2.1 SIERRA ROTORS AND THE TERRAIN-INDUCED ROTOR EXPERIMENT (T-REX)

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1. INTRODUCTION

Atmospheric rotors, low-level horizontal vortices that form downstream of and parallel to the crest of a mountain range in close association with large-amplitude mountain waves, can pose severe aeronautical hazards and have been cited as contributing to numerous aircraft upsets and accidents involving commercial, military and civilian aviation (Carney et al. 1988). On the dry lee sides of mountain ranges, rotor circulations can be important for the lofting and transport of aerosols and chemical and biological contaminants (Raloff 2001). Despite their considerable impact on human activity, and in contrast to the attendant mountain waves, rotors remain relatively poorly understood atmospheric phenomenon. One reason that so little is known about the dynamics of rotors and their internal structure is that it is very hard to measure the flow within a rotor. Rotors are dangerous and difficult to sample using in situ aircraft measurements, and they are intermittent phenomena that are too small in spatial scale to be routinely sampled by conventional observing networks.

A brief historical overview of early studies of rotors is given in Hertenstein and Kuettner (2002). Most of the previous observational evidence and scientific documentation of rotors comes from the Sierra Wave and the Mountain Wave-Jet Stream Projects in the 1950's (Holmboe and Klieforth 1957; Kuettner 1959) as well as the Colorado Lee Wave Program from the late 1960's and early 1970's (Lilly and Toutenhoofd 1969; Lester and Fingerhut 1974). Recently, rotors have received renewed attention (Doyle and Durran 2002, 2004; Hertenstein and Kuettner 2004; Mobbs et al. 2004) due in part to advances in high-performance computing that have made non-hydrostatic model simulations possible at resolutions needed to numerically resolve the rotors. With the emergence of remote sensing observational techinques that allow documentation of rotors without attempting to penetrate these zones of severe turbulence with research aircraft, experimental documentation of rotors and their internal structure appears within reach fifty years after the launch of the Sierra Wave Project (Grubišić and Lewis 2004).

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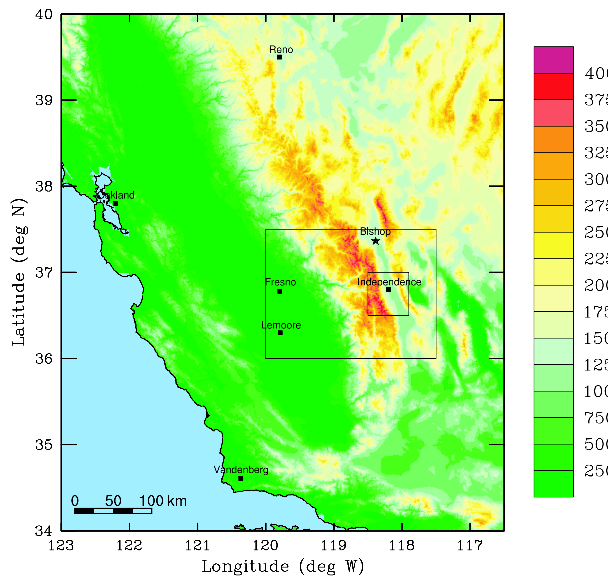

Figure 1: Overview map of the Sierra Nevada mountain range and the T-REX project area. The two inset rectangles enclose the area of the Phase I, Sierra Rotors Project, field operations shown in more detail in Fig. 2.

