Atmospheric Rotors and Severe Turbulence in a Long Deep Valley

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ABSTRACT

The conceptual model of an atmospheric rotor is reexamined in the context of a valley, using data from the Terrain-Induced Rotor Experiment (T-REX) conducted in 2006 in the southern Sierra Nevada and Owens Valley, California. All T-REX cases with strong mountain-wave activity have been investigated, and four of them (IOPs 1, 4, 6, and 13) are presented in detail. Their analysis reveals a rich variety of rotorlike turbulent flow structures that may form in the valley during periods of strong cross-mountain winds. Typical flow scenarios in the valley include elevated turbulence zones, downslope flow separation at a valley inversion, turbulent interaction of in-valley westerlies and along-valley flows, and highly transient mountain waves and rotors. The scenarios can be related to different stages of the passage of midlatitude frontal systems across the region. The observations from Owens Valley show that the elements of the classic rotor concept are modulated and, at times, almost completely offset by dynamically and thermally driven processes in the valley. Strong lee-side pressure perturbations induced by large-amplitude waves, commonly regarded as the prerequisite for flow separation, are found to be only one of the factors controlling rotor formation and severe turbulence generation in the valley. Buoyancy perturbations in the thermally layered valley atmosphere appear to play a role in many of the observed cases. Based on observational evidence from T-REX, extensions to the classic rotor concept, appropriate for a long deep valley, are proposed.

1. Introduction

Atmospheric gravity waves excited in stably stratified flow over a mountain ridge are often accompanied by significant low-level turbulence downwind of the ridge. The great impact mountain waves can have on the lee-side flow was first evidenced by observations of stationary cloud formations, for instance, in the lee of the Dinaric Alps along the Adriatic coast of Croatia (Mohorovičić 1889; Grubišić and Orlić 2007) or over the Sudetes in central Europe (Koschmieder 1920). Inspired by these studies and by reports of severe turbulence encounters by glider pilots (Hirth 1933), Wolf Hirth and Joachim Kuettner coordinated the first systematic measurements in mountain waves and low-level turbulence zones in the lee of the Riesengebirge (Sudetes). In his subsequent work, Kuettner (1938, 1939) coined the term “rotor,” referring to the seemingly rotating lines of cumulus clouds underneath the smooth lenticular wave clouds.

From the 1950s to the 1970s, several observational programs devoted to the study of mountain waves and rotors were organized in the United States and Europe: the Sierra Wave Project in the southern Sierra Nevada and Owens Valley, California (Holmboe and Klieforth 1957; Grubišić and Lewis 2004), a study of lee waves in the French Alps (Gerbier and Berenger 1961), and the

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Colorado Lee Wave Program in the Rocky Mountains (Lilly and Toutenhoofd 1969). From these field programs and related theoretical studies (Queney et al. 1960), conceptual models of the mountain wave–rotor system emerged and soon became an integral part of mountain meteorology textbooks and aviation handbooks (e.g., Whiteman 2000; WMO 1993).

A schematic depiction of a lee-wave rotor, reproduced from Lester and Fingerhut (1974), is shown in Fig. 1a. The rotor flow is described as a turbulent low-level circulation zone underneath the lee-wave crest. The rotor is capped by a rotor or roll cloud; near the surface, the flow occasionally recirculates back toward the mountain. Some of the most severe occurrences of lee-side turbulence have been ascribed to mountain flows of a hydraulic type (Fig. 1b). In the presence of a strong crest-level inversion or a midlevel critical layer (Durran 1990), a shooting flow can form over the mountain lee slope followed by an internal hydraulic jump. The hydraulic-jump-type rotor typically extends beyond the mountaintop level. The rotor flow poses a significant aeronautical hazard (Carney et al. 1997); aircraft penetrating into the rotor typically encounter a sharp transition to severe turbulence in its leading updraft.

The two idealized rotor types have been reproduced successfully in idealized numerical simulations (Doyle and Durran 2002; Hertenstein and Kuettner 2005; Jiang et al. 2007), lending further credence to the conceptual models. However, in more realistic conditions, these models prove to be simplistic. In fact, they are inherently two-dimensional and steady state and represent only the average characteristics of the rotor flow, as noted even in early studies (Holmboe and Klieforth 1957; Vergeiner and Lilly 1970). Also, they often neglect the importance of the atmospheric environment and secondary topography downstream of a mountain ridge. For instance, in the case of two parallel mountain ridges separated by a long deep1 valley, a number of processes can be expected to modify the rotor flow. These include diurnal heating in the valley and resultant thermally driven slope and valley winds (Zardi and Whiteman 2013), terrain-forced and pressure-driven channeling of flow in the valley (Whiteman and Doran 1993; Kossmann and Sturman 2003), the modulation of lee-wave characteristics by the presence of the second ridge (Stiperski and Grubišić 2011), and along-ridge variations in crest height or valley width (Mayr et al. 2007; Gohm et al. 2008).

A new opportunity to study the effects of the downstream environment on rotor formation was offered by the Terrain-Induced Rotor Experiment (T-REX; Grubišić et al. 2008), conducted in 2006 in Owens Valley, California. The core objective of T-REX was to study the interaction of mountain waves, rotors, and the boundary layer. During the experiment, novel ground-based and airborne in situ and remote sensing instruments were deployed, allowing scientists to document both cross-mountain and in-valley flows and their interactions at unprecedented temporal and spatial resolution. Subsequent to T-REX, a few authors have challenged the

1 The term “deep” refers to the effective terrain drop: the valley is deep enough for the atmosphere to be stably stratified in its upper portion (near crest level). This implies that waves are generated by flow over the first ridge and that the effective mountain height (i.e., the height difference between the mountaintop and the top of the valley boundary layer) can become high enough to generate large-amplitude waves. “Long and deep” implies the possible occurrence of processes in the valley other than thermally driven ones, such as flow channeling.
idealized descriptions of rotors (e.g., Doyle and Durran 2007; Doyle et al. 2009; Hill et al. 2010; Cohn et al. 2011). Their observational analyses of individual T-REX cases as well as semi-idealized numerical simulations give insight into the complex, fully three-dimensional inner rotor structure, featuring vigorous subrotor vortices.

In this work, we extend previous T-REX studies by a systematic comparison of multiple T-REX cases. We present a set of observations of rotors and similar turbulent structures in Owens Valley with the aim of collecting comprehensive evidence of how the characteristics of the downstream topography and atmospheric environment modify the rotor flow. Furthermore, we propose extensions to the idealized rotor concepts, appropriate for a long deep valley.

The rest of this paper is organized as follows. In section 2, we provide the T-REX geographical context and discuss the observing systems relevant for this study. In section 3, we present four case studies revealing a variety of in-valley responses to flow over the Sierra Nevada. In section 4, we discuss typical flow scenarios and possible transitions between them. Conclusions are drawn in section 5.

