11.4 ROTOR DYNAMICS IN THE LEE OF THREE-DIMENSIONAL RIDGES

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1. INTRODUCTION

Mountain waves forced by elongated ridges are often accompanied by low-level vortices that have horizontal circulation axes parallel to the ridgeline. These horizontal vortices, known as rotors, were the subject of a number of studies in the 1950's inspired by the observational and theoretical results of the Sierra Wave Project (Holmboe and Klieforth 1957). Low-level rotors are a manifestation of boundary layer separation that occurs due to adverse pressure gradients associated with mountain-induced lee waves and are modulated through boundary layer processes and lee-wave-induced perturbations (Durran and Doyle 2002). Rotors are considered severe aeronautical hazards as evinced by the numerous commercial aviation accidents in the last several decades that have been attributed to rotors. In spite of their obvious importance, mountain-induced rotors still remain poorly understood, particularly with respect to three-dimensional aspects of the flow. In this study, the dynamics of rotors forced by three-dimensional topography are investigated through a series of high-resolution idealized simulations with the non-hydrostatic COAMPS model. The focus of this investigation is on the internal structure of rotors and in particular on the dynamics of small-scale intense circulations within rotors that we refer to as "sub-rotors".

2. NUMERICAL SIMULATIONS

Three-dimensional nonlinear numerical simulations are conducted using the atmospheric portion of NRL's Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS$^{\mathrm{TM}}$), which integrates the fully compressible equations of motion as described by Hodur (1997) and Doyle and Durran (2002). Six nested grid meshes are used in this study with horizontal grid increments of 5400 m, 1800 m, 600 m, 200 m, 67 m, and 22 m, respectively (Fig. 1). The vertical grid is comprised of 90 levels with a vertical grid increment of 20 m at the lowest level and is stretched to an increment of 500 m at 13.1 km, which is the model top. At the lateral boundaries, a radiation condition is applied to the normal velocity assuming constant phase propagation. A linear radiation condition is used at the upper boundary to mitigate the spurious reflection of upward propagating gravity waves. Simulations are conducted using an upstream reference state representative of the conditions under which rotors form in the real atmosphere; in particular a vertical profile approximating the conditions upstream of the Colorado Front Range on 1200 UTC 3 March 1991. This is a few hours prior to a B737 crash at the Colorado Springs, CO airport that was initially linked to rotors and near the time when rotor clouds were observed in vicinity. The model topography is specified as a 1000-m high elongated ridge with a half-width of 15 km on the upstream portion and 5 km on the downstream side. In several experiments, a 500-m circular peak with a half-width of 7.5 km superposed on the uniform ridge (Fig. 1) is used to investigate the sensitivity of the rotor dynamics to topographic variations in the cross-flow direction.

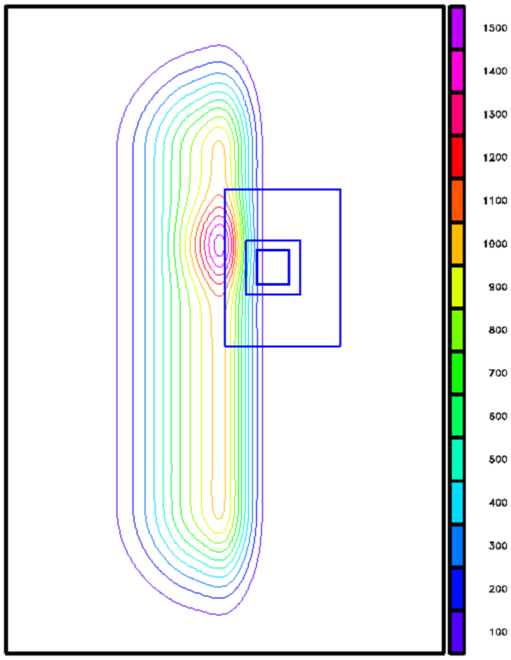

Fig. 1. Terrain height (m, color scale) for the third grid mesh (Δx=600 m) of the model. The locations of the fourth (Δx=200 m), fifth (Δx=67 m), and sixth (Δx=22 m) nested grid meshes are shown by the blue rectangles.

The results from a simulation using the elongated ridge with the circular peak indicate a thin sheet of high-vorticity fluid develops adjacent to the ground along the lee slope and then ascends abruptly as it is advected into the updraft at the leading edge of the first trapped lee wave. This sheet of vorticity is apparent in the vertical section of the y-component of vorticity and streamlines averaged for the 3-4 h simulation period as shown in Fig. 2a. The vertical section is oriented along the mean flow and perpendicular to the ridge axis. This vortex sheet is primarily forced by mechanical shear associated with frictional processes at the surface. Instability of the horizontal vortex sheet occurs along the leading edge of the "parent" rotor and coherent sub-rotor circulations subsequently develop, as shown in Figs. 2b-c for the 200 min. and 202 min. simulation times. These sub-

