9.1 TERRAIN-INDUCED ROTOR EXPERIMENT

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1. INTRODUCTION

The Terrain-induced Rotor Experiment (T-REX) is the second phase of a coordinated effort to explore the structure and evolution of atmospheric rotors and associated phenomena in complex terrain (Grubišić et al. 2004). The initial, exploratory phase of this effort is the Sierra Rotors Project (SRP), which completed its field activities in March and April 2004. The T-REX Special Observation Period (SOP) took place in March and April 2006 in the lee of the southern Sierra Nevada, in the same location as the SRP two-years earlier. Here we describe scientific objectives, experimental design, unique aspects and challenges of the T-REX field campaign, and provide a summary of special operations. Preliminary scientific findings, which are setting the stage for the upcoming research effort, are reflected in a number of scientific contributions at this conference.

2. SCIENTIFIC OBJECTIVES

Atmospheric rotors are intense low-level horizontal vortices that form along an axis parallel to and downstream of a mountain ridge crest in association with large-amplitude mountain waves. High-levels of turbulence characterize rotors, which are known to pose a great hazard to aviation. Recent numerical, theoretical, and observational studies of rotors (Clark et al. 2000; Doyle and Durran 2002, 2004; Vosper 2004; Hertenstein and Kuettner 2005; Mobbs et al. 2005; Grubišić and Billings 2006a) show that rotors are strongly coupled to both the structure and evolution of overlying mountain waves as well as the underlying boundary layer. Consequently, the overarching objective of T-REX is to study synergistic interaction and coupling between rotors, mountain waves and the boundary-layer dynamics.

The core set of T-REX scientific objectives are focused on **improving the understanding and predictability of the coupled mountain-wave, rotor, and boundary-layer system**. This set of objectives includes: i) the role of the upstream flow properties in determining the dynamics and structure of the rotor coupled system, ii) wave/rotor dynamic interactions, iii) internal rotor structure, iv) rotor/boundary-layer interactions, as well as v) the upper-level gravity breaking and turbulence. Additionally, a set of complementary T-REX scientific objectives include: i) understanding the role of mountain waves in the stratospheric-tropospheric exchange, ii) structure and evolution of the complex-terrain boundary layer in the absence of rotors, and iii) layering and phase transitions in wave clouds.

3. EXPERIMENTAL DESIGN

3.1 *Field Site*

The T-REX field site was the central portion of Owens Valley in the lee of the southern Sierra Nevada in eastern California (Fig. 1). This portion of the Sierra Nevada is the tallest, quasi two-dimensional topographic barrier in the contiguous United States with a number of peaks above 4 km, including the highest peak in the lower 48 states (Mt. Whitney 4,418 m) and the steepest lee slopes ($\sim$30 degrees). The $\sim$3 km high White-Inyo range forms the eastern wall of the valley. Aside from the modest coastal mountain ranges of California, absence of significant terrain upstream causes air masses of a general westerly origin off the Pacific Ocean to experience very little perturbation before reaching the Sierra Nevada western slopes. This portion of Owens Valley was also the site of the 1950s Sierra Wave Project that, while primarily focused on mountain waves, provided some information also on the attendant rotors (Holmboe and Klieforth 1957; Kuettner 1959). March and April were selected as months with the highest frequency of wave and rotor events (Grubišić and Billings 2006b), which, climatologically, include also a fair number of days with more quiescent synoptic conditions suitable for study of terrain-induced boundary-layer circulations in the valley.

3.2 *Types of Special Operations*

In order to achieve its scientific objectives, two types of special operations were conducted during the T-REX field campaign:

1. Intensive Observing Periods (IOP) involving comprehensive ground-based and airborne, in situ and remote sensing measurements conducted in transition toward and during strongly perturbed conditions favoring wave and rotor formation, and

2. Enhanced Observing Periods (EOP) for comprehensive observations of complex-terrain boundary layer structure and evolution within Owens Valley during undisturbed conditions.