2. The Terrain-Induced Rotor Experiment

a. Geographical context

Topographic maps of the Sierra Nevada and Owens Valley are shown in Fig. 2. The Sierra Nevada stretches approximately 640 km from south-southeast to north-northwest and is about 110 km wide. Some of its peaks
reach 4000 m MSL and more, the highest one being Mt.
Whitney (4421 m MSL). Gentle westward and steep
eastward slopes characterize the southern section of the
range. There, the average elevation drop between the
main ridge line and the floor of Owens Valley to its east
is about 3000 m, with a 30° slope. The southern Sierra
Nevada exhibits relatively little along-ridge variation in
crest height, but a few high passes exist. Kearsarge Pass
(3600 m MSL, just west of Independence) and Sawmill
Pass (3460 m MSL) lie in the T-REX measurement area.
The highest density of T-REX ground-based in-
strumentation was located in Owens Valley around the
town of Independence. Owens Valley runs approximately
150 km parallel to and east of the southern Sierra
Nevada, and is bound by the Inyo and White Mountains to
its east. Its bottom and crest-to-crest widths are approxi-
mately 15 and 30 km, respectively. The valley floor gently
ascends from Owens (dry) Lake at 1084 m MSL to the
town of Bishop at 1260 m MSL, from which it rises more
rapidly for another 30 km to the north up to 1850 m MSL.

b. T-REX observing systems

T-REX field activities took place in March and April
2006. Ground-based and airborne in situ and remote
sensing measurements were made during 15 Intensive
Observing Periods (IOPs). The locations of ground-
based instruments and the orientation and extent of
aircraft flight tracks are indicated in Figs. 2b and 2c.
Upwind radiosondes were launched from the Naval Air
Station Lemoore and by the NCAR Mobile GPS
Advanced Upper-Air Sounding System (Mobile GAUS)
near the cities of Visalia or Madera. Downwind radio-
sondes were launched in Owens Valley southeast of In-
dependence from the NCAR Integrated Sounding System
(ISS; Parsons et al. 1994), which included a GAUS.
Coordinated flight missions were flown by up to three
research aircraft. The National Science Foundation
(NSF)/NCAR Gulfstream V (GV) High-Performance
Instrumented Airborne Platform for Environmental
Research (HIAPER), the NERC/Met Office Facility
for Airborne Atmospheric Measurement (FAAM) BAe-
146, and the University of Wyoming King Air (UWKA)
research aircraft flew stacked cross-valley flight legs aligned
with the mean wind direction at altitudes from 150 m above
the valley floor to 14 km MSL (Grubišić et al. 2008, their
Fig. 3 and Table III). High-rate (25 Hz) in situ measure-
ments were made of the three wind components, temper-
ature, humidity, and pressure. On UWKA, additional
measures of the energy dissipation rate to the power of
one-third (EDR) were recorded by the MacCready Tur-
bulence Meter (MacCready Jr. 1964), providing turbu-
ulence intensity estimates at and below the Sierra Nevada
crest level. EDR estimates show good agreement with
those obtained from spectral analysis of high-rate wind
measurements for spatial scales of 15–400 m (Strauss
et al. 2015). Recently, EDR has been established as an
aircraft-independent objective measure of turbulence in-
tensity in civil aviation (International Civil Aviation
Organization 2007; Sharman et al. 2014). UWKA was also
equipped with the dual-Doppler Wyoming Cloud Radar
(WCR), providing insight into the two-dimensional wind
field in cap clouds over the Sierra Nevada and roll clouds
over Owens Valley.

Here, airborne data are displayed as composite ver-
tical cross sections composed from flight-level in situ
measurements along individual aircraft legs. Only data
from legs in reasonable temporal and spatial proximity
were admitted to the analysis. Interpolated contours of
vertical velocity and potential temperature were derived
from the composite data using natural neighbor in-
terpolation (Sibson 1981), which is known to perform well
for irregularly distributed data. The interpolation method
is a weighted-average technique and uses Delaunay tri-
angulation to select the local neighbors to each point and
to determine their weights for interpolation. The in-
terpolated contours serve to visualize the wave fields and
stratification in and above Owens Valley.

A network of 32 automatic weather stations (AWS)
covered the floor and slopes of Owens Valley around the
town of Independence. AWS from the Desert Research
Institute (DRI) were arranged in three west–east-oriented
arrays south of Independence. AWS from the University
of Leeds (UL) were distributed to the north and up on the
slopes of the Sierra Nevada and the Inyo Mountains. All
AWS recorded 30-s averages of the horizontal wind, wind
direction, temperature, and humidity.

Three boundary layer wind profilers were deployed as part
of the NCAR ISS. ISS2 was located on the western slope
of the valley, a Multiple Antenna Profiler (MAPR; Cohn et al.
2001) was situated at the valley center, and a mobile ISS
(MISS) was relocated along the valley axis between IOPs.
The wind profilers measured horizontal wind speed and di-
rection and vertical velocity up to 5000 m above ground level,
averaged over 30 min (ISS2/MISS) and 5 min (MAPR).

Finally, several scanning Doppler lidars were deployed. Here, data from the lidar operated by the
Deutsche Zentrum für Luft- und Raumfahrt (DLR)
(Kühnlein et al. 2013) are used. Vertical-slice range-
height indicator scans were performed at azimuthal angles
of 50°, 80°, and 170° east of north (referred to as RHI-50,
RHI-80, and RHI-170, respectively) to sample cross-
valley and along-valley flows. Conical plan position in-
dicator (PPI) scans were carried out at elevation angles
ranging from 3° to 60° (PPI-03–PPI-60). Lidar-measured
fields included the aerosol backscatter intensity, radial
Doppler velocity, and Doppler spectral width.
In addition to the observational datasets, 700-hPa analyses from the European Centre for Medium-Range Weather Forecasts (ECMWF) Integrated Forecast System (IFS) are used here to provide the context of the large-scale synoptic flow.

3. Observations

The main objective of this work is to reexamine the conceptual model of a rotor in the context of a valley. To this end, we analyzed T-REX IOPs 1, 2, 3, 4, 6, and 13, exhibiting the strongest response of the flow to the underlying topography (in terms of, e.g., the amplitude of vertical air motion at the Sierra Nevada crest level or the strength of downslope winds over the mountain lee slope).

In the following section, we summarize the upstream synoptic and downstream in-valley conditions during these IOPs. Four selected cases, displaying different types of rotor flow and mechanisms of turbulence generation in Owens Valley are presented in more detail in section 3b.

### a. Synoptic conditions during T-REX IOPs

The Sierra Nevada is well known for launching large-amplitude mountain waves. The generation of mountain waves in its lee is frequently associated with the passage of frontal systems (Holmboe and Klieforth 1957). From October to May, with the shift of the polar jet to the south, midlatitude synoptic systems tend to travel past the
mountain range, directing strong southwesterly-to-northwesterly, stably stratified flow toward the ridge, thereby favoring the generation of large-amplitude waves and rotors. The frequency of occurrence of mountain-wave events in the lee of the Sierra Nevada peaks in April (Grubišić and Billings 2008). T-REX field activities were therefore planned for the spring of 2006.

