INFLUENCE OF SECONDARY OROGRAPHY ON BOUNDARY LAYER SEPARATION AND ROTORS

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Boundary layer separation and attendant rotors are sources of severe turbulence and mixing in the atmosphere and ocean. In this study we examine the influence of secondary mountain ridges on rotor characteristics by means of laboratory experiments and numerical models. Modeling results have suggested the existence of lee wave interference that modulates rotor strength and also point to the sources of rotor non-stationarity. Laboratory experiments are going to be carried out at the CNRM-GAME (METEO-FRANCE and CNRS) Toulouse large stratified water flume in order to examine and extend the regime diagram determining rotor characteristics over double ridge terrain as well as the internal structure of rotor flow itself with the aim of improved understanding and possible forecasting of rotor intensity.

1. INTRODUCTION

Complex topographic features cover most of the Earth’s surface both on land and within the oceans and influence all scales of motions that permeate the oceans and the atmosphere. Flow of stably stratified fluid over complex topography can lead to the formation of internal gravity waves and in cases of significant wave amplitudes, to the development of rotors. Rotors, turbulent horizontal eddies found in the lee of topography, form as the boundary layer separates from the surface due to adverse pressure gradients caused by topographically induced gravity waves (Hertenstein & Kuettner, 2005). They can extend to considerable heights, exceeding the height of topography which caused them, and are a source of significant turbulence, mixing, dissipation and drag important for both atmospheric and oceanic flows (e.g. Hertenstein & Kuettner, 2005; Chan et al., 2007; Legg & Klymak, 2008; Grubišić & Stiperski, 2009; Texeira et al., 2013).

Boundary layer separation (BLS) and rotor formation in the lee of a single ridge have received renewed interest over the past decade (e.g. Doyle and Durran 2002, 2004, 2007; Vosper, 2004; Jiang et al., 2007; Cohn et al., 2010; Knigge et al., 2010; Sheridan & Vosper, 2012) especially in connection with the recent Terrain-Induced Rotor Experiment (T-REX; Grubišić et al., 2008) that took place in Owens Valley, in the lee of the Sierra Nevada in California. Rotor observations during T-REX have also drawn attention to the influence of secondary ridges on the amplification of BLS and rotors, a topic that has been the subject of only a limited number of studies. Laboratory experiments and numerical simulations of flows over and within valleys, performed in the 1980s (e.g. Tamperi & Hunt, 1985; Kimura & Manins, 1988; Lee et al., 1987) have focused on flow stagnation vs. ventilation and did not address the influence of secondary orography on rotor strength over the valley. They did, however, identify important non-dimensional governing parameters for valley flows: Froude number \( (Fr) \), ridge separation distance \( (V) \) and horizontal wavelength of the terrain-generated waves \( (\lambda) \).

Rotors can generally be classified into two types: non-hydrostatic trapped lee wave rotors and hydrostatic hydraulic jump rotors (Hertenstein & Kuettner, 2005; Jiang et al., 2007). Trapped lee waves forming over double ridges experience lee wave interference (Scorer, 1997; Gyüre & Jánosi, 2003; Chan et al., 2007; Grubišić & Stiperski, 2009; Buijsman et al., 2010; Stiperski & Grubišić, 2011). According to linear theory this interference is governed by the ratio of lee wave horizontal wavelength \( (\lambda) \) to the ridge separation distance \( (V) \) (Scorer, 1997; Stiperski & Grubišić, 2011) that discriminates between the constructive (wave amplitude increases compared to a single ridge case; Fig. 1a) and destructive (decreased wave amplitude; Fig. 1b) interference. The idealized 2D linear and
nonlinear numerical results of Stiperski and Grubišić (2011) on trapped lee wave interference over double bell-shaped mountains show that, although useful for predicting the wave amplitude, the linear interference theory cannot explain the behavior of rotor strength. The secondary ridge does not facilitate boundary layer separation and rotor formation (negative horizontal velocity $U_{\text{min}}$ in Fig. 2) for mountain heights for which it would not occur downstream of a single ridge, nor is the rotor strength increased under constructive interference. It is, however, decreased under destructive interference. As mountain height ($H$) increases, the idealized simulations suggest the existence of a limit to rotor strength over the valley ($U_{\text{min}}$ is constant for $H>1000$ m in Fig 2). If the secondary ridge is lower than the primary one, lee wave interference can lead to almost complete cancellation of waves in the lee of the secondary ridge (Fig. 1c). In this regime, termed complete destructive interference (CDI), waves and rotors over the valley significantly exceed those further downstream.

![Figure 1](image1.png)

**Figure 1** An example of constructive (left), destructive (center) and complete destructive interference (right) for first mountain height equal 600m and second mountain height equal 600m (left and center) and 400m (right). Horizontal wind speed ($\text{ms}^{-1}$), gray scale), potential temperature ($\text{K}$, black solid lines) and horizontal pressure perturbations (white lines).

