SIERRA WAVES AND ROTORS: A STUDY OF THE SIERRA ROTORS IOP 8 EVENT

Vanda Grubišić[1] and Brian J. Billings[1]

[1]Desert Research Institute, 2215 Raggio Parkway, Reno, NV 89512, USA
E-mail: Vanda.Grubisic@dri.edu

Abstract: The Sierra Rotors Project took place in March and April 2004 in Owens Valley, California to study terrain-induced rotors. An intense rotor event was documented during Intensive Observing Period (IOP) 8 on 24-26 March 2004. The event was characterized by a cold frontal passage and strong westerly flow at the mountain top level that induced mountain waves and rotors over Owens Valley. This case was simulated with the Naval Research Laboratory's (NRL) Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS™) run at 333 m resolution. In this study, we analyze the evolution and structure of the observed and simulated mountain waves and rotors during the IOP 8 event, in which horizontal circulation associated with the rotor extended to the valley floor, where it was observed as easterly flow by the DRI mesonetwork of surface stations. The model accurately reproduced the timing and spatial structure of many of the observed phenomena, including thermally forced flow in the valley at the start of the event, an intense mountain wave during the period of observed surface easterly flow, and strong westerlies on the Sierra Nevada lee slopes.

Keywords – Sierra Nevada, Sierra Rotors Project, T-REX, mountain waves, rotors

1. INTRODUCTION

Atmospheric rotors, intense low-level horizontal vortices that form along an axis parallel to and downstream of a mountain ridge crest, can pose severe aeronautical hazards. A multi-year, multi-phase initiative has been launched recently to study atmospheric rotors as well as low- and upper-level turbulence in complex terrain (Grubišić and Kuettner 2004). The Sierra Rotors Project (SRP) represents exploratory Phase I of this effort. The SRP was designed to establish quantitative characteristics of the rotor behavior in Owens Valley, in the lee of the Sierra Nevada, including the rotor type, location and frequency distribution of the related mountain-wave events, and to determine the extent to which current operational mesoscale models can reliably forecast the occurrence of rotors. The information obtained in Phase I has been used in preparation for a more extensive Phase II, the upcoming Terrain-induced Rotor Experiment (T-REX; Grubišić et al. 2004). In this paper, we present the analysis of observations and results of numerical model simulation of one of the strongest wave and rotor events from SRP that occurred during Intensive Observing Period (IOP) 8 on 24-26 March 2004.

2. IOP 8 ROTOR EVENT

2.1. Instrumentation and Data

The SRP took place in Owens Valley in the southern Sierra Nevada of California (Fig. 1). The eastern slopes of the southern Sierra Nevada make up the tallest, steepest, quasi-linear topographic barrier in the contiguous United States and are well known for generating large-amplitude Sierra Waves and attendant strong rotors over Owens Valley. The SRP instrumentation in Owens Valley consisted of the Desert Research Institute (DRI) mesonetwork of automated surface stations with telemetry, two National Center for Atmospheric Research (NCAR) Integrated Sounding Systems (ISS), the Mobile Integrated Sounding System (MISS) and the Multiple Antenna Profiler/ISS (MAPR/ISS), a time-lapse video camera system, and an instrumented vehicle. Each ISS contains a 915 MHz boundary-layer radar wind profiler, a Radio Acoustic Soundings System (RASS) for temperature profiling, surface sensors for wind, temperature, relative humidity, and radiation, and a balloon-borne rawinsonde sounding system. In addition, two rawinsonde systems were located upstream of the Sierra Nevada in Central Valley. A stationary system was located at the Naval Air Station Lemoore and the NCAR's Mobile GPS Atmospheric Observing System (MGAOS) was located near Fresno.