3.3 *Instrumentation*

The T-REX experimental design reflects the need to document a coupled system of tremendous vertical extent, reaching from the ground to the upper tropospheric-lower stratospheric altitudes. For this reason, the field

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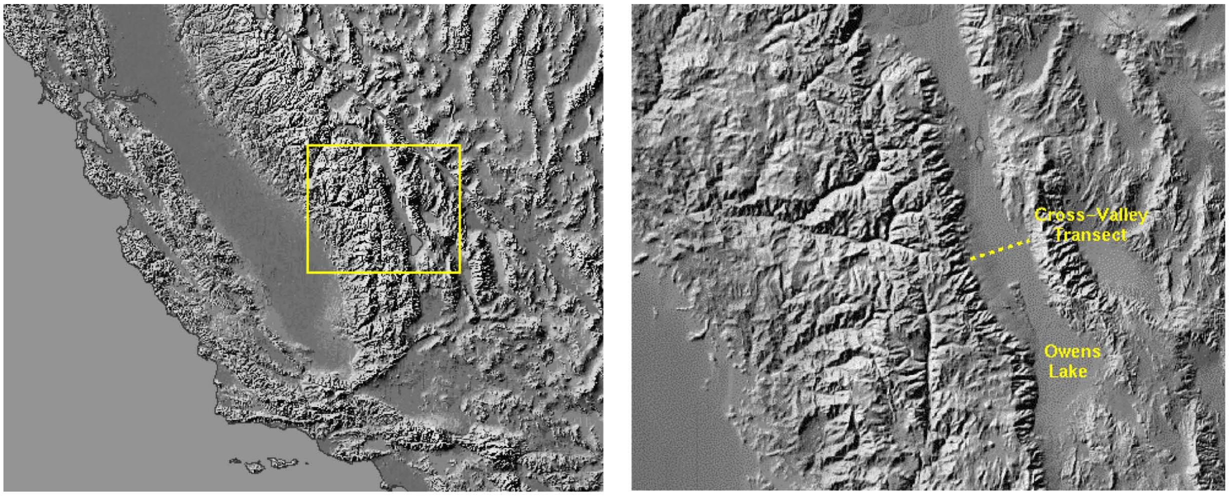

FIG. 1: Shaded relief topographic map of the central and southern Sierra Nevada (left panel) and Owens Valley (right panel). The north-south elongated Owens Valley lies in between the Sierra Nevada and the White-Inyo mountain ranges, which, respectively, define its west and east walls. The yellow dotted line in the right panel shows the position of the cross-valley measurement transect through Independence, California and the location of the dry bed of Owens Lake.

campaign had both substantial ground-based and airborne components. The ground-based instrumentation was also used for the documentation of structure and evolution of the complex-terrain boundary layer in the absence of rotors.

The major portion of the ground-based instrumentation was deployed within the focus area in Owens Valley, extending the scope and the cross- and along-valley extent of the SRP deployment in 2004 (Fig. 2). In addition to the networks of surface sensors (DRI long-term automatic weather stations (AWS) network, U Leeds AWS, U Utah HOBOs, NCAR/U Berkeley soil temperature/moisture sensors), there were three additional major groups of instruments: i) ground-based remote sensors, ii) flux measuring instruments, and iii) radiosondes. The remote sensors include three NCAR 915 MHz wind profilers (of which one was mobile; all part of NCAR Integrated Sounding Systems (ISS)), one aerosol lidar (NCAR REAL), two Doppler lidars (ASU and DLR), RASS (ASU and NCAR), and sodars (U Houston and ASU). The lidars in particular benefited from the presence of the largest point source of particulate matter in the US, Owens (dry) Lake bed (cf. 1) in their capability to reveal the internal structure and measure the flow and levels of turbulence within rotors. The flux measuring capability consisted of three 30-m flux towers (NCAR) and a number of smaller towers within the valley (U Leeds, U Houston, and ASU). Two base stations for GPS radiosonde launches were located near Independence in Owens Valley. In addition to the systems in Owens Valley, a number of profiling systems were deployed on the upwind side of the Sierra (fixed and mobile GPS radiosonde systems, a thermosonde system, and a K-band radar) and used to monitor the state of the incoming flow. Approximately two thirds of the ground-based systems were provided by individual T-REX investigators. One third was provided and supported by the National Center of Atmospheric Research (NCAR).

