Air Circulation Modeling Over Steep Coastal Mountains

By Dinah Luneke and Gary Sivak

This high priority project, "Coastal Mesoscale Modeling" was run at ASC MSRC in FY04 by Principal Investigator Dr. James Doyle of the Naval Research Laboratory, Monterey, California.

Wind current flows along mountains including coastal topography, create a phenomena known as rotors and sub-roters, which, if unanticipated by pilots can result in near- or fatal disasters.

Too Much, Too Little, or Just Right

How much resolution in the model is sufficient to represent the key processes? These researchers found the explicit numerical simulation of the small-scale circulations, known as rotors and sub-rotors, are computationally demanding because of the temporal and spatial scales involved. Too large of a scale, and the model lacks fidelity (accuracy and faithfulness to reality). Too small of a scale, the problem is no longer computationally feasible and the researcher is simply wasting precious HPC computer time.

For example, the principle model employed by this project, Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS®) is typically used with a horizontal resolution of 3-9 km on the finest nested grids for operational applications supporting the Navy and DoD. For the research simulations required for this project, Dr. Doyle was interested in temporal scales of six hours or more, and horizontal scales ranging from less than one kilometer to 1,000 kilometers.

"The study of stratified flow over and around topography is one of the classical theoretical problems in atmospheric and oceanic dynamics," Dr. Doyle stated.

Dr. Doyle provides the rationale that mountain waves are thought to have important influence on the atmosphere because:

- The collective effect of mountain-wave drag on the atmospheric general circulation
- Down slope windstorms
- Vertical mixing
- Clear-air turbulence
- Optical turbulence that impacts high-energy laser weapon systems

Forecasting of orographic (topographic) flows remains a challenging problem for Navy and DoD researchers because of their impact on operations in many environments including coastal regions.

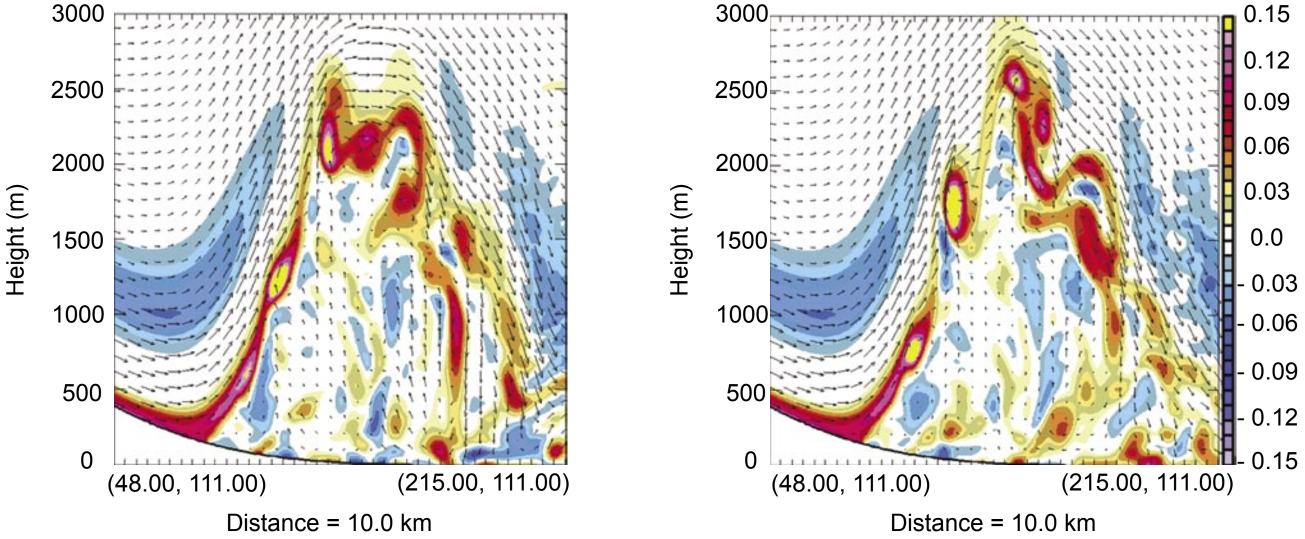

Figure 1. Vertical section of the wind vectors and y-component of the vorticity (color scale, s^{-1}) from grid mesh 5 (Δx=60 m) for the (b) 204 min. and (c) 206 min. simulation times.

