NUMERICAL SIMULATIONS OF LEE-WAVE ROTORS

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1. INTRODUCTION

It is well known that gravity waves forced by flow over mountains often give rise to severe low-level turbulence and gustiness. This turbulence can be associated with the formation of rotors, either downwind of mountain ranges beneath the wave crests of a trapped lee wave field or behind hydraulic jumps on the mountain lee slopes. Despite the fact that rotors represent a serious hazard to aircraft, there are currently no reliable methods for forecasting them.

In this paper we shall present results from a series of numerical simulations of rotor events which were observed during an intensive field campaign on the Falkland Islands. The simulations were conducted in order to identify the conditions under which rotors may form and to investigate the dynamical processes which are important to their formation.

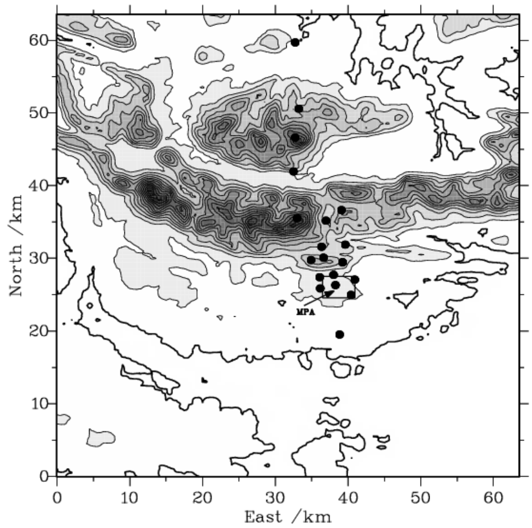

Figure 1: The terrain of East Falkland and locations of the AWS's. Also marked is the position of MPA. The terrain height contour interval is 50 m and the bold line denotes the coastline.

2. ROTOR OBSERVATIONS

A field campaign, aimed at obtaining detailed measurements of rotor formation in the lee of mountains, was recently conducted on the Falkland Islands in the south Atlantic. The experiment was run by a team of scientists from the University of Leeds and UMIST, UK. Data were recorded almost without interruption for a period starting in November 2000 and ending in October 2001. Most measurements were made in the immediate vicinity of Mount Pleasant Airfield (MPA) on East Falkland. MPA is well-known for the frequent occurrence of severe low-level turbulence and this represents a significant hazard to air traffic. Forecasters at MPA often issue warnings of 'rotor streaming', usually under stable northerly flow conditions.

The topography in the vicinity of MPA is shown in Fig. 1. MPA lies to the south of two mountain ridges which run roughly east-west across East Falkland. The maximum terrain height is around 650 m. Also shown in Fig. 1 are the locations of 19 automatic weather stations (AWS's) which recorded data throughout the field campaign. The majority of these instruments were situated close to MPA, in order to obtain high resolution measurements of the flow during rotor events. Additional instruments were located on a north-south transect to the north of MPA. Three AWS's (not shown in Fig. 1) were located on small outlying islands.

Several rotor episodes were encountered at MPA during the field campaign, all of which occurred in northerly flow. An example of the 2 m wind field measured during an event which occurred on 9 February 2001 is shown in Fig. 2. The wind speed is increased significantly on the lee side of the mountains compared with the upstream flow and there are extreme variations in the wind direction near MPA. The wind vectors shown are based on 10 minute averages (measurements were

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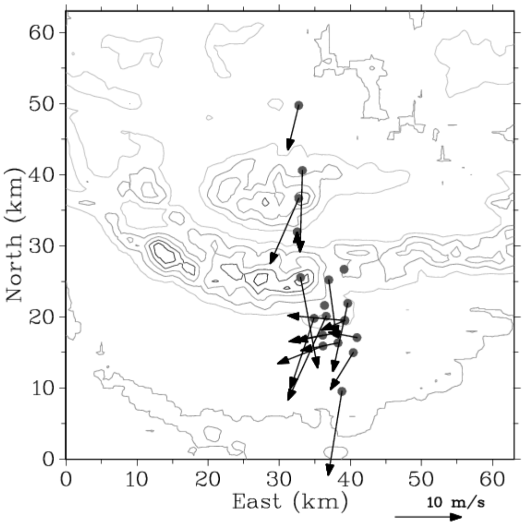

Figure 2: Ten minute average wind measurements (at 2 m) made on East Falkland at 1100 UTC on 9 February 2001.