The Terrain-induced Rotor Experiment (T-REX), an initiative focused on atmospheric rotors and low- as well as upper-level turbulence in airflow over complex terrain, is a response to this new surge of scientific interest in rotors. T-REX is envisioned as a two-phase effort, with experimental activities centered on Owens Valley in the southern

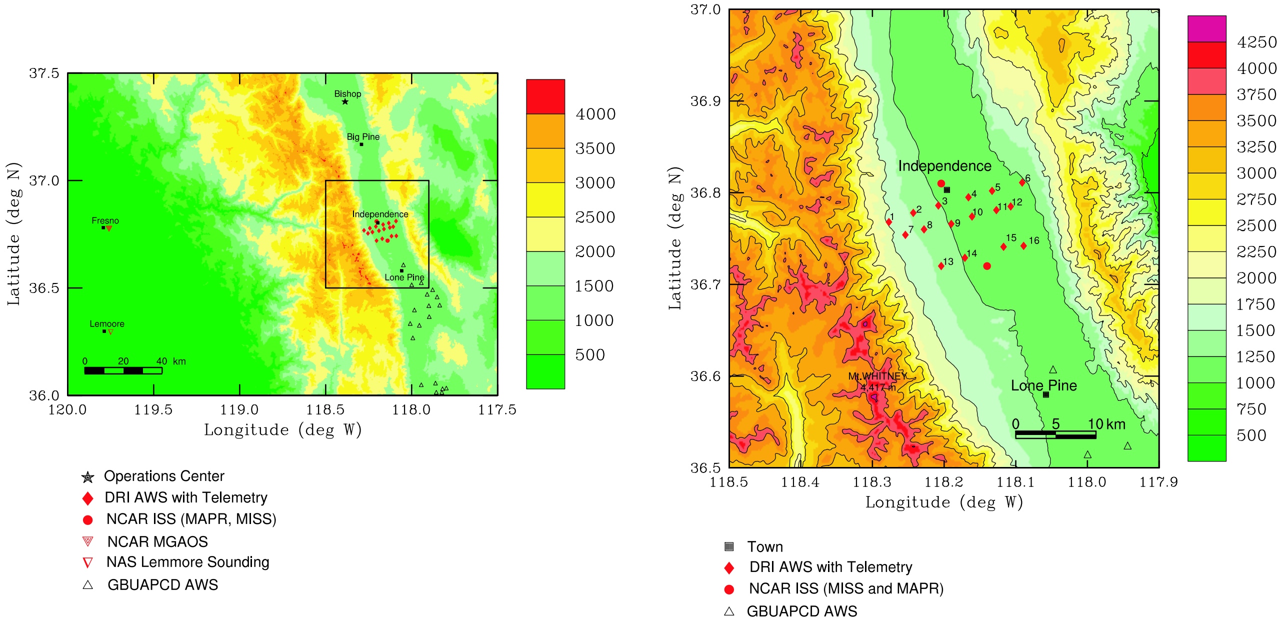

Figure 2: Left: The Sierra Rotors Project field area with the deployed ground instrumentation. Marked is also the preexisting GBUAPCD network of automatic weather stations. Right: An enlargement of the central portion of the Owens Valley and the southern Sierra Nevada showing the DRI ground AWS network and the two NCAR ISS.

Sierra Nevada in California (Fig. 1). The currently ongoing NSF-funded Sierra Rotors Project, with its recently completed Special Observation Period, represents the core of Phase I of T-REX and was designed to establish quantitative characteristics of the rotor behavior in Owens Valley including the rotor type, location and the frequency distribution of the related mountain-wave events. A description of the ground-based field activities of the Sierra Rotors Project, a short preliminary overview of its findings, and plans for future observations are presented in section 2. The hallmark of the planned Phase II of T-REX is a major field experiment, discussed in section 3, featuring the latest advances in remote sensors and an airborne observing program. This phase of T-REX will explore the interaction of lee waves, rotors and related turbulence zones by probing the mesoscale airflow between surface and 20 km altitude.

2. PHASE I: SIERRA ROTORS PROJECT

The Sierra Rotors Project (SRP) was designed to establish the physically-based climatology of the rotors and the related mountain-wave events in the Owens Valley and to determine the extent to which current operational mesoscale models can reliably forecast the occurrence of rotors. In addition to the ground-based observing program described below, an integral part of the project are the theoretical/numerical studies of rotor flow dynamics with mesoscale and microscale models and a climatological study of mountain wave events employing satellite data (Grubišić and Cardon 2002).