T-REX IOPs, aiming for periods of enhanced flow response to the Sierra Nevada, were scheduled when medium-range forecasts predicted the approach of a frontal system toward the U.S. West Coast, as is evident from 700-hPa ECMWF analyses (Fig. 3). Intense IOPs typically featured large-scale midtropospheric troughs to the northwest of the Sierra Nevada. The exception was IOP 3, which stood out for its particularly strong flow being part of the core of the polar jet extending from Alaska to the coast of California.

A set of upstream and downstream in-valley vertical profiles of wind speed, wind direction, and virtual potential temperature $\theta_v$ during these IOPs is shown in Fig. 4. Common characteristics of the upstream profiles (colored in blue) include low wind speed and wind
Table 1. Summary of upstream flow characteristics and strength and scales of the downstream in-valley flow response for the selected T-REX cases. Letters behind IOP numbers identify IOP subperiods. Upward- or downward-pointing arrows behind numbers indicate the tendency of a quantity to increase or decrease during the given period. “Midlevel wind speed” refers to the average wind speed in the layer 4000–6000 m MSL.

<table>
<thead>
<tr>
<th>IOP</th>
<th>1a</th>
<th>4a</th>
<th>6b</th>
<th>6c</th>
<th>13b</th>
</tr>
</thead>
<tbody>
<tr>
<td>Midlevel wind speed (m s(^{-1}))</td>
<td>2700</td>
<td>3200</td>
<td>—</td>
<td>—</td>
<td>1900</td>
</tr>
<tr>
<td>Crest-level potential temperature increase [K (500 m)(^{-1})]</td>
<td>5.0</td>
<td>5.5</td>
<td>3.0</td>
<td>3.0</td>
<td>2.5</td>
</tr>
<tr>
<td>Crest-level stability N (s(^{-1}))</td>
<td>0.018</td>
<td>0.019</td>
<td>0.014</td>
<td>0.014</td>
<td>0.012</td>
</tr>
<tr>
<td>Wavelength (km)</td>
<td>17</td>
<td>19</td>
<td>16</td>
<td>30</td>
<td>—</td>
</tr>
<tr>
<td>Crest-level wind speed (u_{min}) (m s(^{-1}))</td>
<td>−4.5</td>
<td>−8.5</td>
<td>−10</td>
<td>−6.5</td>
<td>−4</td>
</tr>
<tr>
<td>Crest-level wind speed (u_{max}) (m s(^{-1}))</td>
<td>+4.5</td>
<td>+6.0</td>
<td>+10</td>
<td>+7.5</td>
<td>+4</td>
</tr>
<tr>
<td>Valley inversion height (m MSL)</td>
<td>—</td>
<td>—</td>
<td>2700</td>
<td>3200</td>
<td>—</td>
</tr>
<tr>
<td>Valley inversion strength (\Delta \theta) [K (500 m)(^{-1})]</td>
<td>5.5</td>
<td>3.5</td>
<td>—</td>
<td>—</td>
<td>4.0</td>
</tr>
<tr>
<td>Maximum strength of up-valley flow (m s(^{-1}))</td>
<td>17</td>
<td>21</td>
<td>9</td>
<td>—</td>
<td>9</td>
</tr>
<tr>
<td>Maximum adverse surface pressure gradient force (10(^{-3}) m s(^{-2}))</td>
<td>—</td>
<td>0.26</td>
<td>0.29</td>
<td>1.04</td>
<td>0.07</td>
</tr>
</tbody>
</table>

direction considerably deviating from the cross-mountain direction (~255°) below ridge height (indicative of upstream blocking), increased stability at and above crest level, and weaker stability and rapid increase in wind speed in the free atmosphere. Such a vertically layered atmosphere corresponds to a Scorer parameter [defined as \(N^2/U^2 - (1/U)(\partial U/\partial z)^2\), where \(N\) and \(U\) are the upstream stability and cross-mountain wind speed, respectively] that decreases with height, favoring the formation of trapped lee waves (Scorer 1949).

Upon close inspection of the profiles, a few differences between the cases become apparent. These include, for example, stronger crest-level stratification but weaker increase in wind speed aloft for IOPs 1 and 2 compared with IOPs 4 and 13. The resultant differences in the Scorer parameter have been linked previously to the tendency of either of two wave types (lee waves versus propagating mountain waves) to occur in the lee of the Sierra Nevada (Grubisić and Billings 2008). Apart from case-to-case differences, another cause of differing vertical profiles seems to be the timing of radiosonde launches with respect to the approaching cold front, making the IOP 1 and 2 profiles representative of the early prefrontal environment, while the others correspond to the stages when the front has already reached the Sierra Nevada.

The differences in the in-valley profiles (Fig. 4, colored in red) are generally larger; however, almost all profiles show a low-level flow in the valley that is south-southeasterly (up valley). This is a typical characteristic of the elongated Owens Valley and is explained by the position of the synoptic-scale pressure low to the (north-) northwest of the mountain range ahead of cold fronts, leading to pressure-driven channeling of the flow along the valley from south to north (Zhong et al. 2008).

Because of its significant depth and the semiarid nature of its slopes and floor, Owens Valley displays a marked diurnal temperature cycle (Li et al. 2009). Thus, a complex layered structure of stability is evident from the in-valley profiles for some IOPs (e.g., 1a and 4a in the morning), in contrast to a rather well-mixed valley atmosphere in others (e.g., 3a and 4a in the afternoon). The profiles are further characterized by marked shear (up to 20 m s\(^{-1}\) km\(^{-1}\)) in the layer ±1000 m around the mountaintop height. Above ±5000 m MSL, most valley soundings closely follow their upstream counterparts.

While important predictors for wave launching by the Sierra Nevada can be found in upstream profiles (e.g., enhanced crest-level stability), several authors have investigated the additional role of properties of the valley atmosphere for wave generation and penetration of westerly winds into Owens Valley (Jiang and Doyle 2008; Billings and Grubisić 2008a,b; Mayr and Armi 2010). For example, moderate downslope winds may be present at the Owens Valley floor despite weak or no waves aloft, because of the difference between upwind and downwind potential temperatures, allowing the cooler upstream air to flow over the mountain gaps and undercut the valley atmosphere (Raab and Mayr 2008; Mayr and Armi 2010). These potential temperature differences arise from and are modulated by the relative timing of approaching frontal systems (leading to
blocking and gradual buildup of cold air upstream of the Sierra Nevada) and the diurnal temperature cycle in the valley.

b. Case studies

In the Introduction, processes typical of a valley atmosphere have been introduced. In the majority of the selected IOPs, several of these processes (sometimes all of them) were at play, influencing rotor formation and turbulence generation and their temporal evolution. The impact of a single process on rotor formation thus cannot be studied in isolation from the others. This aspect of the data analysis represents a particular challenge, which we aimed to alleviate by selecting cases dominated by a limited set of processes. In the following, four such cases are presented in detail. The upstream conditions and the strengths and scales of the downstream response during these are summarized in Table 1.