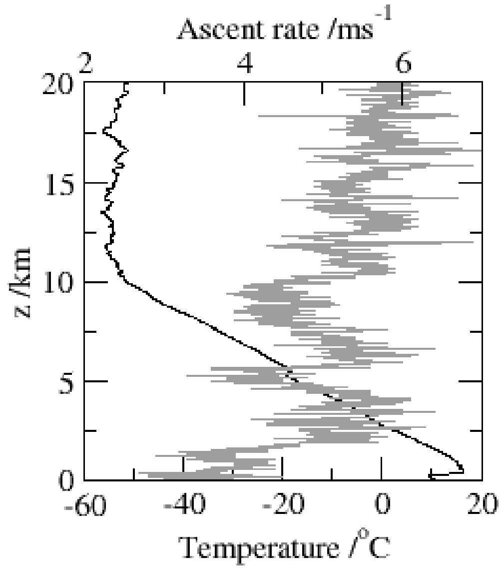

Figure 3: Radiosonde measurements of temperature (solid) and ascent rate (gray) deduced from the 1100 UTC MPA ascent on 9 February 2001.

made at 1 Hz and recorded as 30 s averages) and animation of the wind field reveals that the flow is highly unsteady on this timescale. Localised regions of flow reversal appear intermittently to the south of the mountains and the convergence in the wind field is consistent with flow separation.

A common feature of many of the observed rotor events is the presence of a strong temperature inversion in radiosonde measurements made at MPA. Typically this inversion occurred at a height of around 500 m, which is comparable to the mountain heights, and was up to 10 K in strength. The radiosonde profile for the 9 February 2001 event is shown in Fig. 3. The profile is typical of those obtained during rotor events, containing both a strong temperature inversion and a moderate amplitude gravity-wave signal in the ascent-rate data.

3. THE NUMERICAL MODEL

The numerical model used for this study is the Met Office BLASIUS code. This model has been used extensively for studies of boundary-layer flows over small hills (e.g. Allen and Brown, 2002; Belcher and Wood, 1996). The model is based on the time-dependent Boussinesq equations in a terrain-following coordinate system and employs a finite-difference discretisation and an explicit time integration scheme. The results presented here were obtained using a Richardson number dependent mixing-length turbulence closure scheme. At the lower boundary a no-slip condition is imposed via a log-linear law formulation. Rayleigh damping is imposed beneath the upper boundary to absorb upward propagating gravity waves.

4. ROTOR SIMULATIONS

A two-dimensional (2-D) simulation for the 9 February case has been conducted using idealised topography, $h(x)$, of the form

$$h(x) = \begin{cases} H\,(1+\cos(2\pi x/L)) & |x| \le L/2 \\ 0 & |x| > 0, \end{cases} \tag{1}$$

where the parameters H and L were 250 m and 10 km, respectively. The simulation was initialised with the steady-state wind and potential temperature fields which resulted from a one-dimensional (1-D) simulation. This 1-D simulation was itself initialised with the radiosonde wind (rotated so that the positive x-direction was north-south) and potential temperature data obtained from the 1100 UTC 9 February ascent (see Fig. 3). The surface roughness length was assumed uniform and equal to 5 cm. Figure 4 shows the steady-state flow field in the immediate vicinity of the ridge. A large-amplitude gravity wave is present downwind and above the mountain and a hydraulic jump-like feature is present near the foot of the lee slope. As shown by Fig. 5, close inspection of the flow in this region shows that flow separation occurs near the base of the mountain and a closed rotor

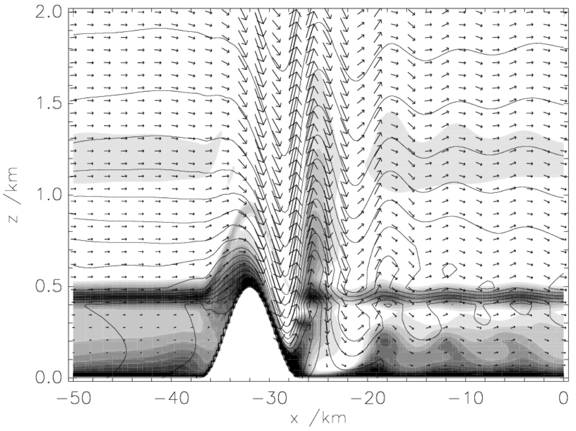

Figure 4: The steady-state flow field over a 2-D ridge. The initial wind and temperature profile is based on the 1100 UTC MPA radiosonde ascent on 9 February 2001. Quantities shown are wind vectors, potential temperature (line contours, interval 1 K) and the cross-stream horizontal vorticity component (shaded, units s^{-1}).

exists downwind of the separation point. Weak reversed flow exists within the rotor and a high degree of wind shear is present both towards the top of the rotor (at around 500 m) and along its leading edge. This wind shear is evidently a consequence, at least partly, of advection of horizontal vorticity from within the boundary layer where the flow separates from the surface.