The ground-based observing program of the Sierra Rotors Project (SRP) is being directed by the Desert Research Institute (DRI; Grubišić) in collaboration with the University of Washington (UW; Durran), the Naval Research Laboratory (NRL; Doyle), and the National Center for Atmospheric Research (NCAR; Kuettner). The Special Observation Period (SOP) of SRP took place in March and April 2004. The field site and the instrumentation deployed in the SOP are described in the following section. The Sierra Rotors Project is expected to yield new insight into the dynamics of rotors and their relation to the large-amplitude mountain waves and severe downslope wind events.

2.a Field Site and Instrumentation

The central portion of Owens Valley, near town of Independence, was the site of the SOP activities (Fig. 2). The Owens Valley, a narrow rift valley confined between two high mountain ranges, is the location of the steepest orographic gradients in the contiguous United States. The two mountain ranges are the White-Inyo Range to the east and the Sierra

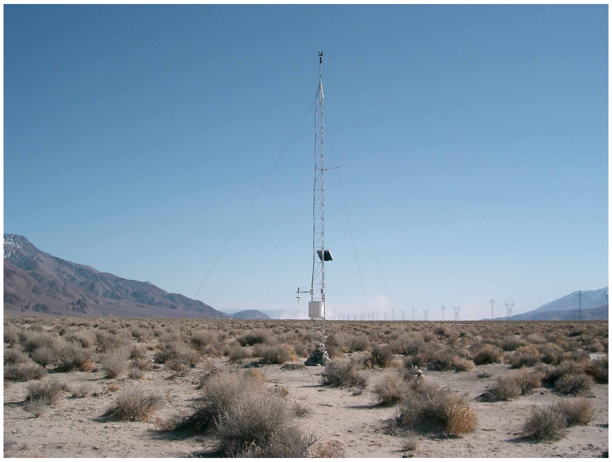

Figure 3: Automatic weather station 12 of the DRI ground network. Dust from the Owens (dry) Lake bed lifted up by strong northerly winds is visible at the south end of the Valley.

Nevada to the west. The southern portion of the Sierra Nevada, in between towns of Big Pine and Lone Pine, is the tallest, steepest, quasi-two dimensional barrier in the lower 48 states with a number of peaks above 4,000 m including the highest peak in the contiguous United States (Mount Whitney; 4,418 m). The average elevation difference of 3,000 m between the valley floor and the Sierra crest occurs over a horizontal distance of less than 10 km (Fig. 2). This portion of the Owens Valley was also the site of the 1950's Sierra Wave and the Mountain Wave-Jet Stream Projects.

The core of the instrumentation deployed in the SOP consisted of the network of automatic weather stations (AWS) with telemetry, designed at DRI and installed for this project in collaboration with the DRI's Western Regional Climate Center (WRCC). The DRI network consists of 16 AWS arranged in three approximately parallel rows. The average separation between individual stations along these three lines is approximately 3 km (Fig. 2). Each station is equipped with a RM Young anemometer with fuselage and tail wind vane for the standard wind measurement at 10 m, a combined temperature/relative humidity Väisäla sensor with a shield for temperature and relative humidity measurement at 2 m, and a Väisäla PTB210 microbarometer with a static pressure head for precise pressure measurement, all mounted on a standard 30 ft (10 m) meteorological tower (Fig. 3). A CR10X Campbell Scientific data logger and a 900 MHz Freeway spread-spectrum radio are placed within a weather-resistant tower-mounted enclosure. The stations' sensors are sampled every 3 seconds, and the data is temporally averaged over 30-second non-overlapping intervals. The temporaly-averaged data are saved on the stations' data loggers before being sent via radio communication to the base station at the Unified Middle/High school in Independence. From there, the data transfer to the central repository at DRI is carried over Internet, allowing near real-time online access to the graphically-displayed data (http://www.wrcc.dri.edu/trex/).