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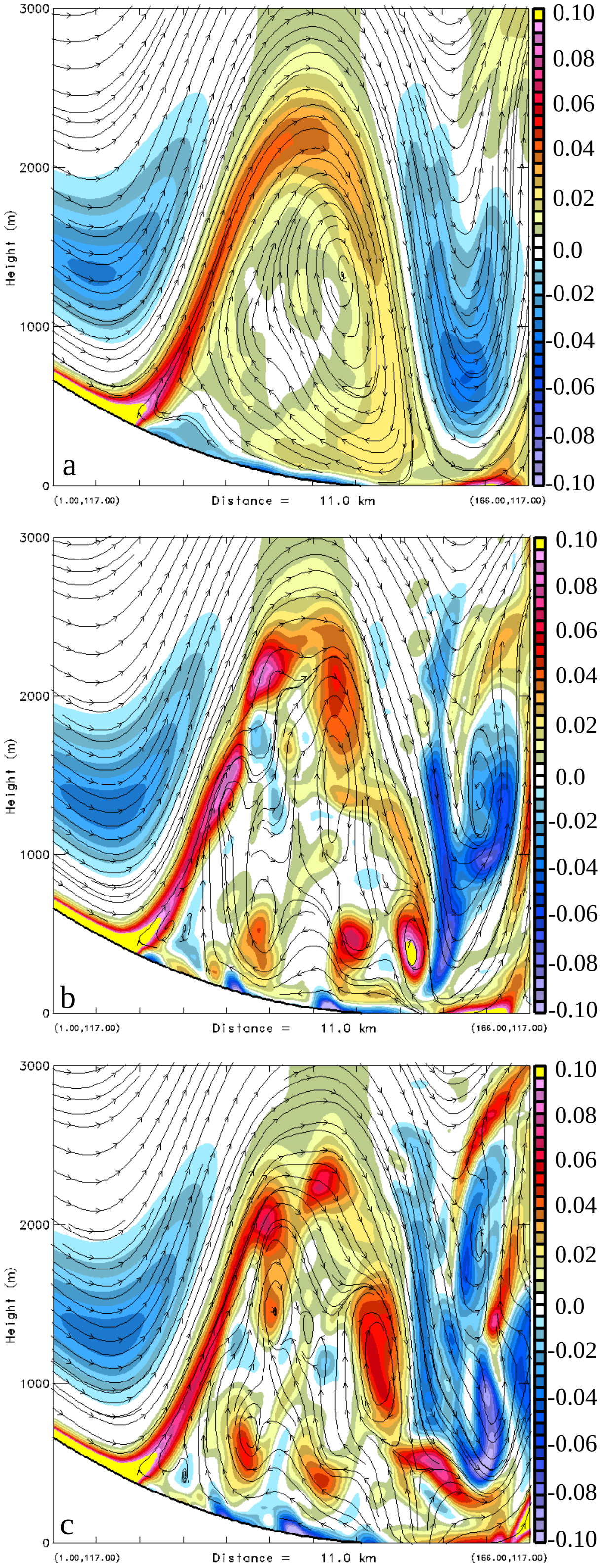

Fig. 2. Vertical section of the streamlines and y-component of the vorticity (color scale, s^{-1}) from grid mesh 5 (Δx=67 m) for the (a) 3-4 h mean fields, (b) 200 min. simulation time, and (c) 202 min. simulation time.

rotors intensify and are advected downstream or back toward the mountain into the parent rotor at low-levels leading to an enhancement of the near-surface horizontal vorticity.

The y-component of the horizontal vorticity within the sub-rotors are enhanced several fold. A preliminary vorticity budget indicates that horizontal vorticity generation due to the stretching of vorticity is 2-3 times larger than tilting and 5-10 times larger than baroclinic generation. The horizontal vorticity generation appears to be enhanced near the edges of the wake emanating from the circular peak due to vortex stretching of the parent rotor and also further maximized due to stretching associated with three-dimensional turbulent eddies. The results suggest that preferred regions of intense rotors may exist near topographic features that enhance vortex stretching. A second simulation with a uniform elongated ridge without a circular peak contains substantially shallower and weaker rotors and sub-rotors, which may result in part from a decrease in the stretching of the vortex sheet.

3. FUTURE DIRECTIONS

The characteristics and dynamics of rotors remain an enigma. High-resolution, three-dimensional simulations suggest that the internal structure of the rotor is complex and contains multiple sub-rotor vortices that are generated along the vortex sheet at the leading edge of the rotor. It is anticipated that remote sensing platforms, with sufficiently high resolution to resolve the internal rotor and sub-rotor circulations, will be required to provide further insight into rotor and sub-rotor dynamics that will ultimately lead to reliable forecasting methods. The forthcoming Terrain-Induced Rotor Experiment (T-REX), which will have two measurement phases during 2004-2006, will collect observations to help unravel the mystery of mountain-wave induced rotors and sub-rotors.

ACKNOWLEDGEMENTS

The research for the first author (JDD) was supported by ONR PE-0601153N. The participation of the second author (DRD) in this research was supported by NSF grant ATM-0137335. Computing time was supported by a grant of HPC time from the DoD MSRC at Vicksburg MS. COAMPS^{TM} is a trademark of the Naval Research Laboratory.

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