1) IOP 1A—The Elevated Turbulence Zone

IOP 1 was conducted from 0000 UTC 2 March to 1500 UTC 3 March 2006. The IOP involved flight missions by UWKA and GV in the morning (IOP 1a) and afternoon (IOP 1b) of 2 March. Mayr and Armi (2010) investigated the onset of a shallow foehn in Owens Valley during this case. Here, we focus on the UWKA turbulence measurements during the morning flight.

IOP 1a was timed well ahead of the passage of a midlatitude synoptic system (Fig. 3a). Upstream conditions were typical of the prefrontal environment, with strong crest-level stability and enhanced lee-side shear but moderate wind speeds and decreasing stability farther aloft (Fig. 4a), providing optimal conditions for moderate-amplitude lee waves. Up-valley flow with wind speeds on the order of 5–10 m s\(^{-1}\) was found in the valley, topped by a sharp inversion (\(\Delta \theta = 5–6\) K) roughly 1500 m above the valley floor.

In situ measurements made by UWKA are shown in Fig. 5. Raw and interpolated vertical velocities (Figs. 5a,b) exhibit a sequence of vertically coherent up- and down-drafts of up to \(\pm 4.5\) m s\(^{-1}\), strongly suggestive of lee waves. A distinct characteristic of the waves is the rapid decay of their amplitude downwind of the second downdraft. This feature may be attributed to destructive interference of lee waves generated by the primary and secondary ridges (Grubišić and Stiperski 2009; Stiperski and Grubišić 2011) or to critical-level or viscous absorption of wave energy by the valley atmosphere (Smith et al. 2002; Jiang et al. 2006).

Along the primary lee-wave crest and below the layer of increased stability, turbulence of moderate (EDR \(\geq 0.22\) m\(^{0.63}\) s\(^{-1}\); Sharman et al. 2014) to moderate–severe (EDR \(\geq 0.35\) m\(^{0.63}\) s\(^{-1}\)) intensity and enhanced mixing is detected in the otherwise stably stratified valley atmosphere (Fig. 5e). Below that region, the inversion-capped valley atmosphere remains largely undisturbed. A core of nonturbulent air flowing up-valley east of the valley axis is revealed by aircraft measurements below 3000 m MSL.

Jiang et al. (2010) suggested that the significant crest-level turbulence in this IOP results from the interaction of the lee waves with strong vertical shear (discussed in more detail in section 4a). The confinement of turbulence to around mountaintop height is in stark contrast to the well-known low-level turbulence zone (Fig. 1a). We will refer to this type of structure as an “elevated turbulence zone” of moderate–severe turbulence intensity, limited to a layer \(\pm 750\) m around crest level.

2) IOP 13B—Downslope Flow Separation at a Low-Level Valley Inversion

One of the strongest windstorms of T-REX occurred on 16 April 2006 (IOP 13; Reinecke and Durran 2009). During the local morning and early afternoon (IOP 13c), scanning lidars sampled the turbulent interaction of strong westerly winds and pressure-driven channeled up-valley flow, providing some of the best evidence of subrotor vortices in T-REX (Doyle et al. 2009; De Wekker and Mayor 2009). A few hours earlier (IOP 13b), another remarkable event was observed by the DLR lidar, which has not received attention thus far.

With the approach of the frontal system, cold air was building up upwind of the Sierra Nevada and started to flow through the mountain gaps toward the valley floor at 0800 UTC 16 April. However, about 7 km west of the DLR lidar, the strong (\(-15\) m s\(^{-1}\)) downslope flow terminated abruptly, detaching from the surface and sliding over another air mass in the core of the valley, as revealed by Fig. 6 for 1115 UTC. The flow in the lowest valley layers was mainly directed up-valley, with a small easterly component evident in the vertical-slice lidar scan and wind vectors from the wind profilers. This configuration persisted for more than 5 h (0800–1330 UTC). At various times during this period, wavy features reminiscent of Kelvin–Helmholtz billows (Fig. 7, couplets of positive and negative radial velocity) formed along the directionally sheared interface between the westerly flow and the lower-level up-valley flow. The couplets were collocated with turbulent intrusions into the otherwise nonturbulent valley air (Figs. 7b,d,f), similar to, albeit not as vigorous as, the subrotor vortices observed during IOP 13c. The origin of the observed billows can be attributed to the onset of shear instability. To confirm the plausibility of this hypothesis, we estimate the gradient Richardson number, defined as
FIG. 5. Composite vertical cross section of UWKA in situ measurements made between 1700 and 1930 UTC 2 Mar 2006 (IOP 1a) along a cross-valley track (Fig. 2b). (a) Vertical velocity, (b) interpolated vertical velocity overlaid with isentropes (drawn at 1-K increments), (c) horizontal wind speed, (d) wind direction, and (e) EDR. The Sierra Nevada is located to the left (west), and the Inyo Mountains are to the right (east). Distance is upwind (<0) or downwind (>0) of the valley axis, which runs through the town of Independence.
Using wind and temperature data from the ISS2 wind profiler and the radiosonde around 1115 UTC in the 3100–3600-m MSL layer (Fig. 6), the estimate yields \( \text{Ri}_g' \approx 0.16 \) (\( \text{Ri}_g < 0.25 \) is a necessary condition for Kelvin–Helmholtz instability). Further insight into the dynamics of the event can be gained from a comparison of upstream and in-valley vertical profiles (Fig. 8), similar to the analysis by Mayr and Armi (2010). Upstream profiles are again characterized by blocking, extending to 2300 m MSL and higher, while up-valley flow dominates in the valley. The \( \theta_v \) profile reveals that the upstream flow above the blocked layer is cooler than the valley atmosphere and is thus able to penetrate well below crest level on the lee side (cf. arrows in Fig. 8c). Its initially negative buoyancy, however, vanishes as it encounters the low-level valley inversion \( \approx 700 \) m above the valley floor. This level coincides with the height at which the flow separates in the lidar images (Figs. 6 and 7), pointing to the likely role of the stratification of the valley atmosphere in determining the position of the separation point (see discussion in section 4c).

Since no aircraft measurements are available for this period, direct evidence of waves at and above crest level is missing. Wind profiler measurements, however, indicate sustained upward motion up to \( 4 \) m s\(^{-1} \) above the ISS2 site between 3 and 4.5 km MSL (Fig. 6). In addition, enhanced downward motion above the eastern part of the valley is evidenced by the temporary descent of the radiosonde (Fig. 6) launched at 1100 UTC from the valley center (cf. Wang et al. 2009). However, in the absence of spatially more extensive aircraft measurements, no satisfactory answer can be given as to the type and amplitude of the waves.