Particularly severe rotors can form in relation to hydraulic jumps (Hertenstein & Kuettnner, 2005; Jiang et al., 2007; Legg & Klymak, 2008). The influence of secondary ridge on hydraulic jump rotors is expected to be significantly different from that for trapped wave rotors. Real case numerical simulations of bora-induced rotors along the Croatian coast (Gohm et al., 2008; Grisogono & Belušić, 2009; Stiperski et al., 2012) show that even significantly smaller-scale terrain downstream of the primary ridge can, in this regime, significantly alter the rotor strength and vertical extent and could facilitate boundary layer separation where it would not occur in the absence of this secondary topography (Stiperski et al. 2012).

![Figure 2](image2.png)

**Figure 2** Minimum horizontal wind speed ($U_{\text{min}}<0$ signifies rotors) underneath the first lee wave crest in the lee of the first ($U_{1\text{min}}$) and second ($U_{2\text{min}}$) mountain as functions of mountain height ($H$) for a single ridge (black) and double ridges for different ridge-separation distances ($V$) leading to constructive (orange) and destructive (blue) interference (from Stiperski & Grubišić, 2011).

In this study we seek to understand the impact of downstream ridges on BLS and rotor formation under different flow regimes. Following the experimental work of Knigge et al. (2010) and numerical simulations of Stiperski and Grubišić (2011) we explore the rotor development over double ridges in a stratified water flume in connection with both trapped lee waves and undular hydraulic jumps. Particular stress is given to the investigation of the inner structure of the rotor
flow as well as unsteadiness of the boundary layer separation, evidenced in observable shifts of the location of the BLs point, and to the intensity of turbulence along the separation line and within the rotor.

2. LARGE EDDY SIMULATIONS

Large Eddy Simulations (LES) of boundary layer separation and rotors were performed prior to the stratified water flume experiments in order to guide the laboratory set-up and provide the rough guideline on the correct choice of governing parameters needed to produce the phenomena of interest. The numerical model used in this study is the Cloud Model 1 (CM1; Bryan, 2009), suitable for idealized simulations of mesoscale as well as boundary layer phenomena. CM1 is a 3D, time-dependent and non-hydrostatic numerical model that conserves total energy and mass of a moist atmosphere. The model was employed at a horizontal resolution of \(dx = 50\text{m}\), stretched to \(dx = 1\text{km}\) at the lateral boundaries and a variable vertical resolution stretching between 3m to 30 m. The simulations were run in a two- and three-dimensional configuration. The model was initialized with an idealized sounding, which contrary to Stiperski and Grubišić (2011) had a temperature inversion and a constant wind profile to facilitate wave trapping. This idealized upstream sounding is relatively easy to reproduce in the laboratory experiments.

A series of tests was performed studying the sensitivity of rotor flow to terrain shape and width, inversion strength and height, wind speed and surface friction. The simulation results show that the proposed set-up is able to produce both trapped lee wave and hydraulic jump rotors (Fig. 3). The Froude number reliably predicts different flow regimes and the shift between them (trapped lee wave vs. hydraulic jump) is most easily achieved by changes in wind speed (towing speed for the flume experiments) rather than changes in inversion strength or height. Surface friction facilitates boundary layer separation and together with terrain shape and inversion strength has a profound impact on wave amplitude. Gaussian shaped terrain, as opposed to bell-shaped mountain or cosine mountain, was shown to produce largest amplitude waves and strongest rotors.

Placing a secondary ridge downstream of the first one causes the emergence of an interference pattern. This pattern, however, is not identical to the one obtained by Stiperski and Grubišić (2011), due to the strong inversion that causes stronger flow non-linearity. A lower downstream ridge (ratio of second to first ridge = 2/3) does produce complete destructive interference and almost total cancellation of wave field in the lee of the second ridge for certain ridge separation distances in agreement with Stiperski and Grubišić (2011).

The strength and height of the inversion has a strong impact on the intensity of the flow, the location of the BLs point and on the steadiness of the simulation through controlling nonlinear wave-breaking events, but the main flow regime remains mostly governed by the Froude number. The results thus conform to the flow regime diagram proposed by Vosper (2004) with some modifications.

The flow regime is not affected by the change from two-dimensional to three-dimensional simulations. The amplitude of the phenomena, however, is affected so that 3D trapped lee waves induce weaker rotors than in the respective 2D simulations. Unlike 2D, the 3D simulations on the other hand reproduce the inner rotor structure and development of intense sub-rotors that are responsible for most severe turbulence. Trapped lee waves are also shown to be steadier than the hydraulic jump rotors.
3. LABORATORY EXPERIMENTS

Laboratory experiments take place in the CNRM-GAME (METEO-FRANCE and CNRS) large stratified water flume, which allows generation of stratified flow at high Reynolds number with low confinement effect.

The numerical simulations have shown that regime diagram of Vosper (2004) can be reliably used to predict the occurrence of trapped lee wave rotors or hydraulic jump rotors. Whereas Knigge et al. (2010) were already able to reproduce the trapped lee wave rotors in the stratified water flume using this regime diagram as a guide, it wasn’t clear whether the unsteady hydraulic jump rotors can be reproduced as well, since they did not occur in the simulations of Vosper (2004).