In order to document the mesoscale structure and evolution of the wave/rotor part of the coupled system over Owens Valley as well as the kinematic and thermodynamic structure of airflow through the depth of the troposphere up- and down-stream of the Sierra Nevada, three research aircraft were involved in the T-REX campaign (Fig. 3). Those are NSF/NCAR HIAPER (120 hrs, 2 month deployment), UK FAAM BAe146 (50 hrs, Mar 17–Apr 9 deployment), and the University of Wyoming King Air (UWKA) (100 hrs, 2 month deployment). The three aircraft covered the range of altitudes from nearly 150 m above ground within Owens Valley to about 14 km in the lower stratosphere. The theater of airborne special operations extended both upwind of the Sierra Nevada ($\sim$200 km) over the Central Valley of California, and downwind to the east of the Inyo Range ($\sim$100 km). HIAPER documented the structure of mountain waves and mountain-wave induced mixing in the region of the upper troposphere-lower stratosphere. The BAe146 operated in a middle-range of altitudes, whereas UWKA flew closest to rotors, documenting the flow structure and evolution near and below the mountain-ridge height, and penetrating a number of rotors. In addition to the probes for *in situ* kinematic and thermodynamic measurements, the special instrumentation carried by aircraft includes: i) a cloud radar (UWKA), ii) *in situ* chemical tracer instruments and microphysics probes (HIAPER and BAe146), and iii) dropsonde systems (HIAPER and BAe146) (Fig. 4). In addition to the coordinated multiple-aircraft coupled rotor system missions, the BAe146 aircraft flew several cold pool, cloud microphysics, and atmospheric chemistry research missions.

