Wind Profiler Observations of Mountain Waves and Rotors during T-REX

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ABSTRACT

A network of three boundary layer radar wind profilers is used to study characteristics of mountain waves and rotors and to explore the utility of such a network. The data employed were collected as part of the Terrain-Induced Rotor Experiment (T-REX), which took place in Owens Valley, California, in early 2006. The wind profilers provide a continuous time–height representation of wave and rotor structure. During intensive observing period 3 (IOP 3), the profiler network was positioned in an L-shaped configuration, capturing key features of the mountain waves and rotor, including the boundary layer vortex sheet (or shear layer), turbulence within this shear layer, the classical lower turbulence zone (LTZ), and wave motion above the LTZ. Observed features were found to be in good agreement with recent high-resolution numerical simulations. Using the wind profiler with superior time resolution (Multiple Antenna Profiler Radar), a series of updraft–downdraft couplets were observed beneath the first downwind wave crest. These are interpreted as signatures of subrotors. Such detailed observations of subrotors are rare, even though subrotors are believed to be a common feature of rotor circulations in Owens Valley. During IOP 6, the network was repositioned to form a line across the valley. A simple algorithm was used to determine the amplitude, wavelength, and phase of the primary wave over the valley and to observe their changes over time and height. In the IOP-6 case, the wavelength increased over time, the phase indicated an eastward-shifting wave crest, and the amplitude increased with height and also varied over time.

1. Introduction and background

The 2006 Terrain-Induced Rotor Experiment (T-REX) and its 2004 pilot study, the Sierra Rotors Project (SRP), had the goal of exploring the formation, structure, and evolution of atmospheric rotors. A rotor is traditionally described as a circulation about a horizontal or nearly horizontal axis that is associated with flow over an elongated barrier such as a mountain range (Glickman 2000).

Rotors typically form in close association with large-amplitude mountain lee waves and are associated with strong turbulence, wind shear, and variable and gusting surface winds (e.g., Grubisić and Billings 2007). Besides being a challenging fluid dynamics problem, they affect human activities as a hazard to both commercial and general aviation. They can also affect air quality by lofting and transporting aerosols and contaminants from the earth’s surface (Raloff 2001).

This paper investigates characteristics of mountain waves, rotors, and rotor internal structure with a small network of three boundary layer wind profilers (WPs). We also examine ways in which the wind profilers can contribute to our understanding of these phenomena. During T-REX the wind profilers, including one mobile system, were deployed in Owens Valley, California. Many other instruments used in T-REX provide context for the profiler observations.
observations, including detailed measurements of surface conditions in the valley, flow aloft in the lee of the mountain barrier, and upwind conditions. Episodic observations were made with three instrumented aircraft, two of which released dropsondes, as well as two Doppler lidars and one backscatter lidar, two sodars, rawinsondes launched both within and upwind of the valley, a dense network of surface stations in the valley, several in situ flux towers, and other supporting instruments (Grubišić et al. 2008). In addition to its phenomenological value, the full T-REX dataset is also being used to evaluate and improve numerical simulations of waves and rotors as well as simulations of valley flows under more quiescent conditions. This includes the performance of forecast and research models under such conditions and simulation of small-scale features of rotors (Doyle et al. 2009, 2011; Schmidl et al. 2011). In turn, interpretation of the observations benefits from insights gained from the model simulations.

Prior to T-REX and SRP, the majority of observations of rotors and the conditions surrounding them were made in the four decades following the observational discovery of mountain lee waves in the 1930s (Kuettner 1939). These were primarily visual observations and in situ measurements obtained using instrumented sailplanes, theodolite-tracked weather balloons, surface meteorological stations, and visual cloud observations (Grubišić and Lewis 2004). Instrumented aircraft were also occasionally used (Lester and Fingerhut 1974). Early on, a classical, idealized description of a mountain wave–rotor system emerged (Scorer and Klieforth 1959), which is still featured in today’s textbooks (e.g., Whiteman 2000). Figure 1, reproduced from Lester and Fingerhut (1974), shows the main characteristics of the lee-wave rotor: a lower turbulence zone (LTZ) beneath laminar wave flow, a closed rotor circulation centered beneath the rotor (or roll) cloud at the wave crest, gusty surface winds beneath the first wave trough, reversed surface winds (sometimes) at the bottom of the rotor, and regions of turbulence. Extreme turbulence is indicated in the updraft upwind of the crest and severe turbulence in the downdraft on the downwind side.

It is important to recognize that the in situ measurements of the 1930s–1970s do not uniformly support the rotor circulation of the idealized description. Holmboe and Klieforth (1954, 1957) describe rotor observations, also in Owens Valley, as an LTZ that often does not contain a coherent rotational structure; the air in the LTZ may have no discernible streamlines with occasional pockets of severe turbulence within the LTZ reported by glider pilots. Although on average the winds in the LTZ were weak and sometimes reversed, Holmboe and Klieforth describe instantaneous flow as inhomogeneous turbulence, with the air “in a state of continuous mixing.” Lester and Fingerhut (1974) present similar in situ (primarily aircraft) observations within and around the LTZ from the Rocky Mountain Lee Wave Program and the National Center for Atmospheric Research (NCAR) Chinook Study (Lilly and Toutenhoofd 1969). Their observations and conclusions are very similar to those of Holmboe and Klieforth (1957). Both studies indicate an LTZ characterized by well-mixed turbulence, containing variable and gusty winds. According to both studies, turbulence is strongest in the wave updraft but intermittently strong turbulence is also found between the surface and the rotor cloud as well as in the wave downdraft region. At the surface, reverse flow was occasionally observed.