The nighttime flow separation of IOP 13b bears some similarity to the elevated turbulence zone of IOP 1a (Table 1). A major difference, however, is the considerably deeper penetration of westerly flow in IOP 13b, which is due to the different timing of the frontal passage with respect to the diurnal cycle in the valley. In IOP 1a, the flow through the passes started in the local morning, after nocturnal cooling in the valley had led to a strong, elevated inversion \( \approx 1500 \) m above the valley floor. In IOP 13b, the overflow set in early in the night, when a low-level inversion \( \approx 700 \) m above the valley floor had just formed, resulting in a penetration deeper by almost 1000 m and a well-defined separation of the flow from the lee slope at the height of the low-level inversion. Another distinguishing feature of the two cases seems to
be the turbulence production mechanisms, as discussed in section 4a.

3) IOP 4A—TURBULENT INTERACTION OF IN-VALLEY WESTERLIES WITH ALONG-VALLEY FLOW

Some of the highest turbulence intensities in Owens Valley were encountered by UWKA on its morning flight on 14 March 2006 (IOP 4a). Upstream profiles (Fig. 4d) were characterized by prefrontal-to-frontal conditions. Both the strengthening of upper-level winds and diurnal heating in the valley led to considerable transience of wave patterns throughout the IOP.

Composite cross sections of in situ data collected by UWKA during 1700–1930 UTC are shown in Fig. 9. Large-amplitude, long waves are detected in the lee of the Sierra Nevada (cf. Table 1). In contrast to IOP 1a (Fig. 5), westerly momentum and strong vertical motion are present well below crest level above the lee slope and the valley center (Figs. 9a,c). The turbulence structure in and above the valley is complex. Moderate–severe turbulence above the mountain tops and at crest level over the valley (arrows 1 and 2 in Fig. 9d) is located at the edges of the cap cloud, which was particularly well developed and spilled over into the valley on that day (cf. overlay of WCR data in Figs. 9a,b). In the cloud, regions of upward vertical motion in excess of $5 \text{ m s}^{-1}$ and vertical wind shear on the order of $20 \text{ m s}^{-1} \text{ km}^{-1}$ are found. The most
interesting turbulent region is located at lower levels in the valley and tilts upward across the valley from west to east (Figs. 9c,d). Figure 9c, showing wind direction, reveals the low-level turbulence to be localized at the directionally sheared interface between the in-valley westerlies (10–15 m s\(^{-1}\) from the west-southwest) and the strong up-valley flow (up to 20 m s\(^{-1}\) from the south-southeast) in the eastern part of the valley. The magnitude of turbulence in that region falls, too, into the moderate–severe category, comparable to that reported for the interior of rotors (e.g., Darby and Poulos 2006; Strauss et al. 2015).

The end of IOP 4a and the subsequent evolution of the event, extending beyond the available aircraft measurements, was covered by lidar observations. DLR lidar data from the 2.5 h (1920–2200 UTC) after the flight mission are shown in Figs. 10 and 11. The spatial distribution of turbulence (Fig. 10c) is consistent with that in the composite cross section (Fig. 9d). Note that the lidar was situated roughly 2 km...
west of Independence, which serves as the origin of aircraft composite cross sections. The PPI-20 scan at 1926 UTC overlaid with station measurements (Fig. 10d) indicates a strong up-valley flow (10–20 m s\(^{-1}\)), beneath the cross-mountain flow. Within an hour, the flow in the valley changes significantly (Figs. 10e–h). At 2025 UTC, a shallow westerly downslope flow is present down to 3 km east of the lidar, where it encounters the strong up-valley flow. The period 2000–2130 UTC coincides with the appearance of roll and wave clouds over the eastern portion of the valley, as visible from GOES-10 satellite images (not shown). The vertical structure of the flow in the valley throughout this period is quite complex. The relatively shallow downslope current results from the cold air from upstream of the Sierra Nevada spilling over the mountain passes. Above it, up-valley and upslope-directed flow is detected southwest of the lidar in the range of 4–6 km (Figs. 10f,h). The middle layer flow (interposed between the low-level current and strong crest-level westerlies and displaying significant shear-driven turbulence at its boundaries) is a typical characteristic of the transition from the initially up-valley (Figs. 10b,d) to the fully in-valley westerly regime.
In this and other cases, transition concurs with the amplification and expansion of waves above the mountain-top; however, it seems to be initialized, or at least greatly facilitated, by the daytime warming of the valley air (Fig. 4d).

A photograph taken near the DLR lidar site at 2130 UTC, shown in Fig. 12, provides an impressive snapshot of this event. The nicely formed line of roll clouds east of the valley axis would normally be interpreted as visual indication of a rotor. The clouds, instead, formed at and downstream of the convergence line between the low-level cross-valley and eastern up-valley flows, as revealed by the lidar scans (Figs. 10e,f,h).

4) IOP 6—TRANSIENT MOUNTAIN WAVES AND ROTORS

The most severe downslope windstorm of T-REX occurred on 25 and 26 March 2006 (IOP 6). Maximum wind gusts of 36 m s\(^{-1}\) were recorded at DRI station 2 around 0240 UTC 26 March. Damage was caused in the town of Independence, and severe turbulence over Owens Valley was encountered by a private aircraft crossing the valley en route from San Francisco to Las Vegas. Owing to the severity of the event, IOP 6 became the subject of many observational and numerical modeling studies (e.g., Reinecke and Durran 2009; Hill et al. 2010; Doyle et al. 2011; Sheridan and Vosper 2012; Kühnlein et al. 2013).

IOP 6 lasted from 2000 UTC 24 March to 0500 UTC 26 March. Sheridan and Vosper (2012) have documented the dynamic evolution of this event, including details of the cold-frontal passage, based on observations and real-case simulations. The marked transience of the flow in Owens Valley during the second phase of IOP 6 [1600 UTC 25 March–0500 UTC 26 March (IOPs 6b and 6c)] has been analyzed by Kühnlein et al. (2013) using data from the DLR lidar. The objective of this section is to reexamine the observations and link them to the evolution of waves above Owens Valley.

Soundings from IOPs 6b and 6c (Fig. 4e) are characterized by frontal-to-postfrontal conditions. Cross-mountain winds above the mountaintop height continue...
to increase with time, reaching 30 m s\(^{-1}\) at crest level and exceeding 50 m s\(^{-1}\) at the tropopause in the 2258 UTC sounding. Initial upstream blocking is gradually reduced, and enhanced crest-level stability yields to more uniform stratification. Crest-level shear increases, peaking at \(\frac{20}{\text{km}}\) in the 2000 UTC valley profile.