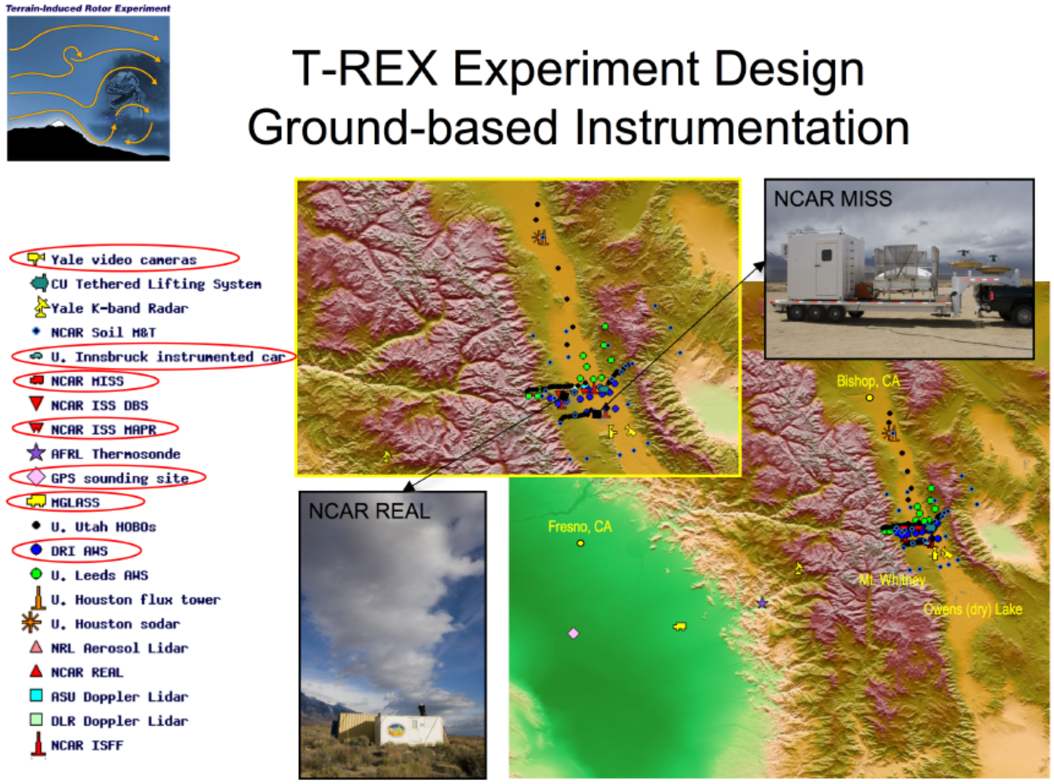

FIG. 2: Color relief map of the southern Sierra Nevada showing the T-REX field campaign area and the ground-based instrumentation suite. The inset map is the zoom of the focus area within Owens Valley. The photos illustrate two NCAR systems: aerosol lidar (REAL) and mobile wind profiler (MISS). The instrumentation systems circled in the legend were deployed also in the Sierra Rotors Project in 2004.

3.4 *Operation Center and Logistics*

The main T-REX Operations Center was located in Bishop, CA. The Bishop Operations Center (BOC) was located at the Owens Valley campus of the White Mountain Research Station (WMRS), the field station of the University of California system. The NCAR Field Project Support (FPS) provided logistical and operational support for the BOC and coordinated ground-based and airborne operations. The weather forecasting in support of T-REX operations was provided by the National Weather Service (NWS) Las Vegas Forecast Office.

The UWKA and its support staff were located at the nearby Bishop Airport. The BAe146 and its support staff were stationed at the Fresno International Airport (FIA). HIAPER operated out of its home base at the NCAR/RAF facility in Broomfield, CO. The Daily Planning Meetings involved connections between the BOC and a number of other sites (NCAR/RAF, FIA, NWS Las Vegas, and a number of auxiliary sites).

3.5 *Real-Time Forecasting*

The field operations were supported by a real-time forecasting efforts that included a number of mesoscale, large-scale medium-range, as well as mountain wave prediction models. The special real-time models and output provided in support of T-REX were augmented by the widely available forecast models from the U.S. and international operational centers.

High resolution mesoscale forecast models were executed by various groups to specifically support the T-REX forecasting operations. The NWS Las Vegas Forecast Office performed twice daily 48-h forecasts using the Weather Research and Forecasting Nonhydrostatic Mesoscale Model (WRF-NMM) with a horizontal resolution of 4 km. The Naval Research Laboratory (NRL) in Monterey, CA ran the atmospheric module of the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS) at a horizontal resolution of 2 km. The initial conditions for COAMPS were obtained through mesoscale data assimilation, which were used for twice daily 48-h forecasts. Other supporting mesoscale model efforts included the NOAA/NCAR WRF-Developmental Test Center (DTC) WRF-NMM and WRF-ARW 24-h forecasts and the Army Research Laboratory 24-h WRF-ARW forecasts. Both of these endeavors used a 2 km horizontal grid increment. The Air Force Weather Agency ran a 5 km resolution version of MM5 that covered the Sierra Nevada and the western U.S. Because of timeliness and availability issues, the T-REX forecasters primarily relied on the 2-km resolution COAMPS, 4-km resolution WRF-NMM, and the NCEP Eta for mesoscale model guidance.