During SRP SOP, additional instrumentation in the project area was deployed by the NCAR's Atmospheric Technology Division (ATD) Research Technology Facility (RTF). Two Integrated Sounding Systems (ISS) were deployed in Owens Valley and an atmospheric sounding system was deployed upwind in San Joaquin Valley. The two ISS are the NCAR Multiple Antenna Profiler/ISS (MAPR/ISS) and the Mobile Integrated Sounding System (MISS). SRP was the first field deployment of MISS, which is designed to make measurements similar to those made by the regular ISS (Parsons et al. 1994), but with the ability to move more quickly between locations (Cohn et al. 2004). MISS sensors include a 915 MHz boundary layer radar wind profiler, a Radio Acoustic Sounding System (RASS) for temperature profiling, and surface sensors for wind, temperature, relative humidity, and radiation, and a balloon-borne radiosonde sounding system (Fig. 4). The Independence airport, north of town, was the home site for MISS. A number of suitable deployment sites was determined in advance of the project, and a subset of those used during the SOP. Unlike

Figure 4: NCAR Mobile Integrated Sounding System (MISS) trailer, 915 MHz wind profiler antenna, and RASS at an east Owens Valley location. The snow-covered eastern Sierra Nevada slopes are visible in the background.

MISS, MAPR/ISS is a fixed system, and was located just south of the main SRP AWS array (Fig. 2). MAPR is a unique spaced antenna (SA) boundary layer wind profiler (Cohn et al. 2001) that measures the wind vector while pointing continuously in the vertical (Fig. 5). Unlike the more common Doppler beam swinging profilers, such as that used at MISS, that rotate between several beam directions and provide a wind vector about every 30 minutes, SA profilers provide a horizontal wind vector every few minutes (5-min is typical) and a vertical measurement every dwell (approximately 30 seconds). All NCAR data were periodically transferred back to Boulder using a mobile internet satellite system, plotted, and displayed on the project web page (http://www.atd.ucar.edu/rtf/projects/srp2004/).

Figure 5: The antenna of the Multiple Antenna Profiler (MAPR) at the site in Owens Valley. From left to right: Bill Brown (NCAR/ATD), Bruce Morley (NCAR/ATD), and Joachim Kuettner (NCAR).

Other instrumentation deployed in the Owens Valley during the SOP includes a time-lapse video camera system deployed by Ron Smith from Yale University, and an instrumented car (Mayr et al. 2002) operated by Georg Mayr from the University of Innsbruck in Austria (http://meteog.uibk.ac.at/trex/).

Given the importance of documenting the upstream thermodynamic and kinematic flow structure for interpreting the mountain wave response, substantial effort has been made to obtain adequate upwind upper-air sounding data. The NWS regular sounding stations closest to the area of interest and upwind of the Sierra Nevada are located in Oakland, CA and at Vandenberg AFB, CA (Fig. 1). During the SOP, two supplemental upstream sounding sites were located in San Joaquin Valley. The NCAR mobile GPS atmospheric sounding system (MGAOS) was based in Fresno, with an ability to change its position to be placed optimally for different upstream wind directions. The Naval Air Station (NAS) Lemoore (675 m ASL), which lies upwind of the Owens Valley under southwesterly winds was the other, fixed site (Fig. 2).

While the ground-based instrumentation was deployed in the central portion of the Owens Valley, the Sierra Rotors Project Operations Center was located in Bishop, at the northern end of the Valley. During the two-month SOP, daily conference calls took place in between the Operations Center, University of Washington, NRL, DRI, and the National Weather Service Las Vegas office (NWS LV). The latter had provided daily weather briefings in support of the Sierra Rotors operations in the Owens Valley and the San Joacqin Valley upwind. In addition, real-time COAMPS model forecasts, run at the horizontal resolution of 3 km in the innermost domain zoomed over the project area, were carried out at NRL in support of the field experiment (http://www.nrlmry.navy.mil/shared-bin/TREX/trex.cgi).