In recent decades, remote sensors such as radar wind profilers, Doppler lidars, and sodars have increasingly been applied to mountain meteorological research. These instruments have the advantage of continuous temporal coverage over a range of heights; thus, they are more likely to capture transient or small-scale features. Two noteworthy observational studies made use of a sodar and a Doppler lidar. Combining a sodar and tower-based instruments, Holets and Swanson (1988) observed back-and-forth movement of the wave crest and intermittent reverse flow in the LTZ. Ralph et al. (1997) present Front Range observations of a rotor circulation mapped with a scanning Doppler lidar. That study presents perhaps the most direct observational evidence of a coherent rotor circulation rather than an LTZ characterized by intermittent circulation and turbulence. T-REX and SRP made much greater use of remote sensors than any past study.
The advances in remote sensing systems of which T-REX took advantage are well complemented by numerical simulations of rotor flow that have become possible with improved computational techniques and faster computers. Several numerical studies investigate factors that lead to rotor formation and provide insights into their internal structure (e.g., Doyle and Durran 2002, 2007; Hertenstein and Kuettner 2005; Vosper 2004; Vosper et al. 2006). These too can be compared with observations and with the classical description provided by early conceptual models. The seminal numerical simulations by Doyle and Durran (2002) focus on the role of boundary layer vorticity in formation of rotors that are associated with trapped lee waves. Because of surface friction, strong vertical wind shear will form near the surface as air flows over the mountain and down the leeward slope, resulting in cross-flow horizontal vorticity or a boundary layer vorticity sheet. If the adverse pressure gradient generated by lee waves is sufficiently strong to induce boundary layer separation, then the boundary layer vortex sheet may get lifted from the ground underneath the first lee-wave trough and get advected downstream through the wave. Rotor simulations have produced cases of large-scale closed circulations but also cases of intermittent eddies and turbulence similar to the majority of observations. Doyle and Durran (2002) refer to these eddies as subrotors and note that the strong turbulence generated by them may pose a great hazard to aviation. Factors that lead to one case or the other (larger-scale coherent vortex or primarily small-scale vortices) have been a topic of investigation. Whereas two-dimensional (2D) simulations tend to produce a larger, more coherent and persistent rotor circulation underneath the lee waves, 3D studies with increasingly high resolution have produced smaller and less coherent vortical structures (Doyle and Durran 2007). These small-scale vortices have been attributed to Kelvin–Helmholtz instability of the separated vortex sheet. Doyle et al. (2009), using T-REX observations and large-eddy-simulation (LES) modeling, examine subrotors in more detail, documenting, for example, their intensification as they break away from the vortex sheet.

During T-REX, continuous time–height observations were available from a network of three wind profilers. Having these spatially distributed measurements provides a unique opportunity to make inferences not only about the temporal changes but also about the spatial structure of the flow. In this study, we show the ability of these wind profilers to measure characteristics of lee waves and to explore rotor structure. During several intensive observing periods (IOPs), this network captured the evolution of the lee-wave structure and the position and movement of wave crests across the profilers’ field of view. High-resolution observations directly beneath the lee-wave crest show subrotor characteristics in great detail. In this analysis combined wind profiler and aircraft measurements are found to be especially useful. In section 2, the T-REX instruments are briefly described. Section 3 presents wave and rotor observations from T-REX IOP 3, including the rotor internal structure. In section 4 we use observations from three collinear profilers during IOP 6 to document changes in amplitude, phase, and position of the mountain wave. Section 5 concludes the paper.

2. Observing systems

The strong wave events of T-REX IOP 3 on 9 March 2006 and IOP 6 on 24–26 March 2006 were well documented by the sensors available early in the T-REX experimental period. The observations we describe in this study come from three radar wind profilers and one Doppler sodar deployed as part of the Integrated Sounding Systems (ISS). In situ wind and turbulence measurements made with the University of Wyoming King Air research aircraft, and surface measurements made at the ISS sites, add to this analysis. The instrument sites and terrain are shown in Fig. 2.

a. ISS instruments

Three ISS were deployed in T-REX at the center, west, and mobile ISS (MISS) sites (Fig. 2). The location of the MISS site changed as the system moved between IOPs. As described in Parsons et al. (1994), the ISS consists of a 915-MHz boundary layer wind profiler with a Radio Acoustic Sounding System (RASS), an enhanced surface meteorological station (with a 10-m instrumented tower and solar radiation sensors), and a variety of optional sensors. ISS also usually includes a GPS Advanced Upper-Air Sounding System (GAUS) launching Vaisala RS-92 radiosondes. In T-REX the three sites were as follows:

1) ISS-MAPR is located at the center site in Owens Valley, 1.5 km southeast of the town of Independence. This system included a GAUS, ceilometer, sodar, and a Multiple Antenna Profiler (MAPR; Cohn et al. 1997, 2001). MAPR uses spaced antenna techniques to make wind measurements on time scales of 5 min or less, as compared with 30-min wind measurements with the Doppler beam-swinging (DBS) wind profilers used in the other ISS. This capability enables MAPR to observe all components of the wind during rapidly evolving events. Approximately 2 km northwest of the other ISS-MAPR instruments, a sodar was installed at Independence Airport. This system was a METEK...
DSDPA.90-24, a 24-speaker, phased-array minisodar that is similar to the larger DSDPA.90-64 (64 speaker) model described by Engelbart et al. (1999). The sodar produced wind measurements every 10 min from 40 m up to around 200 m above ground level (AGL). This sodar is equipped with RASS operating at the same 915-MHz band used by the wind profilers, which necessitated the 2-km separation between the sodar and the MAPR sites. The sodar is used to observe the wind and virtual temperature in the region below the lowest range gate of the wind profilers.

2) ISS2 is located at the west site on the western slope of the valley, approximately 5 km west of Independence. This system operated with a standard DBS wind profiler. Although this system produces horizontal winds every 30 min, it measures vertical velocity every 2 or 3 min and can capture the vertical component of rapidly evolving events.

3) MISS, a trailer-mounted moveable ISS. Like ISS2, it uses a DBS wind profiler. MISS was moved to various locations around the valley, depending on the focus of each IOP. During IOP 3, MISS was operated on the western slope, approximately 11 km north of the west site, and the three ISS were placed in an “L” configuration. For IOP 6 MISS was located between the center and west sites, so the three ISS were approximately collinear.

b. King Air flight and sensors

The University of Wyoming King Air research aircraft provided in situ measurements of air motion, thermodynamic, and microphysical variables. The aircraft also carried a cloud radar. The King Air generally flew a stack of transects above and within Owens Valley. The aircraft and the wind profiler measurements provide complementary insights into the mountain wave and rotor structure and evolution. The aircraft provides a spatial picture of the wave and associated turbulence, both across the valley and over a range of altitudes, while the wind profiler documents changes over long time periods as well as over a range of altitudes.

3. Wave and rotor observations of IOP 3

a. Wave and LTZ features seen by aircraft

Between 1700 and 1940 UTC 9 March, the King Air flew a series of level flight legs across the valley, descending over time from the altitude of 8500 to 1800 m above mean sea level (MSL). The data collected by the aircraft provide an overview of the wave structure and turbulence signatures that can be directly compared with those in Fig. 1. Figure 3 shows flow streamlines above the terrain profile of Owens Valley, which were constructed using the east–west component $u$ of horizontal velocity and vertical velocity $w$. 
The streamlines were derived from the aircraft in situ measurements along a series of horizontal flight legs after making the assumption that the flow field is purely two-dimensional and steady. In color, Fig. 3 also shows the eddy dissipation rate (EDR)—a common measure of atmospheric turbulence strength calculated by the power spectrum method described in Smalikho (1997) and Cornman et al. (1995). The precision of this calculation is not available, but comparisons such as by Chan (2011) show it to be closely related to turbulence measured by in situ means. For a subjective sense of the EDR scale, Lester and Fingerhut (1974) provide values of EDR for a Queen Air, a similarly sized research aircraft as the King Air used in T-REX. Their specified EDR thresholds for light, moderate, and severe turbulence are 0.09, 0.23, and 0.35 m$^{2/3}$ s$^{-1}$, respectively.

Above 4 km MSL (the upwind terrain height), the King Air measurements show lee waves whose amplitude decreases with increasing height. The wave amplitudes also decrease fairly rapidly downwind of the Inyo Mountains, the second mountain range, except near the Sierra Nevada ridge height, where the lee-wave pattern maintains better coherence. As in Stiperski and Grubišić (2011), the cancellation of waves downwind of the second mountain range likely results from destructive interference of lee waves generated by these two mountain ranges. Turbulence is light at these higher altitudes. As the aircraft descended into the valley, the strength of the leading-edge updraft increased further; however, the flow behind this leading-edge updraft became less coherent. This stronger flow is air that has come over the Sierra Nevada, descending deeply into the valley and ascending to the wave crest over the valley center. Along the short flight legs within the valley, weak-to-moderate turbulence was encountered with measured EDR from about 0.1 to more than 0.2 m$^{2/3}$ s$^{-1}$. The strongest turbulence coincides with the leading-edge wave updraft.

The aircraft data were collected over more than 2 h, between 1724 and 1939 UTC. Most of this time was spent on the longer, higher-altitude legs. Flight legs at altitudes below 5000 m MSL were shorter, in particular those within the valley where it took approximately 30 min to collect all the data. As a consequence, the measurements inside the valley more closely approximate an instantaneous cross section of the airflow and turbulence pattern. Above approximately 5000 m MSL, the waves show a westward tilt of phase lines with increasing height; below that altitude, the phase lines are more nearly vertical, indicative of wave energy ducting and trapped lee waves. There are two alternate explanations for the upward phase line tilt in Fig. 3. It could be either indicative of wave energy leakage above the layer of wave trapping (below 5000 m MSL), leading to mountain waves with upward energy propagation or it alternatively could be indicative of a gradual eastward shift of the trapped lee-wave pattern over the time span of slightly more than 2 h that it took the aircraft to complete this vertical cross section. The analysis of the wind profiler data presented in section 3b supports the latter. It must be pointed out, however, that in the semiarid environment of Owens Valley the wind profiler data do not reach much beyond 4 km AGL (~5.5 km MSL). It is thus plausible that, although the trapped lee-wave pattern at low levels was unsteady and drifted eastward, the upward phase line tilt is still indicative of the presence of internal gravity waves (mountain waves) above 5000 m MSL.