Diagnostic fields from the European Center for

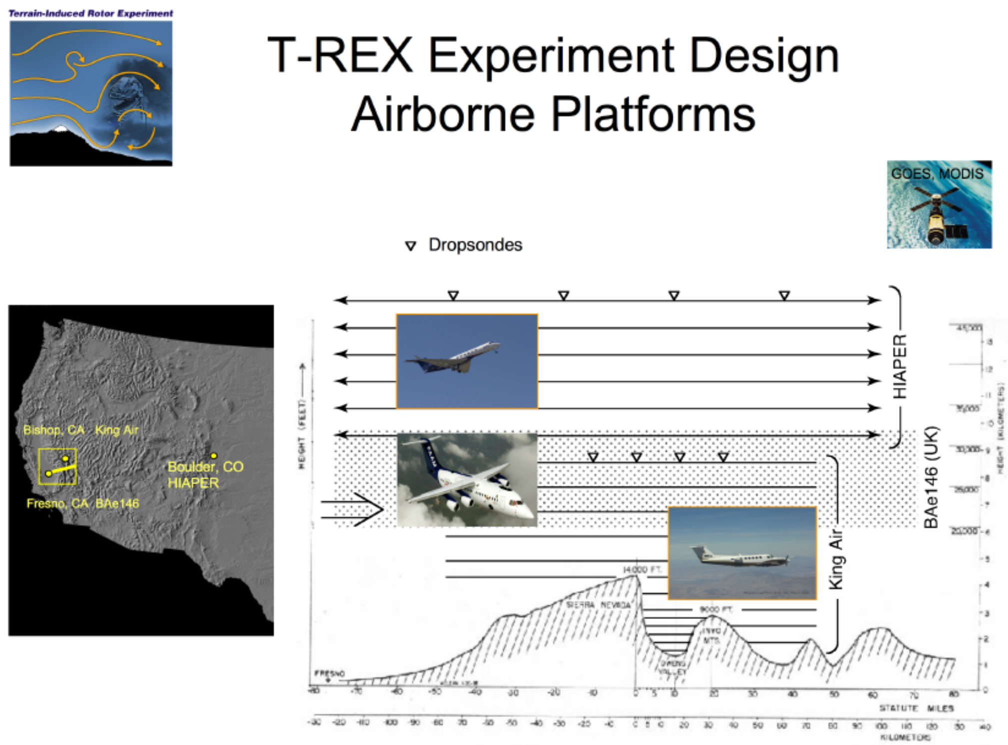

FIG. 3: The composite image of the T-REX aircraft with generic cross-mountain flight tracks and the vertical range of the aircraft shown in relation to the terrain. The baseline of this vertical cross-section is indicated with a solid yellow line in the shaded relief map to the left. Yellow circles indicate the three aircraft operation bases: Boulder, CO (HIAPER); Fresno, CA (BAe146); Bishop, CA (UWKA).

Medium Range Forecasts (ECMWF) Integrated Forecasting System (IFS) were computed by DLR and disseminated to the BOC daily. The diagnostics included basic state variables along with T-REX relevant parameters such as vertical motion, divergence, and cloud cover. Additionally, east-west oriented vertical cross sections through Owens Valley were available. The forecasts were available at 6 hourly intervals up to 156 h, which enabled reasonably accurate medium range forecasts of mountain wave events to be achieved.

Linear model forecasts for the T-REX region were performed by the UK MetOffice and NRL-Monterey groups. Although these models are rather simple in formulation relative to the more complex research and operational nonhydrostatic prediction systems, the linear tools provided valuable short-term and medium range guidance for T-REX mission planning.

4. SUMMARY OF SPECIAL OPERATIONS

Spring 2006 was a very active wave season. A large number of mid-latitude weather systems, larger than the climatological average in particular in March, passed over the T-REX target area, creating many opportunities for special operations for the rotor coupled system documentation. Periods of quiet weather optimal for boundary-layer studies were short, increasing in number and length only in the second half of April. This was also a very wet spring in the Sierra Nevada, bringing the effect of moisture on mountain waves and rotors stronger into our focus. Fifteen (15) IOPs and five (5) EOPs were conducted during the two-month field campaign. The IOPs ranged in length from 4 to 39 hours, with the average length of close to 24 hours. The majority of IOPs covered both transitions toward as well as the periods of strongest wave/rotor activity. EOPs were fixed-length 21-hour observing periods starting in the afternoon (at 2300 UTC) of day one and ending at noon (2000 UTC) the next day.

Twelve (12) HIAPER and twenty-five (25) UWKA research flights were flown using total of 88% of allocated flight hours for each of these aircraft. BAe146 completed eleven (11) research missions using slightly over 50 research hours. This leads to an average research mission length of 8.8 hrs for HIAPER, 4.5 hrs for BAe146), and 3.5 hrs for UWKA. The majority of these flights were part of coordinated aircraft missions involving two (HIAPER and UWKA or BAe146 and UWKA) or all three aircraft. The exceptions to this are the UWKA single aircraft missions in IOP 5 (Mar 20), IOP 11 (Apr 9), and IOP 12 (Apr 11), and the BAe146 missions in EOP 1 (Mar 23), EOP 2 (Mar 30), and in IOP 8 (Apr 2) and IOP 10 (Apr 8). The three aircraft coordinated missions were flown in IOP 6 (Mar 24), IOP 9 (Apr 2), IOP 10 (Apr 8), and in the aircraft intercomparison on Apr 6. The total number of GPS dropsondes released from HIAPER