2.b Preliminary findings

Sixteen Intensive Observation Periods (IOPs) were carried out during the two-month SOP, ranging in duration from 4 hours (IOP 3) to 4 days (IOP 12), with the majority of IOPs lasting approximately 12–18 hours. Wave formation over the Owens Valley was observed in approximately half of the IOPs, whereas strong rotor activity was limited to a smaller subset. The majority of wave and rotor events during SOP had occurred in April. An unusually small number of the wave and rotor events in March comes as a consequence of anomalous weather patterns that had prevailed during this month and had caused climatologically extreme March temperatures and low precipitation amounts in the western U.S. (Kelly Redmond, WRCC, private communication 2004). The strongest downslope wind event of the project had occurred during IOP 16, with the maximum winds of 35.8 m s^{-1} (128.8 km h^{-1}) measured by station 1 of the ground network. Figure 6 shows the rotor (roll) cloud observed in the Owens Valley during this IOP. Preliminary analysis of another strong rotor event that had occurred on 25 March 2004 during IOP 8 is discussed in the companion paper by Grubišić and Cohn (2004).

Figure 6: The roll (rotor) cloud observed over the Owens Valley during IOP 16 on 28 April 2004. The foehn wall and foehn clearing are evident over and downwind of the Sierra Nevada to the left. Photo by James Pinto.

2.c Future observations

The DRI network will continue to operate autonomously in 2004 and beyond into Phase II of T-REX. Over the next several wave seasons (fall and spring), radiosonde releases will continue to be carried out at NAS Lemoore, and in conjunction with the DRI ground network data, used to build the climatology of rotors and to address the question of their predictability. In preparation for Phase II, The University of Leeds (Stephen Mobbs) plans to install a network of weather stations without telemetry to be placed further up the mountain slopes from the existing DRI network.

3. PHASE II: WHAT DO WE DO NEXT?

Phase II of T-REX, with a field program of substantially larger scope, is planned for early spring 2006. Results of the Sierra Rotors Project will provide essential scientific guidance in planning for this experiment. Core objectives of Phase II of T-REX are the rotor flow dynamics including rotor/wave interaction, tropospheric and stratospheric gravity-wave breaking, sensitivity of mountain-scale flow to upstream and downstream conditions, numerical predictability of mountain-wave/rotor flows, and the aviation safety aspects under rotor flow conditions. Supporting objectives identified thus far include orographic precipitation mechanisms, rotor/wave climatology, stratospheric/tropospheric exchange, and moisture distribution and microphysics in lenticular clouds.

The emphasis with Phase II instrumentation is on enhanced ground-based remote sensing systems and research aircraft. Among the latest advances in remote sensing instrumentation planned for this experiment for documenting rotors and rotor substructures are dual Doppler lidar and K-band radar arrays. The types of research aircraft requirements to study the airflow between ground and 60,000 ft are illustrated in Fig. 7. They may also include gliders as well as unmanned platforms. Advanced airborne observing systems such as a Microwave Temperature Profiler (MTP) (Denning et al. 1989, Dörnbrack et al. 2002) will also be required. A cooperation with other research programs operating in the area is currently under discussion.

4. SUMMARY

We have presented a short overview of T-REX, a new two-phase international initiative to study mountain-wave/rotor flows, and low- and upper-level turbulence in airflow over complex terrain. The currently ongoing Sierra Rotors Project, with its recently completed Special Observation Period in March and April 2004, represents the core of Phase I of T-REX. The results of the Sierra Rotors Project are expected to yield new insight into the dynamics and predictability of rotors and their relation to the large-amplitude mountain waves and severe downslope wind events, and to provide an invaluable guidance in planning for the large Phase II field experiment.