The King Air observations show some correspondence to the idealized picture in Fig. 1, with laminar wave flow above and turbulence at or below the mountain crest.
height. Strong turbulence was seen upwind of the wave crest and downwind of the leading edge of the wave updraft corresponding to “E” in Fig. 1. The horizontal winds measured by the King Air (not shown) do not show a coherent large rotor circulation. Two brief pockets of easterly flow were encountered at 2.5 and 3.0 km MSL just west of the wave crest, however. Each of these segments of easterly flow was approximately 2 km long.

b. Wave and LTZ features seen by wind profilers and surface measurements

Wind profiler observations of vertical velocity can be used to study changes in the wave over height and time. The strength and sign of measured vertical velocity depend on the amplitude of the wave and on its phase above the wind profiler (cf. Fig. 1). If the profiler is at location WP1 or WP2, it will see the maximum updraft or downdraft; if the profiler is at location WP3 or WP4, it will see no vertical motion. Other locations will show intermediate values. For a stationary wave, the measurement will persist over time. However, if the wave-crest position, the horizontal wavelength, or the wave amplitude change over time, the observed vertical velocity will also change.

Figure 4 shows a time–height cross section of vertical velocity from both the west (ISS2) and center (MAPR) wind profilers over 10 h of IOP 3. These come from the Doppler velocity directly observed with the vertical profiler beam. For clarity these data have been smoothed over 15 min and 250 m in height, with white space indicating regions where the backscattered signal-to-noise ratio was less than −15 dB—too weak for a measurement. The center profiler also has missing data from 2000 to 2200 UTC because of a power failure due to strong winds. Areas of blue are persistent downdrafts while orange and red show persistent updrafts. Green and yellow may indicate weak vertical motions either up or down. The precision of wind profiler measurements depends on the integration period and signal-to-noise ratio. Comparisons with other sensors show vertical (radial) velocity precision of a few tenths of a meter per second even for integration periods of less than 1 min (Cohn and Goodrich 2002) and horizontal wind precision of better than 1.5 m s$^{-1}$ for 1-h comparisons (Strauch et al. 1987).

The patterns of updrafts and downdrafts above both wind profilers change over time. For example, at the west site vertical velocity at most of the altitudes changes from positive (an updraft) at or before 1830 UTC to negative (a downdraft) by 1900 UTC; at the center site above 3 km MSL vertical velocity changes from a downdraft to an updraft between 1700 and 1800 UTC. At altitudes below about 3 km MSL, the strength and sign of vertical motions are variable rather than persistent. The depth of this layer of variable vertical motion decreases with time above both profiler sites.

At 1930 UTC, approximately the time when the King Air measurements inside the valley were collected, there was downward motion over the west profiler and upward motion of increasing strength with height over the center site. Red dots in Fig. 3 indicate the wind profiler locations. Thus, the profiler and aircraft measurements qualitatively agree. The profiler data at this time are consistent with the wave trough being east of the west profiler and the wave crest being east of the center profiler.

This is very different from earlier observations, for example, at 1600 UTC when there is an updraft over the west site and a weak downdraft over the center site. Although no verifying aircraft measurements are available for that time, it appears that at 1600 UTC the first wave trough was located west of the west profiler and the first wave crest was to the west of the center profiler. The descending patterns of updraft over time at both sites are consistent with an approaching wave trough. These measurements indicate that the wave trough and crest appear to have moved eastward between 1600 and 1930 UTC.

Surface measurements from the west and center ISS sites (Fig. 5) conform to the conceptual model of a downwind-shifting wave pattern. Surface winds at the west site are light and generally northerly until just after 1800 UTC. Over the next 3 h, they increase to 20 m s$^{-1}$ and become westerly. This increase matches the time when the pattern of strong vertical motion aloft documented by the wind profiler descends toward the surface. Surface winds at the center site are light until 1900 UTC, at which time they abruptly increase to 10–15 m s$^{-1}$. During the period of light winds, the direction shifts; it is initially from the northwest, becoming easterly after 1545 UTC. In Owens Valley easterly flow would be consistent with a coherent rotor reaching the surface, as depicted in Fig. 1.