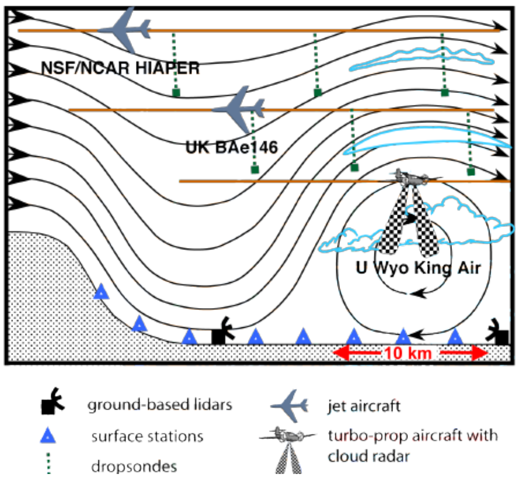

FIG. 4: Schematic view of the composite T-REX airborne observing system showing the three aircraft and major instrumentation in approximate relation to the rotor phenomenon.

is 314, with 52 additional dropsondes released from the BAe146. Close to 300 GPS radiosondes were released from the two sites in Owens Valley, another 130 radiosondes from the two sites in the Central Valley of California, and around two dozen of AFRL thermosodes and GPS sondes from the site in the eastern Sierra Foothills. The catalog of all T-REX missions and operations is available at http://catalog.eol.ucar.edu/trex.

5. UNIQUE ASPECTS AND CHALLENGES

As with any field campaign, there were unique aspects and challenges, some of which we mention here.

T-REX was the first science mission for the new NSF/NCAR HIAPER aircraft. HIAPER "commuted" to work from its home base at the NCAR/RAF facility at the Jefferson County Airport in Broomfield, Colorado. The approximately 3,000 km round-trip commute took little over four hours for this Gulfstream V jet aircraft with valuable data collected en route.

T-REX is the first field campaign in which an airborne remote sensor (Wyoming Cloud Radar) was used to remotely sense motions within atmospheric rotors.

T-REX is the first mountain meteorology field campaign to have two ground-based Doppler lidars, creating an opportunity for the first-ever dual Doppler analyses of terrain-induced flows.

T-REX aircraft were located in three different bases, creating a need for multiple operation centers. The AccessGrid (AG) technology was used successfully for the first time in support of an atmospheric science field campaign to connect the BOC with the two satellite operation centers (FIA and NCAR/RAF), and to entrain investigators at other off-site locations (DRI, other NCAR sites). In spite of a fairly low-bandwidth available at BOC, the AG helped to overcome some of the challenges arising from the distributed nature of the T-REX operations.

T-REX theater of operations included military restricted areas in the air and some of the most tightly protected wilderness areas on the ground. Through an incredible cooperation of the military and federal agencies with the T-REX staff, the T-REX aircraft operated almost exclusively within the restricted area R–2508, completing a number of successful coordinated missions and releasing a large number of dropsondes.

T-REX transformed the Sierra Nevada from one of the sparest data regions into the most intensively observed mountainous region on earth for the two months of the field campaign.

ACKNOWLEDGMENTS

T-REX investigators and participants come from a large number of US universities and agencies, the National Center for Atmospheric Research (NCAR), and several European universities and research institutes. The outstanding efforts of the T-REX field campaign participants, including the NCAR Field Project Support (FPS), the NWS Las Vegas Forecast Office, and the T-REX staff are greatly acknowledged. The primary funding for T-REX has been provided by the National Science Foundation. The first author (VG) was supported in part by NSF, Grants ATM–0242886 and ATM–0524891 to DRI. The second author (JDD) was supported by ONR PE–0601153N.

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