Two flight missions were conducted on 25 March, the first one involving all three research aircraft. A composite cross section of aircraft measurements from the first mission (1625–1850 UTC) is shown in Figs. 13a–c. A strongly nonlinear mountain wave is present downstream of the Sierra Nevada, with isentropes bending downward by \(\frac{2}{\text{km}}\) in the lee and quickly recovering their original height over the valley center. The aircraft measurements coincide with the appearance of in-valley westerlies, taking the form of low-level eastward-propagating pulses of high-momentum air, with turbulent structures similar to a rotor at their front, as observed by the DLR lidar (Kühnel et al. 2013; their Figs. 3 and 5). During the same period (~1730–1830 UTC), the vertical velocity above the ISS2 wind profiler (Fig. 14b) changes sign, likely related to the shift of the primary wave updraft to the east. By the time of the afternoon flights, the horizontal wavelength of the wave has increased, placing the leading updraft of the wave over the windward slope of the Inyos (Figs. 13d,e; Table 1).

While the valley atmosphere above the ISS2 site remains disturbed after 2100 UTC (Fig. 14a), surface westerlies take hold at the valley floor, continuously gaining strength and exceeding 20 m s\(^{-1}\) by 0200 UTC 26 March. The most severe downslope windstorm of T-REX occurs from 0200 to 0330 UTC 26 March (Fig. 14a). By 0230 UTC, lofted dust becomes visible in the DLR lidar RHI-80 scans over the eastern part of the valley, reaching a vertical extent of 2.5 km within only 10 min (Figs. 15a,c). In the next 30 min, the leading edge of this feature rapidly moves upstream across the valley (Figs. 15c,e), gradually decelerating and lingering over the lidar site for the next hour (also cf. Kühnel et al. 2013, their Fig. 9).

The above observations represent the best evidence of boundary layer separation and the development of a large rotor in T-REX. Radial velocities away from the lidar in excess of 20 m s\(^{-1}\) are found near the rotor edge (Fig. 15c). Distinct zones of easterly (i.e., reversed) flow of up to 10 m s\(^{-1}\) are located eastward of the separation point and underneath the rotor edge, resulting in strong shear and severe turbulence (Fig. 15d), which is typical of the separated boundary layer (Doyle and Durran 2002). Once the rotor fully developed (Fig. 15e), its downwelling branch, characterized by flow away from the lidar and another region of increased turbulence
Fig. 14. Time–height Hovmöller diagrams of (a) wind speed and wind direction and (b) vertical velocity measured by the ISS2 wind profiler between 0400 UTC 25 Mar and 0800 UTC 26 Mar 2006, covering the transient phases of the IOP 6 windstorm. Vertical dotted lines indicate periods with nonstationary waves and rotors.

(Fig. 15f), becomes visible and seems to reattach to the ground.

Despite its strong similarities to the idealized rotor, the flow displays a high degree of three-dimensionality and transience (Kühnlein et al. 2013). Beyond a region with a marked easterly flow component, immediately downstream of the separation point, wind vectors in the eastern portion of the valley are predominantly down valley. Also, the rotor structure is not always as well defined as in Fig. 15e. The strong interaction with the along-valley flow perturbs its average shape continuously. After 0330 UTC, the rotor retreats upstream and eventually decays. At the same time, upward motion reappears above the ISS2 site (Fig. 14), suggesting that the leading updraft of the wave in the valley has shifted back to the west.

In summary, the onset and cessation of the IOP 6 downslope windstorm appear to be tightly linked to the eastward and westward shifts of the wave patterns aloft. As the primary wave updraft moves to the east and downslope winds gradually follow, a rotorlike turbulent structure is found at their front. As the wave updraft reaches the second ridge, this structure is suppressed but resurrects as a fully developed rotor downwind of the retreating windstorm as the wave updraft moves back toward the Sierra Nevada. In any of these phases, the destructive/constructive interference of lee waves over the double-ridge configuration of the Sierra Nevada and the Inyo Mountains could play a role in the weakening/strengthening of the observed wave amplitude and rotor (Grubišić and Stiperski 2009).

The last phase of IOP 6 bears striking resemblance to two rotor events observed on 26 January and 5 February 2006 in the lee of the Medicine Bow Mountains, southeast Wyoming. Detailed observational analyses (French et al. 2015; Strauss et al. 2015) and high-resolution numerical simulations (Grubišić et al. 2015) have identified transient midtropospheric wave breaking as the key mechanism behind the rotors’ movement in those cases. Indeed, in an investigation of the predictability of the IOP 6 severe downslope windstorm (Reinecke and Durran 2009), only those ensemble members that involved the upper-tropospheric turbulent breakdown of a large-amplitude mountain wave above the Sierra Nevada reproduced severe downslope windstorms. It is thus plausible that the nonstationary waves and transient rotors of IOPs 6b and 6c are closely related to wave breaking and concomitant changes in the flow across the Sierra Nevada.

4. Discussion

The above case studies reveal the rich variety of wave and turbulence patterns over the Sierra Nevada and Owens Valley. The observational analysis shows that the classic elements of the rotor concept, and the types of rotorlike structures that may form from their combination, are considerably affected by in-valley processes. In the following, we present schematic diagrams (Fig. 16) that describe the typical flow scenarios and relate these to frontal passage across the region. In Table 2, we provide a classification of T-REX IOPs according to the idealized scenarios.

a. Categorization of turbulent structures in Owens Valley

A schematic of the elevated turbulence zone (scenario A) is shown in Fig. 16a. Trapped lee waves of moderate amplitude are present over the Sierra Nevada. Below the lee-wave crest, moderate to moderate–severe
turbulence is found. The inversion-capped up-valley flow in the valley remains decoupled. Lines of roll clouds similar to rotor clouds occasionally form in the wave crests over the valley.

It is tempting to think of this case as an elevated rotor, induced by the detachment of the flow at the elevated valley inversion. However, turbulence intensity is equally high below the upwelling and downwelling branches of the wave. This is in contrast to previous findings showing that the strongest rotor turbulence is located along its upstream edge (generated from the shear of the separated boundary layer), while it is generally weaker and more diffuse on its downstream side (Lester and Fingerhut 1974; Doyle and Durran 2002).

Here, instead, turbulence is likely generated by the interaction of the waves with enhanced crest-level shear, resulting in a local decrease (increase) of Richardson number in wave crests (troughs) and consequent promotion (suppression) of shear instability (as suggested by Jiang et al. 2010).