Together, the aircraft, wind profiler, and surface measurements describe many characteristics of the flow in and above Owens Valley during IOP 3. The apparent eastward progression of the wave crest could be the result of the increase of horizontal wavelength with time or of the eastward shift of the wave pattern, either of which could take place if the background wind or temperature profile changes. In the IOP-3 case, the time sequence of surface and profiler observations at the west and center sites supports that the wave pattern moved eastward over time. We have examined soundings upwind of the Sierra Nevada for

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1 At the center ISS, surface measurements continued on battery power during the 2000–2200 UTC power-outage period that affected the wind profiler.
changes in the wind or temperature profiles that would bring about this shift. A series of soundings from 1400 through 1958 UTC (Fig. 6) show only small changes at altitudes near the crest height. The wind direction above 3 km MSL backed from about 320° to 295° during this time, and the atmosphere cooled and became less stable in a layer from 3 to 4 km. A horizontal wavelength of 25 km was computed using linear theory and a similar atmospheric profile during IOP 6 (Grubišić and Stiperski 2009). This is slightly longer than the King Air observation, which is closer to 15 km (Fig. 2). The Sierra Nevada is a complex barrier to the flow and, as shown by Reinecke and Durran (2009), small changes in approaching wind may change the wave response over Owens Valley. Although there is an evolution of upwind conditions, we cannot confidently relate changes of the wave position in the valley to this variation in forcing.

Migration of a wave crest directly over a wind profiler, as happened over the center profiler between 1600 and 1845 UTC, is extremely fortuitous. Rotor flow is expected beneath the wave crest; in section 3c, the expected rotor region is examined using the high-resolution MAPR profiler data.

c. Rotor and couplet observations from the center ISS site

Based on the wave position determined from the vertical velocity pattern, we examine the flow within the
region where rotor flow would be expected. The three indicators examined are 1) regions of enhanced turbulence in the LTZ, 2) reverse (easterly) flow at the surface or aloft, and 3) coherent structures seen in the vertical velocity field.

As seen in Fig. 5, surface flow at the center site is easterly between 1545 and 1900 UTC, suggesting reverse flow due to a rotor. The Doppler sodar/RASS measures wind in the lowest few hundred meters, extending the surface observations upward. Winds measured by this
instrument during IOP 3 at a location 2 km northwest of the center site are shown in Fig. 7. Surface winds from a collocated 10-m tower are added at the bottom of the diagram. The winds measured by the sodar correspond well to the surface winds at the center site. Prior to 1600 UTC, winds are northerly. From 1600 to 1930 UTC, they become light and generally easterly in a shallow layer from the surface up to 200 m AGL (approximately 1400 m MSL). Surface easterlies were seen in a wide area of central Owens Valley, both at the MAPR site and at nearby stations in the Desert Research Institute (DRI) surface network (not shown). After 1930 UTC strong westerlies appear both at the surface and aloft.

At the center site, MAPR backscattered signal during IOP 3 was sufficiently strong to obtain vertical velocity at 1-min temporal resolution and horizontal wind at 5-min resolution. Winds and the corrected Doppler spectrum width $s_c$ from MAPR are shown in Fig. 8 for a 2-h subset (for clarity) of this period. Most of the lowest-level measurements are from the west or west-northwest, with a few southerly, showing that the layer of easterlies seen by the sodar is indeed shallow. The only easterly flow seen by MAPR is between 1840 and 1845 UTC below 1 km AGL.

As the wave crest migrated over the center site, the vertical motion pattern was observed in great detail. Most interesting is the period from 1545 to 1900 UTC. Figure 8 focuses on 2 h of this time period for greater clarity. A series of updraft–downdraft couplets are visible early in the subset period, in which the updrafts are generally located closer to the surface and slightly offset later in time in comparison with the downdrafts. We associate these couplets with subrots, patches of high horizontal vorticity that originate from the highly sheared vortex sheet near the wave crest and propagate into a more stagnant region beneath the crest (Doyle et al. 2009). Although Fig. 8 shows these couplets on the upwind side of the crest, similar signatures are visible on the downwind side in the more compressed Fig. 4.

Characteristics of this couplet pattern are as follows:

1. Ten clear downdraft–updraft couplets are captured between 1545 and 1740 UTC. The downdrafts penetrate downward from the strong winds aloft while most of the updrafts extend from the surface to 1.5 or 2 km AGL. Two updrafts (at 1550 and 1705 UTC, not shown) appear to be detached from the surface.

2. Not only is each updraft generally below the downdraft but most are also shifted slightly later in time. Without horizontally spaced measurements, we do not know if these coherent structures begin aloft or if they are sheared and only the upper segment is seen by the profiler.

3. The maximum magnitudes of the updrafts and downdrafts are approximately 3 m s$^{-1}$. 

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**Fig. 6.** (a) Wind speed, (b) wind direction, and (c) potential temperature from T-REX soundings taken approximately 140 km west-southwest (upwind) of Owens Valley.
4) The updrafts are quasi periodic, separated in time by about 15 min from 1515 until 1700 UTC, and occurring more frequently, every 7–10 min, in the later part of this period (1700–1745 UTC).

The corrected spectrum width is the measured Doppler spectrum width corrected for broadening effects unrelated to turbulence. It is an indication of turbulence strength (e.g., Hocking 1985). As seen in Fig. 8, a layer of strong turbulence (yellow and orange) coincides with the layer of strong vertical wind shear. This layer of strong turbulence descends over time. The updrafts of the couples are confined within the region of lighter turbulence beneath the descending layer of strong turbulence.

Vertical velocities measured by the sodar have been examined for similar features. The sodar-measured vertical velocity, a subset of which is shown in Fig. 9, shows more activity than is usual within the lower boundary layer, with many isolated updrafts and downdrafts exceeding 1 m s\(^{-1}\) and some even exceeding 2 m s\(^{-1}\). These updrafts and downdrafts are fairly coherent with height from about 75 m AGL to the top of the observations. Because of the vigorous vertical motions in this lowest part of the flow, we cannot discriminate between possible couples and more random, isolated vertical motions.