The following guidelines for the laboratory experiments were obtained from the numerical simulations. The optimal mountain shape was shown to be Gaussian. The size of the ridges similar to Knigge et al. (2010) was tested and is used in the experiments (Table 1).

Fig. 4 shows two sketches of the laboratory setup. In panel a, two equally high ridges are placed at a certain ridge separation distance, which is varied in order to examine lee wave interference. Single mountain tests have to be conducted first though, in order to determine the horizontal lee wave wavelength that governs the interference pattern. For the experiments on the influence of a lower downstream mountain and the associated rotors (Fig. 4b), a strong inversion is important in order to induce large-amplitude lee waves that lead to rotor formation. In this latter setup, lower-lying inversions may be useful for testing the reverse flow strength behind both obstacles. The suggested non-dimensional parameters for the simulations are given in Table 2.
Table 1. The choice of topography for the laboratory experiments

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Setup 1</th>
<th>Setup 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mountain height [cm]</td>
<td>13.2</td>
<td>13.2</td>
</tr>
<tr>
<td>Horizontal scale (2L^2) [cm^2]</td>
<td>1060</td>
<td>1060</td>
</tr>
<tr>
<td>Total mountain width (L_0) [cm]</td>
<td>66.3</td>
<td>66.3</td>
</tr>
</tbody>
</table>

Figure 4 Possible laboratory setups for the rotor measurements. Both setups include an idealized vertical profile with a neutral lower layer and a stable upper layer, but in setup 2, the inversion is stronger. Setups also differ in mountain height ratio, the mountain heights (i.e. inversion height) and the horizontal wind speed (from Goger, 2014, unpublished master thesis).

The unique characteristics of the large stratified water flume combined with the CNRM-GAME fluid mechanics laboratory team expertise on measurements in high Reynolds number stratified flows allows not only the study of rotor development within the valley and downstream of the two ridges, but also an unprecedented insight into the inner rotor structure, such as sub-rotors, breakup into turbulence, characteristics of the boundary layer at the separation point etc.

Table 2. Non-dimensional parameters for the laboratory experiments

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Setup 1</th>
<th>Setup 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>1121 kg m(^{-3})</td>
<td>1121 kg m(^{-3})</td>
</tr>
<tr>
<td>Inversion strength</td>
<td>13 kg m(^{-3})</td>
<td>31 kg m(^{-3})</td>
</tr>
<tr>
<td>Brunt-Väisälä frequency</td>
<td>1 s(^{-1})</td>
<td>1 s(^{-1})</td>
</tr>
<tr>
<td>Valley width</td>
<td>50-150 cm</td>
<td>200 cm</td>
</tr>
<tr>
<td>Inversion height</td>
<td>26 cm</td>
<td>16.3 cm</td>
</tr>
<tr>
<td>Mountain height/inversion height</td>
<td>0.5</td>
<td>0.8</td>
</tr>
<tr>
<td>Wind speed</td>
<td>26 cm s(^{-1})</td>
<td>26 cm s(^{-1}) (Lee waves)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>13 cm s(^{-1}) (Hydraulic jump)</td>
</tr>
</tbody>
</table>

4. DISCUSSION

Laboratory experiments are going to be performed in the summer of 2014 in the CNRM-GAME (METEO-FRANCE and CNRS) large stratified water flume. They will allow us to investigate, for
the first time in the laboratory, the influence of secondary obstacles on the rotor flow. The relevance of laboratory experiments carried out in this tank on atmospheric lee waves and rotors has been demonstrated by Knigge et al. (2010). It relies on the unique characteristics of this tank, combining large dimensions to the ability to generate high Reynolds number and stratified flows.

These experiments will extend the results from Knigge et al. (2010) carried out with a single obstacle, and therefore extend the regime diagram of Vosper (2004) adding valley width and second mountain height as additional parameters. They will also allow a closer look at the turbulence and inner structure of the rotor flow. It will give a unique opportunity to compare an extensive dataset on a perfectly controlled high Reynolds number stratified real flow to prediction of numerical simulations, in which turbulence properties may be affected among other things by small scales parameterizations.

ACKNOWLEDGEMENTS

This work has been supported by European Community’s Seventh Framework Program through the grant to the budget of the Integrating Activity HYDRALAB IV within the Transnational Access Activities, Contract no. 261520. Work of Brigitta Goger and Stefano Serafin was financed through the STABLEST - Stable boundary-layer separation and turbulence grant to FWF. This document reflects only the authors’ views and not those of the European Community. This work may rely on data from sources external to the HYDRALAB IV project Consortium. Members of the Consortium do not accept liability for loss or damage suffered by any third party as a result of errors or inaccuracies in such data. The information in this document is provided “as is”, and no guarantee or warranty is given that the information is fit for any particular purpose. The user thereof uses the information at its sole risk and neither the European Community nor any member of the HYDRALAB IV Consortium is liable for any use that may be made of the information. We thank A. Belleudy, R. Calmer, J.-C. Canonici, F. Murguet, A. Paci and V. Valette of the CNRM-GAME (UMR3589, METEO-FRANCE and CNRS) fluid mechanics laboratory for their work preparing the experiments.

REFERENCES