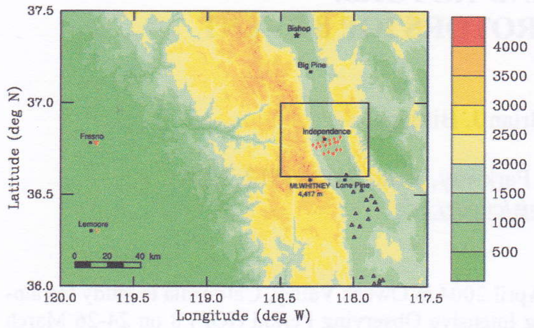

Figure 1 Base map of the Sierra Rotors Project (SRP) location and instrumentation. Red symbols show the location of the SRP instrumentation. Shown is also a preexisting network of the Great Basin Unified Air Pollution Control Distrct (GBUAPCD) automatic weather stations clustered around the dry Owens Lake bed at the southern end of Owens Valley (from Grubišić and Kuettner 2004).

The IOP 8 extended from 18 UTC March 24 to 18 UTC March 26. The 24-hour period from 12 UTC March 25 to 12 UTC March 26 was the core period, during which the strongest waves and rotors were observed in Owens Valley. During the core period rawinsonde releases in Owens Valley and upwind were carried out every 3 hours. In this paper, we present selected observations from the DRI surface mesonetwork as well as the upstream rawinsonde systems. A companion paper by Grubšić et al. (2005) delivers the comparison of model simulation results with the wind profiler measurements.

2.2. Synoptic Overview

The west coast upper-air pattern at the start of IOP 8 (18 UTC March 24) was dominated by a closed low off the coast of British Colombia and an associated shortwave trough that extended sufficiently far south to bring southwesterly flow over the southern Sierra Nevada. This disturbed flow steered two different surface cyclones onto the US west coast during the next seventy-two hours. The trailing cold front of the first storm dissipated before it reached the west coast of California. The second cyclone and its trailing cold front began to move onshore at 00 UTC March 26. The surface system was followed by the eastward propagation of the upper-level trough, creating strong winds over the southern Sierra Nevada and leading to advection of ample moisture over the area. It was before the cold frontal passage at 09 UTC March 26 that large mountain waves and rotors formed in the valley. This synoptic pattern with strong cross-barrier flow and pre-frontal stability has previously been identified as conducive to strong mountain-wave generation in the lee of the southern Sierra Nevada (Holmboe and Klieforth 1957).

2.3. Observations

The morning of 25 March began with weak thermal circulations in the valley (southerly, up-valley flow in the middle, flat part, of the valley and southeasterly flow on the western slope), although upper-air soundings showed that winds were quite strong aloft. By the afternoon, surface winds had increased and turned to westerly throughout the valley, reaching their maximum value at approximately 01 UTC March 26 (17 PST March 25). Two hours later, while winds remained westerly at stations along the western slope, stations in the middle of the valley began to observe an easterly wind. This is strongly suggestive of the horizontal circulation of a rotor reaching the valley floor. A lee-wave induced low-pressure perturbation forcing the reversed, easterly, flow at the ground is evident in the reduced pressure field (Figure 2).

3. MODEL SETUP AND RESULTS

The model used in this study is NRL's COAMPS (Hodur 1997). The run discussed here was carried out on six stationary nested domains with resolutions of 81, 27, 9, 3, 1, and .33 km. Sixty vertical sigma levels were used with finer resolution in the lower levels, the model top at 34.8 km, and a 10.4 km thick absorbing layer at the top. The NRL's Naval Operational Global Atmospheric Prediction System (NOGAPS) data was used for initial conditions and 6-hourly boundary updates. The control simulation was initiated at 12 UTC March 23, and, after a 12 hour spin up period, a full incremental update was applied at 00 UTC March 24, after which point the simulation was run for seventy-two hours. All parameterizations and model physics options used were the default COAMPS options.