A depiction of downslope flow separation at a low-level valley inversion (scenario B) is shown in Fig. 16b. At nighttime, the cold upstream air mass starts to flow over the Sierra Nevada but is prevented from progressing to the valley bottom by the presence of even colder and more stable air. The downslope flow separates from the lee slope well above the valley floor and flows over the stably stratified up-valley flow. Kelvin–Helmholtz billows that form at the directionally sheared interface between the two air masses are advected and break down into turbulence, reminiscent of subrotors observed for other T-REX cases. Scenario B highlights the importance of potential temperature differences between the upstream and downstream air masses for the location of flow separation. The scenario displays several characteristics of a classic rotor: flow separation, shear at the lower edge of the separated flow, Kelvin–Helmholtz instability, and the associated formation of billows and enhanced turbulence. On the other hand, a closed rotor circulation below the separated flow is absent; instead, channeled up-valley flow prevails.
Note that the idealized diagrams of scenarios A and B are somewhat similar to two of those by Jiang and Doyle (2008, their Fig. 12). The latter, however, refer to a weak westerly wind event during the Sierra Rotors Project (SRP) IOP 12, primarily determined by thermal forcing in the valley.

A schematic of daytime turbulent interaction of in-valley westerlies with channeled up-valley flow (scenario C) is shown in Fig. 16c. The wave amplitude tends to be considerably larger than in scenarios A and B. This may be attributed in part to the well-mixed valley atmosphere: compared to the latter scenarios, the absence of a valley inversion results in a larger effective mountain height (Smith et al. 2002; Armi and Mayr 2015). Frequently, a convective cap cloud is present over the Sierra Nevada. In the course of the day, the valley atmosphere becomes increasingly well-mixed, permitting the cross-mountain flow to reach the valley floor [similar to the later stages of the weak westerly wind event described by Jiang and Doyle (2008)]. Severe turbulence is found in the cap cloud and where the penetrating westerlies interact with the up-valley flow, with intensities similar to those in the interior of rotors. At times, a rather well-defined line of directional shear at the interface between the westerly and up-valley winds is present in the valley and roll clouds form east of the valley axis. The scenario typically lasts until westerlies become strong enough to flush out the valley air (IOP 4a), but along-valley winds may also continue to resist for several hours (IOP 13c).

The class of strongest events (scenario D) is presented in Fig. 16d. This scenario is characterized by the highest cross-mountain winds and largest-amplitude waves, capable of fully controlling the flow in the valley. The wave amplitudes may be particularly strong because of the positive interference of lee waves over the primary and secondary mountain ridges (Grubišić and Stiperski 2009). In response, a large rotor can form, the leading edge of which is aligned with the updraft of the wave aloft. The wave field, however, exhibits a high degree of transience. It strongly responds to the strengthening (weakening) of cross-mountain winds by extending (shortening) its wavelength and shifting across the valley to the east (west), thereby steering the downslope windstorm with the rotor at its leading edge. In the strongest phase of the event, the wave updraft is located...
over the windward slope of the secondary ridge, and rotor formation is temporarily suppressed. The scenario contains all elements of the classic rotor: in particular, a rather well-defined, albeit short-lived, reversed flow downstream of the boundary layer separation point. The distinct additional element to the steady-state picture is the rapid rotor evolution on a temporal scale of less than 3 h, likely related to the onset and cessation of mountain-wave breaking at mid-to-upper levels (cf. Jiang et al. 2007; Grubišić et al. 2015).

Note that none of the cases presented in this paper supports a simple distinction between the lee-wave-type and hydraulic-jump-type rotors (Fig. 1), which have been referred to as type-1 and type-2 rotors in the literature (Hertenstein and Kuettner 2005). This is again attributed to the dominant in-valley atmospheric conditions often overpowering the classic rotor characteristics. However, in other environments that are less dominated by lee-side dynamic and thermal processes, almost prototypical realizations of the idealized rotor types have been found (e.g., Ralph et al. 1997; French et al. 2015).

b. Stages of frontal passage over the Sierra Nevada and Owens Valley

The essential characteristics of the upstream and downstream in-valley soundings associated with the above four scenarios are shown in Fig. 17. Close inspection of the idealized profiles indicates that they may be related to different stages of the passage of frontal systems across the region. The following description of the profiles focuses on three aspects: the effect of the frontal passage on the upstream environment, its impact on wind speed and direction within the valley, and the distinct effect of in-valley diurnal processes on the vertical profile of potential temperature.

The upstream environment in scenarios A and B (identical in the idealized profiles) is associated with prefrontal conditions. The upstream flow is blocked (as is evident in both wind speed and direction below 2 km MSL); wind shear is strong at the mountaintop level and moderate aloft. Stability exhibits a marked peak around crest level, favoring short trapped waves. In scenario C, associated with prefrontal-to-frontal conditions, the upstream flow is more deeply blocked at low levels. Winds are stronger at the ridge height and continuously increase up to the tropopause. The layer of increased stability has shifted upward. In scenario D, displaying significant transience, upstream profiles of wind speed and direction transition from frontal to postfrontal conditions. Initial upstream blocking is gradually reduced and winds amplify throughout the troposphere. The low-level wind switches from initially southerly to westerly and finally to northerly, as the front passes. At the same time, the potential temperature profiles remain relatively unaltered, with the rather uniform profiles of stability and wind shear promoting the generation of long trapped waves or even upward-propagating mountain waves.

The kinematic characteristics of the valley atmosphere in the four scenarios are mainly determined by pressure-driven channeling of the flow toward the pressure low in the northern Sierra Nevada. As the front approaches the mountain range, the up-valley flow strengthens (from scenarios A/B to C). In scenario D, in-valley winds switch to westerly and finally northerly. The thermal structure of the valley atmosphere is primarily determined by the diurnal heating cycle. Low or elevated valley inversions (scenarios B or A, respectively) can be generated through nocturnal cooling. Daytime warming leads to an increasingly well-mixed valley atmosphere (scenario C). The diurnal cycle can, however,

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<tr>
<th>Table 2. Classification of T-REX cases, according to the four scenarios presented in section 4a and Fig. 16.</th>
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<tr>
<td>Scenario</td>
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<tr>
<td>Elevated turbulence zone (scenario A)</td>
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<tr>
<td>Flow separation at a low-level inversion (scenario B)</td>
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<tr>
<td>Turbulent interaction of in-valley westerlies and up-valley flow (scenario C)</td>
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<tr>
<td>Transient mountain waves and rotors (scenario D)</td>
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*a Documented by De Wekker and Mayor (2009).*
be largely superseded when cold-frontal air reaches the center of Owens Valley from the north (scenario D).

The four scenarios and the associated schematic diagrams (Fig. 16) can thus be interpreted as representative of different stages of the pre-to-postfrontal evolution of gravity waves launched by the Sierra Nevada. An individual wave event may run through a sequence of these stages. The specific combination of the upstream conditions with the thermodynamic and kinetic characteristics of the valley atmosphere appears to predetermine the evolution of each individual case. The evolution depends crucially on the relative timing of the approach and passage of the synoptic system with respect to the diurnal cycle in the valley. For example, despite similar upstream conditions (scenarios A, B, and C), nighttime cooling (A and B) and daytime warming (C) in the valley can lead to distinct downstream flow responses.