The dependency of the rotor formation on the presence of the temperature inversion has been investigated through some additional 2-D idealised simulations. The terrain considered was again that specified by Eq. (1) but in this case the background profile consisted of a northerly 10 ms^{-1} wind which was independent of height above the boundary layer and a three-layer Brunt-Väisälä frequency (N) profile. The potential temperature increased linearly with height in all three layers so that in the lowest layer (the surface up to a height of 450 m) and the uppermost layer (above 550 m) the Brunt-Väisälä frequency was 0.01 s^{-1}. Values of N in the middle layer (450 m to 550 m) were chosen in order to represent inversions of different strengths. These profiles were used to initialise 1-D simulations in which a fully developed boundary-layer was obtained and these results were then used to initialise the 2-D simulations. Figure 6 shows the steady-state flow above the lee-slope of the ridge when the value of the middle layer Brunt-Väisälä frequency was 0.06 s^{-1}. Such a value corresponds to an increase in potential temperature across the layer of around 10.5

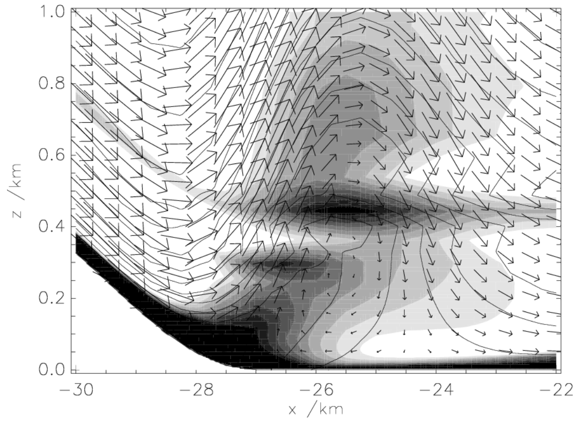

Figure 5: As for Fig. 4 but a more limited region of the domain, focusing on the lee-slope rotor and associated regions of high vorticity.

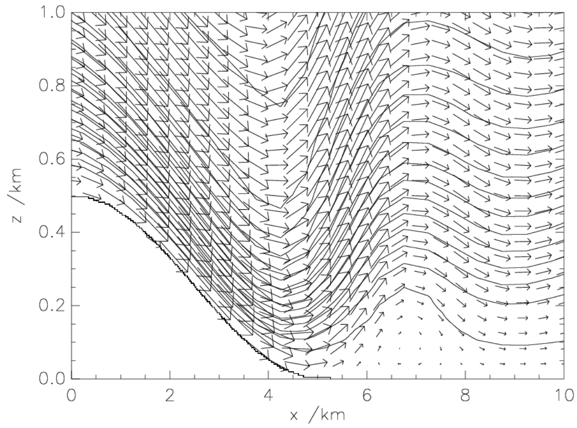

Figure 6: The idealised steady-state flow field over a 2-D ridge in the case where the middle layer Brunt-Väisälä frequency is 0.06 s^{-1}. Quantities shown are wind vectors and potential temperature (interval 1 K).

K which is similar to that observed on 9 February. As for the 9 February simulation, flow separation occurs at the downwind foot of the mountain and a rotor is present. Figure 7 shows the results of a second simulation in which the inversion was weaker. The middle layer Brunt-Väisälä frequency was only 0.03 s^{-1} in this case (corresponding to a potential temperature increase of 2.6 K) and no rotor is present downwind of the mountain. It appears that the strength of the upwind inversion plays a crucial role in the rotor development.

5. CONCLUSIONS

The Falklands field campaign has resulted in a vast amount of high quality data. Although analysis of the data is still in the preliminary stages, it is clear

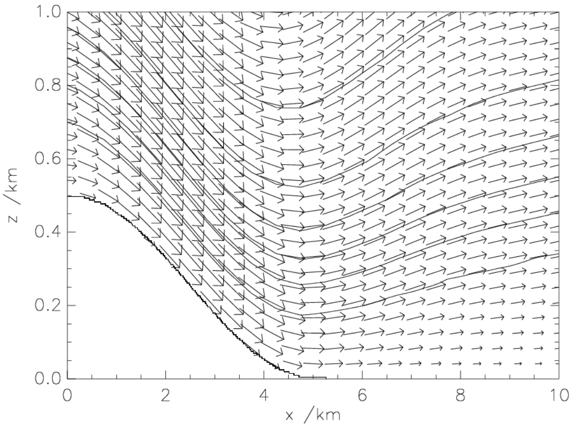

Figure 7: As for Fig. 6 but for the simulation in which the middle layer Brunt-Väisälä frequency is 0.03 s^{-1}.

that the experiment has captured several events in which strong downslope winds and rotor formation occurred near MPA. The high spatial and temporal resolution of the surface observations coupled with radiosonde soundings offer new insight into these flows. Although a systematic analysis is required, initial results indicate that a strong temperature inversion at around 500 m usually accompanies the rotor events.

Two-dimensional numerical simulations, initialised with either real radiosonde measurements or idealised profiles indicate that a strong temperature inversion at height similar to the mountain height is conducive to rotor formation. When the inversion is weak (e.g. less than 0.03 Km^{-1}) rotors do not form.

6. REFERENCES

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Belcher, S.E. & Wood, N. 1996: Form and wave drag due to stably stratified turbulent flow over low ridges. *Q. J. R. Meteorol. Soc.*, **122,** 863–902.