Hill et al. (2010) used dual-Doppler analysis of two lidars to capture subrotors for a short period of a later T-REX period (~1900 UTC 25 March 2006; IOP 6). Their results show a subrotor as a small region of high vorticity advecting eastward over time. Finescale horizontal wind measurements with dual-Doppler lidar analysis and accurate vertical winds from wind profilers would be complementary if observing the same event.

d. **Rotor observations from the northern MISS (IOP 3) site**

Surface winds at the IOP 3 MISS site on the western slope of the valley, approximately 11 km north of the west site (M3 in Fig. 2) are shown in Fig. 10. There is an extended period of easterly flow at this site, consistent with reverse flow from a rotor, before the winds turn to the westerly downslope direction. The winds are light and gradually turn from northerly at 1600 UTC through easterly to southeasterly by 1930 UTC. Afterward, stronger westerly winds dominate.

A time–height cross section of vertical velocity and horizontal winds (Fig. 11) shows two times at which the vertical velocity sign changes over this site. The first change falls between approximately 1430 and 1630 UTC. A sustained downdraft above this site, at altitudes between 2 and 4 km AGL, is replaced by a sustained updraft that slowly descends with time to lower altitudes. The top of the wind profiler echo is also gradually eroded as dryer air is advected aloft. The surface winds, change of vertical velocity sign above this site, and descent of the coherent updraft are similar to what was documented at the MAPR site at a later time (1700 and 1800 UTC; Fig. 4)—features that we attributed to the passage of the wave crest over that site. It is noteworthy that the descent of the coherent updraft and the shift to westerly surface winds at the MISS site are several hours later than at the west site. This seems to indicate an along-valley variation in the wave structure.

The pattern at the MISS site shows that the wave crest passed overhead between approximately 1430 and 1630 UTC, with the profiler positioned under the wave downdraft prior to about 1430 UTC and under the updraft...
after 1630 UTC. This is about 2 h earlier than the time of crest passing over the center site farther to the southeast. The LTZ, identified by lighter horizontal winds, extends to about 3 km AGL between 1600 and 1800 UTC and is much shallower before and after these times.

Although temporal resolution of the MISS measurements is poorer than the MAPR measurements, the vertical velocity measured by MISS shows several vertical velocity couplets (Fig. 12), at about 1545, 1650, and 1725 UTC. These measurements show that the couplets are not unique to the center site during IOP 3. Similar couplets were also seen by MAPR during IOP 13 (Doyle et al. 2009), which was another strong, trapped lee-wave event.

Within the LTZ, the winds above the surface occasionally have an easterly (reverse flow) component. Two such occurrences are evident in Fig. 11b. In the first, between 1700 and 1730 UTC, the easterly winds are found near the top of the LTZ. This reverse flow appears to be closely related to the coinciding updraft–downdraft couplet in Fig. 12. The second occurrence is seen in wind profiles between 1830 and 1930 UTC and extending from ~1.3 km AGL down to the lowest measurable range. With the conceptual model of the wave crest passing over the wind profiler site, these patches of reversed flow would, respectively, fall just upwind of the wave crest and behind the leading edge of the wave updraft.

The second change in the vertical velocity sign above the MISS site falls between 2130 and 2200 UTC (Fig. 11a), during the period of sustained westerly winds that extend from the surface to the top of the wind profiler echo. At this time, the wind profiler data are limited to below 2 km MSL, presumably because of the presence of very dry air above this altitude. Again, a similar pattern is evident in the MAPR measurements—between 2230 and 2300 UTC, 1 h later than at the MISS site. This signature was seen much earlier over the west site, again indicating along-valley variation. These vertical velocity signatures are consistent with the trough of the wave moving over
a wind profiler site and with the erosion of the echo being caused by dry air that is brought down toward the surface within the wave trough.

e. Spatial relationship of the features

Using the MISS measurements, one can study the relative position of features of the LTZ and rotor flow in this case and compare them with the conceptual model from Fig. 1. As shown in Fig. 11, the boundary between the LTZ and primarily laminar flow aloft is evident in both the vertical and horizontal velocity diagrams, where contours in Figs. 11a,b indicate a vertical velocity of ±1.5 m s⁻¹ and horizontal speeds of 10 and 15 m s⁻¹. The changing position of the wave over the profiler effectively provides a slice through a part of the LTZ. The location of turbulence is revealed in Fig. 11c through the spectral width σc, with the thick contour indicating a value of 1.25 m s⁻¹. In Fig. 13, the same vertical velocity and spectral width contours are superimposed on the horizontal wind field.

From these figures it is clear that there is a transition layer between fairly laminar flow at higher altitudes and the LTZ with weak winds near the ground. Within this
transition layer, there is strong vertical shear of the horizontal wind, consistent with the vortex sheet of Doyle et al. (2009). This layer also has the strongest turbulence, presumably generated by wind shear. The up and down motions associated with the wave do not penetrate through the transition layer. Within the LTZ the winds are light and generally in the down-valley direction, although occasionally they do have an easterly (reverse flow) component. In at least one case, the updraft–downdraft couplet (Fig. 12; the MISS couplet at 1725 UTC) coincides with a patch of easterly flow (Fig. 11; 1700–1730 UTC). Closer to the ground, a shallow layer of easterly flow is present as seen by the sodar and some surface towers.