Acknowledgments. The success of field projects is secured through active collaboration of many individuals and organizations. We thank all those involved in the Sierra Rotors Project for their individual contributions to this project. Special thanks are due to Harold Klieforth for providing office space for the Sierra Rotors Project Operations Center in Bishop and his help with organizational aspects of this project. The Sierra Rotors Project has been funded by the National Science Foundation. The first author was supported in part by the National Science Foundation (NSF), Division of Atmospheric Sciences, Grant ATM–0242886.

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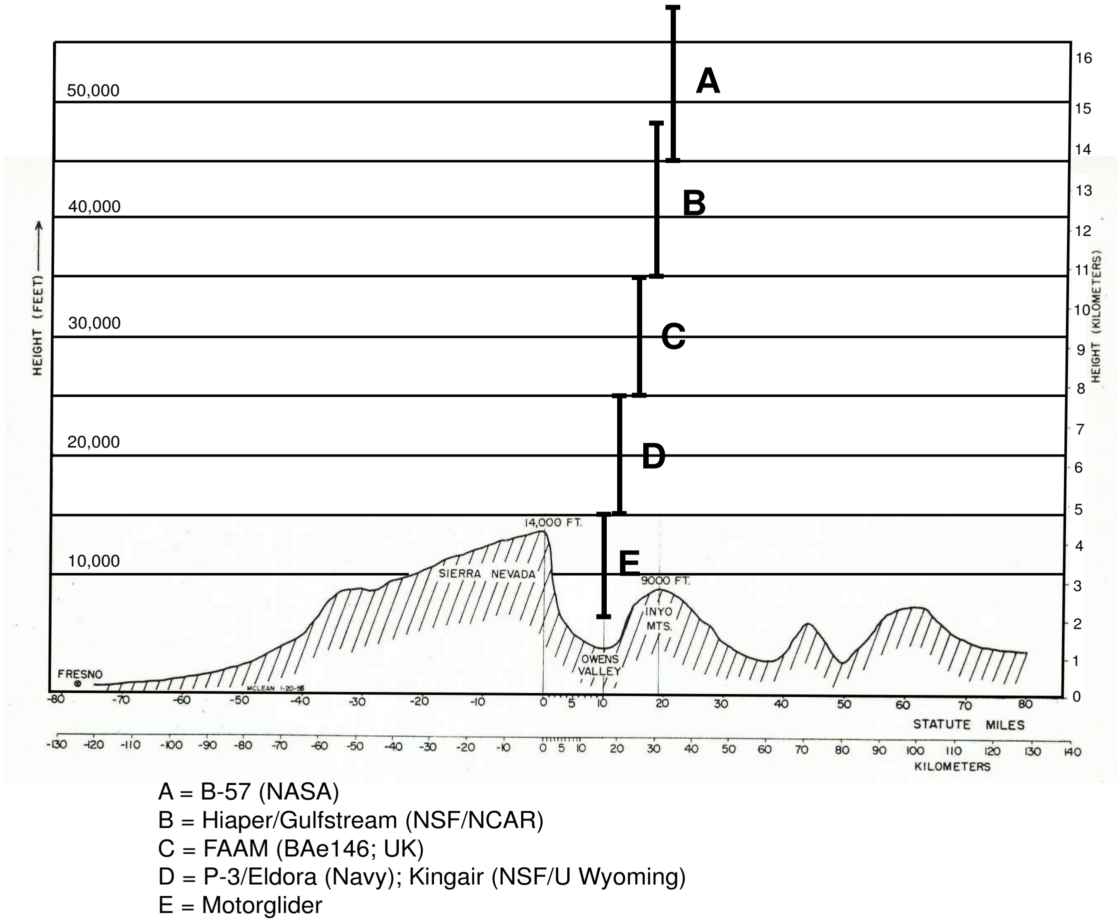

Figure 7: Vertical cross-section over the Sierra Nevada, Inyo Mountains and Owens Valley showing vertical ranges of aircraft planned in Phase II of T-REX.

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