timeseries of the 10 minute average surface winds and pressure perturbations for the periods (a) 8 February 2005, 22:00 UTC March 2005 to 9 February 2005 22:00 UTC, at AWS stations Lancaster (solid bold line), F3 (solid line) and L4 (dashed line), and (b) 17 March 2005, 04:00 UTC to 18 March 2005, 04:00 UTC, at AWS stations Lancaster (solid bold line), F3 (solid line) and L4 (dashed line). Note that *x*-axis divisions represent 1 hour periods.

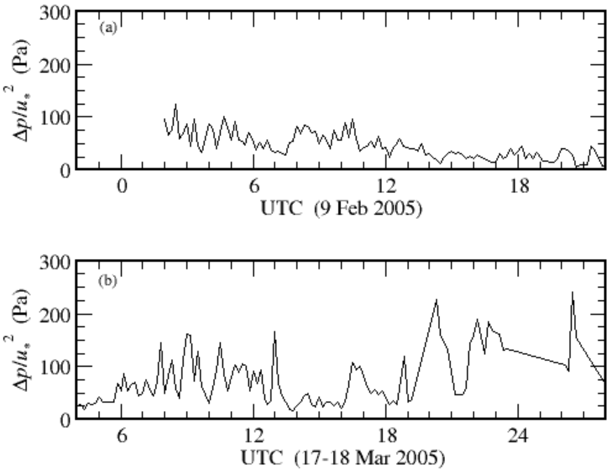


Figure 4: The orography of the Pennines (terrain heights shown in metres) with locations of all automatic weather stations marked as red dots.

4. Conclusions

The examination of trapped lee wave cases from the Pennines field data set indicates that rotors tend to form when the quantity $\Delta p/u_*^2$ is large. This is consistent with the work of Vosper *et al.*, who used idealised 2-D simulations to show that $\Delta p/u_*^2$ controls the value of the fractional deceleration of the wind beneath a lee wave crest, Δs. The ability to explain the occurrence of rotors induced by waves downstream of a complex mountain range in terms of a single ratio in this way may prove useful in developing generalised techniques for forecasting lee wave rotors.

References

Vosper SB, Sheridan PF, Brown AR. 2006. Rotor formation by two-dimensional trapped lee waves. *Quarterly Journal of the Royal Meteorological Society, in press.*

Scorer RS. 1949. Theory of waves in the lee of mountains. *Quarterly Journal of the Royal Meteorological Society* **75:** 41–56.