The conceptual model that emerges from the above description is very much like the result of the large-eddy simulation shown in Fig. 21 of Doyle et al. (2009). There the reverse flow is found above the ground at the point where the vortex sheet, corresponding to the turbulent shear layer shown here, separates from the ground. Farther downwind of the separation point, the vortex sheet breaks up into smaller vortices (subrotors) and an extensive thin layer of easterly flow is present at the ground. Asymmetry in our observations, including appearance of the couplet updraft later in time and also at lower altitudes than the downdraft, is consistent with couplets or subrotors generated at the altitude of the vortex sheet and with stretching and tilting of subrotors as discussed in Doyle et al. (2009). Features of the wind profiler observations from IOP 3 that appear different than those of the simulated case of Doyle et al. (2009) are the vertical extent of the subrotors, often through the depth of the LTZ, and their periodicity.

4. Diagnosing changing wave structure: IOP 6

During IOP 6, MISS was sited between the west and center sites forming, with the other two wind profilers,
an approximately west–east line of observations (Fig. 2). It is rare—perhaps unique—to have a cross section of wave observations over height and time. Figures 14a–c present time–height plots of vertical velocity from the three wind profilers over a 12-h period from IOP 6. Areas of blue are updrafts that persist over time and height, and yellow and red show persistent downdrafts. As was the case during IOP 3, the wave evolved over time with changes between updraft and downdraft (for example, near 1000 UTC at the west and center sites and 1100 UTC at the east site).

To examine the changing characteristics of the wave over the valley, a least squares sinusoidal fit algorithm was developed. At each time and altitude level, the vertical velocities from the three wind profilers were fit to the function

$$w(x) = A \sin(2\pi x/\lambda - \varphi),$$

where $x$ is eastward distance relative to ISS2 and $A$, $\lambda$, and $\varphi$ are the amplitude, wavelength, and phase (also relative to ISS2) of the best fit wave, respectively. This fit is of vertical velocity, not vertical displacement, which would be shifted in phase by $\pi/2$.

The algorithm for finding the wave characteristics is not a simple unconstrained fit. First, measurements from the three profilers are interpolated to a common time and height grid. With only three closely spaced sites, the fit is sensitive to small changes in vertical velocity. Such changes could result from variance in low-signal-strength conditions or a variety of other effects. For this IOP, data were averaged over 10 min in time and 150 m in height (although for clarity we interpolated onto a much finer grid of 5 min $\times$ 100 m). The fit parameters were also constrained to be within reasonable limits, with solutions rejected when...
the amplitude exceeded 20 m s$^{-1}$ or the wavelength was outside the range $6 \leq \lambda \leq 40$ km. With only three wind profilers, the algorithm is ill conditioned for some wavelengths or wave positions and is also susceptible to noise. The fit algorithm searched for local best (minimum least squares) solutions. When more than one local solution was found, the choice of solution was made based on consistency with fit solutions at surrounding heights and times.

Figure 14d shows the results of the wave structure analysis using the measured vertical velocities from Figs. 14a–c. The abscissa in this figure is the across-valley distance relative to the west site (ISS2). The terrain profile is indicated by the thick black line. At 0830 UTC at 4300 m MSL (blue vertical line and circles in Figs. 14a–c), the west profiler sees a downdraft while the center and east profilers see updrafts. In Fig. 14d those measurements are indicated by blue stars, whereas the blue curve represents the sinusoidal fit for the vertical velocity provided by the algorithm. Similarly, the red data are measurements obtained at 1300 UTC when the western profiler measured an updraft and the center and east profilers observed downdrafts. Last, the green data are for 1720 UTC. The 4300-MSL level is near the top of available wind profiler observations. The vertical wind measured during a 5240-MSL cross-valley leg of a research flight by the University of Wyoming King Air from 1717 to 1722 UTC is also shown (thin green line). The good agreement between the profiler fit at 1720 UTC and this in situ transect shows that wave parameters can be reliably extracted from the line of profiler measurements. The parameters of the fits are summarized in Table 1.

The same algorithm was applied to a longer period of IOP 6. Figure 15 shows the results of this analysis over 6 h, indicating how the wave amplitude, wavelength, and phase change with time and height. Results for vertical velocity amplitude of less than 1.5 m s$^{-1}$ are not shown because the parameters of such low-amplitude waves are poorly characterized; this accounts for the lack of results (white spaces) throughout the LTZ. Additional points are missing where the fit did not result in a solution within the amplitude and wavelength limits. This is most common from about 0930 to 1030 UTC.