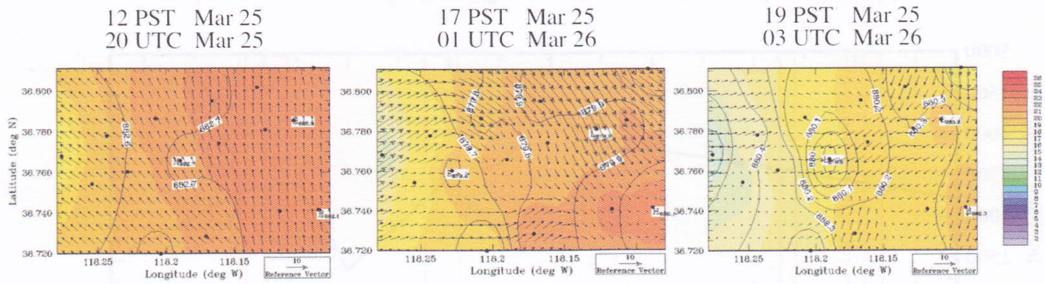

Figure 2 Surface observations by the DRI mesonetwork (black dots) during 25 March 2004 in SRP IOP 8. Temperature (°C in color), wind vectors, and reduced pressure (hPa) are shown at three different times during the day. For the discussion see text above.

During the morning of the rotor event (March 25), thermally forced circulation patterns were observed in the valley, with southeasterly upslope winds on the western slope and southerly, up-valley, flow in the middle part of the valley (Figure 2). In the model simulation, upslope flow does develop along the lee slope of the Sierra at the times they were observed but the northerly flow prevails in the middle part of the valley all the way up to 20 UTC (12 PST), close to the start of the strongest part of the wave event.

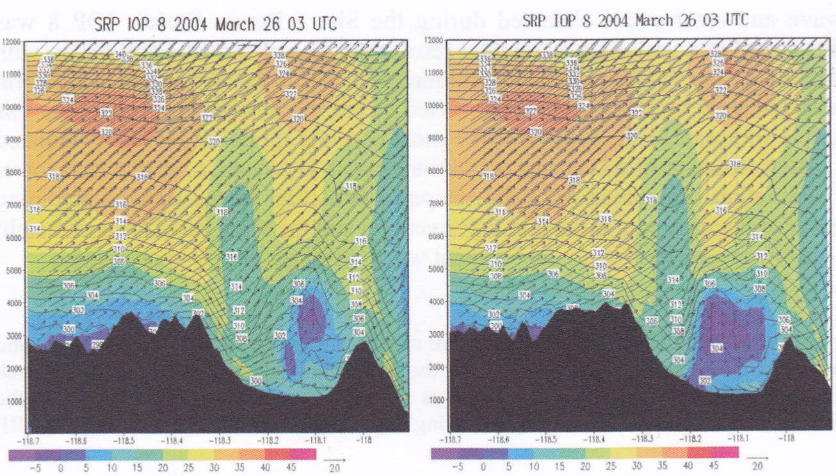

Figure 3 Model predicted isentropes (K), westerly component of wind speed (m s-1 in color), and wind vectors in the vertical cross-sections along the middle and southern line of DRI surface stations at 03 UTC March 26. A strong resonant low-level wave and an elevated rotor are seen in both of these sections but there is no reversed flow at the ground.

By late afternoon, strong westerlies had developed throughout the valley, and wave and roll clouds were observed. Figure 3 shows model solutions at 03 UTC March 26 (19 PST March 25) in two vertical cross-sections parallel to the middle and southern line of surface stations. The isentropes reveal a large amplitude wave over the valley. Underneath the wave crest is an area of easterly flow, a sign of the rotor. Neither at this time nor any other time does the simulated rotor extend to the valley floor in the model solutions. The transition from the thermally forced flow to strong westerly winds throughtout the valley is accurately reproduced by the model but the strength of the lee side downslope winds is overpredicted on the lee slope.

While a single large amplitude wave dominated the valley during the observed periods of reversed flow at the ground, shorter wavelength trapped lee waves were simulated before and after this period. Observed wind profiles from upstream MGLASS radiosondes launches match these transitions. Before and after the rotor event, the mountain normal wind speed decreases very rapidly with height above 2500 meters, leading to a sharp decrease of the Scorer parameter with height. Wind speeds during the rotor event were also found to decrease with height, but not as rapidly as when the trapped lee waves were observed. An inversion at the mountain top level is another dynamical ingredient required for a strong low-level wave response. Figure 4 shows a time series of upstream inversion height derived from the MGLASS and Lemoore soundings. Red boxes in this figure mark the time periods when strong westerly winds were observed in the valley, exceeding 7.5 m s^{-1} at both of the two westernmost stations on the northern line (stations 1 and 2) of the DRI network. These times appear to correlate very well with inversion located approximately at the Sierra Nevada ridge height (~ 3200 – 3600 m).