The Mountain-rotor Connection

This study investigated the dynamics of rotors forced by three-dimensional topography through a series of high-resolution idealized simulations.

“This type of research simulation can only be performed on large supercomputers, such as those within the DoD HPCMP,” Dr. Doyle explained. “A single simulation of a four-hour duration requires approximately 24 hours of computational time using 120 processors on the SGI Origin 3900 at the ASC MSRC. Many simulations can be conducted to explore the sensitivity of the rotor and mountain evolution to changes in the terrain shape and the background atmospheric state, including wind and stability profiles. Thus, the computational resources available from the DoD HPCMP were critical for the success of these simulations, and this project.”

Going With the Flow

Vortices, or rotors, represent severe aeronautical hazards due to intense wind shear and have been cited as contributing to numerous aircraft accidents, including occurrences involving modern commercial and military aircraft. This type of phenomena is thought to be common in steep mountainous regions. Topographic effects near a coast impact the weather conditions and make for challenging weather forecasts. Studies include a variety of weather conditions with different coastlines and topography, such as the “Bora” - the cold, strong northeasterly winter wind that occurs on the northern part of the Adriatic Sea, and affects ocean circulation.

Although mountain waves have been intensively studied for decades, relatively little attention has been given to the impact of boundary layer effects on wave dynamics, in part because of the difficulty in treating these processes in a theoretical manner. One important example is the determination of the onset of flow separation, that is, the uncoupling of laminar (boundary layer near surface) flow, and turbulent (distant free wake) flow. This flow separation results in a fundamental change in character of the turbulent flow over an obstacle. Therefore, in spite of their obvious importance, mountain-induced rotors still remain poorly understood, particularly with respect to three-dimensional aspects of the air flow.

Rotating Rotors

This investigation focused on the high-resolution simulation of the internal structure of rotors-circulation flows of air that form on the downwind or leeward side of a mountain. Dr. Doyle focuses on the dynamics of small-scale, extremely strong winds and turbulence produced within rotors that he refers to as sub-rotors, which may be the most hazardous aspect of rotor circulations with respect to aviation safety. Wind shear and its associated aviation problems are well-documented phenomena.

The results from Dr. Doyle’s research involved a series of high-resolution simulations that indicate that 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 wind vectors shown in Figure 1. In this case, the rotor is a tube of air with its axis parallel to the mountain ridge, such as pointing west to east. The rotor spins, as if it were rolling up the mountain, so the motion of the air flow is always perpendicular to the axis of the mountain.

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“Mountain waves may be accompanied by severe downslope winds near the surface, occasionally in excess of 50 meters per second, that rapidly decelerate in the lee and flow toward the mountain as part of an intense circulation (Figure 2),” Dr. Doyle said.

Figure 2. Mountain wave lenticular clouds, rotor cloud, and blowing dust over the Owens Valley in the lee of the Sierra Nevada (from Robert Symons). The flow is from right to left.

In particular a vertical profile approximates the conditions upstream of the Colorado Front Range on 12 UTC (universal time) 3 March 1991. This is a few hours prior to a B737 crash at the Colorado Springs Airport that was initially linked to rotors, near the time when rotor clouds were observed in the vicinity.

Why Study Coastal Wind Currents?

The earth’s topography plays an important role in the generation of a multitude of extreme weather phenomena that can adversely impact military operations for the Navy and DoD. Because of the prevalence of hills and mountains included in coastal regions, it is critically important that numerical models, such as COAMPS® accurately predict the weather associated with mountain flows. The results from this study provide insight into the characteristics of intense topographic flows that adversely impact military aviation, military weather forecasting, ground-based operations, and pilot safety.

For more information, please contact the ASC MSRC Service Center at msrchelp@asc.hpc.mil, or (888) 677-2272 or (937) 255-1094.

References

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