Figure 15 illustrates both consistency and gradual changes of wave parameters over time and height. The phase (indicating the phase of vertical velocity above the west site) is very steady at around 5.2 radians (300°) from 0600 to 0800 UTC. Over this time period, the wave
amplitude is around 3 m s\(^{-1}\) and the horizontal wavelength around 8 km. The phase then decreases slowly over time until 1100 UTC, reaching the value of around 1.9 radians (110\(^{\circ}\)). Over the same period, the horizontal wavelength increased to around 11 km. One surprise is that the wavelength is expected to be constant with height but instead it is slowly changing. This may be the result of nonlinear wave effects. The phase change (from 300\(^{\circ}\) to 110\(^{\circ}\)) indicates eastward movement of the wave by about 2 km, assuming a 10-km wavelength. A final point is that the wave amplitude varies slowly over time, but it nearly always increases with height. The strongest amplitude is expected where stability is largest. Therefore, this increase with height is expected up to the height of the inversion, which lies just below 5 km AGL.

A network of three profilers is the minimum needed for this fit analysis. The spacing of our three profilers is not optimized for any particular wave geometry, and the algorithm is not sophisticated. Measurement errors propagating through to errors in fit parameters will depend on the geometry; even with these limitations, however, Fig. 15 clearly illustrates the information on wave structure that a line of wind profilers can provide.

5. Conclusions

We have examined the structure and evolution of the mountain-wave and rotor events during T-REX IOP 3 and IOP 6 using a network of three radar wind profilers and the in situ data measured by the University of Wyoming King Air research aircraft. Supporting observations come from a Doppler sodar, surface stations, and soundings.

Many observed characteristics of the LTZ during the wave event of IOP 3 were similar to the classical conceptual model. However, the high-resolution measurements from our wind profilers reveal the wealth of detail within the LTZ underneath the wave crests that is absent from the classical model of a rotor. These details, which qualitatively agree well with the LES results presented by Doyle et al. (2009), are illustrated in Fig. 16. Numbers on this figure correspond to the following list:

1) The wind profilers show a vortex sheet or shear layer that separates laminar wave flow aloft and the LTZ. Surface observations show a transition from weak flow to strong westerly flow that is consistent with a surface separation point moving eastward over time.
2) The vertical shear of the horizontal wind generates strong turbulence, reflected in the profiler spectral

<table>
<thead>
<tr>
<th>Time (UTC)</th>
<th>0830</th>
<th>1300</th>
<th>1720</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplitude (m s(^{-1}))</td>
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<td>7.9</td>
<td>5.4</td>
</tr>
<tr>
<td>Wavelength (km)</td>
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<td>15.7</td>
<td>17.6</td>
</tr>
<tr>
<td>Phase over west ISS ((^{\circ}))</td>
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<td>104</td>
<td>52</td>
</tr>
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</table>

### Table 1. Wave characteristics derived from sinusoidal fits at 4.3 km MSL at 0830, 1300, and 1720 UTC 25 Mar 2006 (IOP6).
The strongest turbulence lies on the upwind side of the crest. At the point where the vortex sheet separates from the ground, reverse flow is seen by the wind profiler that extends to several hundred meters AGL.

In the vicinity of the wave crest, subrotors separate from the vortex sheet and rotate within the LTZ. The subrotors give rise to the downdraft–updraft couplets and also cause the intermittently observed easterlies. Some of the couplets descend far into the LTZ while others remain confined to its upper half.

Beneath the wave crest, a shallow layer of easterlies was seen by the sodar up to about 200 m AGL. Surface easterlies were also measured by the DRI surface network as well as by other surface towers in the valley. This feature persisted over several hours and was not intermittent like the couplets. The easterlies may connect to the reverse flow near the separation point, which is another feature revealed by the LESs.

The lee wave of IOP 3 was not stationary. Over about 8 h of this IOP (1400–2200 UTC), surface measurements indicate the separation point moving eastward, first past the west site and later past MAPR. In a similar way, the wave crest moves over both sites. It is because of this fortuitous movement that the profiler network maps large portions of the LTZ.

The couplets observed by MAPR can be seen in considerable detail because of the temporal resolution of this wind profiler. Similar couplets were observed by MISS as the wave crest moved over that wind profiler, and similar wind profiler observations were also obtained during a rotor event in IOP 13 (Doyle et al. 2009). It may be that this is a common feature of rotor circulations in Owens Valley.

Wind profilers are also useful in monitoring the properties of mountain waves. Using the network configuration of IOP 6, when the three ISS were aligned across the valley, we have documented the position, wavelength, and amplitude of the wave and monitored changes over time and height. Although the number and placement of profilers were not optimized for the observed wave and the algorithm used was basic, shifts in the wave position and a general increase in wavelength over a 6-h period were observed, as was increasing wave amplitude with height. As far as we know, this is the first use of a profiler network for this purpose.

The profilers used in T-REX were pushed to their limits. As profilers with greater sensitivity, more mobility, and greater time and vertical resolution are developed, they will be even more capable of mountain-wave and rotor studies. In addition, a larger network of profilers, preferably mobile, could better show variations in the

FIG. 16. Observed features of the IOP-3 wave–rotor systems: 1) shear layer (vorticity sheet) separating the LTZ from laminar flow above, 2) turbulence strongest on the upwind side of the crest, 3) reverse flow where the vorticity sheet separates from the surface layer, 4) transient couplets (dashed curve) observed descending from region of high vorticity, 5) shallow surface easterlies beneath the wave crest, and 6) eastward migration of the wave (both the crest and separation point).
wave, rotor, and LTZ, both along and across Owens Valley.

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REFERENCES


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