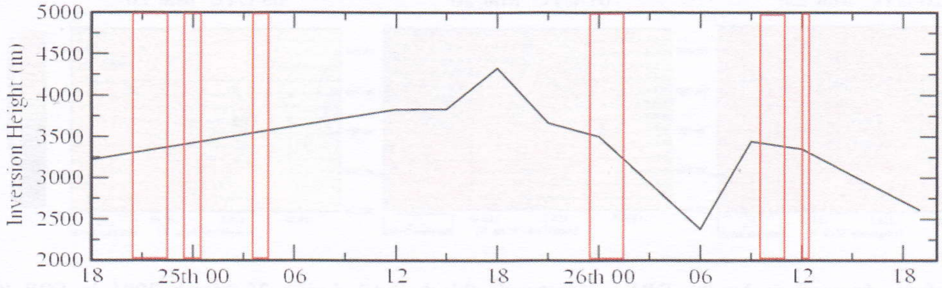

Figure 4 Time series of the upstream inversion height determined from the MGLASS soundings. The red boxes mark the periods of strong westerly winds in Owens Valley, exceeding 7.5 m s^{-1} at both stations 1 and 2 of the DRI network. These periods correlate well with the base of the inversion located at approximately the Sierra Nevada ridge height.

4. CONCLUSIONS

An intense mountain wave and rotor event observed during the Sierra Rotors Project IOP 8 was simulated with the COAMPS model at a very high horizontal resolution. The observed event began with the thermally forced circulations in the valley, which transitioned into a strong downslope windstorm leading eventually to the reversed flow on the valley floor. Based on all the available observations this surface reversed flow is likely a footprint of the rotor. For the most part, the model accurately simulated the temporal evolution and spatial structure of this strong wave/rotor event. However, only elevated rotors were present in the model simulation. Examination of the temporal evolution of the upwind sounding profiles point to the importance of the upstream mountain top inversion and the wind increase with height in trapping the wave energy at low levels, leading to the resonant wave response over Owens Valley.

Acknowledgements: The high-resolution real-data COAMPS runs were carried out on the Mesoscale Dynamics and Modeling Laboratory's 68-processor Sierra cluster at DRI funded by the NSF grant ATM–0116666. This research was supported in part by the NSF grant ATM–0242886. The SRP was a joint effort between DRI, NRL, and the University of Washington. We thank Dale Durran, Jim Doyle, and Qingfang Jiang for their efforts during the SRP field phase.

REFERENCES

Grubišić, V., and J. P. Kuettner, 2004: Sierra Rotors and the Terrain-induced Rotor Experiment (T-REX) *Proceedings. 11th Conference on Mountain Meteorology/MAP Meeting.* Bartlett, NH, Amer.Meteor. Soc., Avaiable online at http://ams.confex.com/ams/11Mountain/techprogram/paper_77364.htm.

Grubišić, V., J. D. Doyle, J. Kuettner, G. S. Poulos, and C. D. Whiteman, 2004: Terrain-induced Rotor Experiment (T-REX) Overview Document and Experiment Design. 72 pp.

Grubišić, V, B. J. Billings, S. A. Cohn, and W. J. Brown, 2005: Sierra Rotors IOP 8: Comparison of model simulations and wind profiler observations of terrain-induced waves and rotors. *Proceedings. International Conference on Alpine Meteorology/MAP Meeting, Zadar, Croatia.*

Hodur, R. M., 1997: The Naval Research Laboratory's Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS). *Mon. Wea. Rev.,* **111**, 1414–1430.

Holmboe, J. R., and H. Klieforth, 1957: Investigation of mountain lee waves and the airflow over the Sierra Nevada. Final Report. Department of Meteorology, UCLA, Contract AF 19(604)-728, 283 pp.