Beyond the timing of the front, a large case-to-case variability of upstream and downstream conditions exists, regarding, for instance, the strength of crest-level stability or the magnitude of up-valley winds. The resultant predominance of a particular process can alter the evolution of an individual event and can give preference to one scenario over another despite similar initial conditions. For example, in IOP 13c (Doyle et al. 2009), the along-valley flow was too strong to be completely replaced by the incoming westerlies, in contrast to IOP 6 [Kühnlein et al. (2013) and section 3b(4)].

It is thus not possible to provide a unique prototypical sequence of in-valley flow patterns during a frontal passage. Frequently, however, two or three of the four scenarios are met along the evolution of an event. Examples from T-REX (Table 2) include IOP 1 (A–C), IOP 6 (A–C–D), and IOP 13 (A–B–C). Another notable event is the SRP IOP 8 (24–27 March 2004). Observations and numerical simulations by Grubišić and Billings (2007) show striking similarities of this case with T-REX IOP 6, involving midlevel wave breaking and rotor...
formation and the same sequence of stages (A–C–D). Similar flow patterns are also observed in the Alps. For example, scenario B is well known in the Inn Valley, Austria, where a shallow south foehn frequently separates on top of a wintertime valley cold pool, inhibiting its breakthrough at the valley floor (Gohm and Mayr 2004; Mayr et al. 2007).

The above discussion points to the ubiquitous transience of the flow in Owens Valley during all T-REX cases, clearly surpassing the steady-state conceptual models. In an effort to quantify the temporal scales of the contributing processes, we subjected the measurements by the ISS2 wind profiler (continuous throughout the 2-month field experiment) to a statistical analysis. Events were selected by defining objective thresholds for the lee-side wind speed and direction and vertical motion at various heights in the valley. Results, summarized in Table 3, reveal three leading time scales: \( \geq 1 \) day, set by the time it takes for synoptic systems to cross the Sierra Nevada; \( \sim 7 \) h, related to both dynamically and diurnally controlled turbulent perturbations of the valley atmosphere; and finally \( 3 \) h, governed by the transition to and duration of strong westerly wind events, often associated with rapid variations in wave phase and amplitude or with midlevel wave breaking. The last phenomena frequently involve short-lived rotor structures and severe in-valley turbulence. In these cases, subrotor-type vortices grow and are advected along shear lines at time scales on the order of 10 min (Doyle et al. 2009). These vortices cannot be adequately resolved by the ISS2 profiler because of its 30-min-average sampling strategy. It is the conjunction and interplay of large-scale and small-scale phenomena and their characteristic temporal scales that constitutes the major source of complexity in describing, and ultimately forecasting, the turbulent flow scenarios in Owens Valley.

c. Role of surface pressure gradients for rotor formation in a valley

Lyra (1943) was the first to note that pressure perturbations induced by trapped lee waves may produce regions of adverse pressure gradient force (PGF) and decelerate the flow sufficiently to make it separate from the surface (Queney et al. 1960). Much later, Doyle and Durrant (2002) corroborated Lyra’s conjecture, showing the key role of wave-induced boundary layer separation in rotor formation. The wave-induced pressure perturbations and rotor strengths in their numerical simulations revealed that rotors form when the PGF exceeds a value of

\[
\frac{|\nabla p|}{\rho} = 2.2 \frac{U^2}{L},
\]

where \( U \) is the upstream wind speed (in the model) and \( L \) is the mountain half-width. A rough calculation of the threshold PGF required for rotor formation in Owens Valley (using \( U = 20 \text{ m s}^{-1} \) as a typical value for the wind speed of strong lee-side westerlies and \( L = 7.5 \) km as the half-width of the Sierra Nevada lee slope) yields an order-of-magnitude estimate of \( 10^{-3} \text{ m s}^{-2} \) (or 1 hPa km\(^{-1} \) for the pressure gradient).

Hovmöller diagrams of pressure perturbations across DRI stations 1–6 for a selection of IOPs are shown in Fig. 18. Only rarely did the PGF at the valley floor attain the required threshold. A PGF close to or beyond the threshold only occurred during IOP 6c (Fig. 18f), which stands out for its windstorm of particularly intense and wave-mediated character. This finding is remarkable, since both medium- to large-amplitude waves and rotorlike flow patterns were present in Owens Valley during all periods highlighted in Fig. 18. The lack of

<table>
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<tr>
<th>Observed phenomenon</th>
<th>Duration (h)</th>
<th>Median</th>
<th>10th percentile</th>
<th>90th percentile</th>
<th>Sample size</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Crest-level westerlies</td>
<td>24.0</td>
<td>12.4</td>
<td>37.2</td>
<td>19</td>
<td></td>
</tr>
<tr>
<td>2) Crest-level westerlies to along-valley flow</td>
<td>27.0</td>
<td>18.8</td>
<td>47.8</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>3) Crest-level westerlies to northerly flow</td>
<td>32.8</td>
<td>22.0</td>
<td>49.0</td>
<td>6</td>
<td></td>
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<tr>
<td>4) Disturbed valley atmosphere</td>
<td>7.0</td>
<td>3.5</td>
<td>13.5</td>
<td>21</td>
<td></td>
</tr>
<tr>
<td>5) Up-valley flow to westerlies</td>
<td>2.5</td>
<td>1.8</td>
<td>3.6</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>6) Downslope windstorms</td>
<td>3.0</td>
<td>2.0</td>
<td>3.5</td>
<td>7</td>
<td></td>
</tr>
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</table>
Large perturbations in the surface pressure is consistent with results by Parish and Oolman (2012), who noted that amplitudes of isobaric height perturbations over Owens Valley are damped rapidly within the boundary layer such that no appreciable wave-induced horizontal pressure gradient remains below crest level. This is further supported by our composite cross sections of flight-level pressure perturbations from four UWKA flights (Fig. 19).

Recently, Jiang et al. (2006) proposed turbulent dissipation and critical-level absorption as two possible wave absorption mechanisms in the boundary layer. They found that a stagnant boundary layer is most efficient in absorbing wave energy and momentum by critical-level absorption. Indeed, the sustained up-valley flow in Owens Valley likely acts as a critical level to waves forming in the predominantly westerly flow at crest level. Even when strong westerlies dominate in the valley, the resultant turbulent motions may diffuse and dissipate originally coherent wave-induced pressure perturbations. We thus hypothesize that turbulence or stagnant layers in the valley tend to absorb a significant portion of the wave energy, thereby preventing large wave-induced pressure perturbations from reaching the valley floor.

The question remains as to what caused rotors and rotorlike structures in the absence of large pressure gradients. Note that the pressure perturbation argument is based purely on the magnitude of the PGF in the horizontal equations of motion. However, in real flows evolving in complex environments, other terms in the full set of momentum equations may become equally important. For example, in the presence of very stable air in the valley, wave-induced pressure gradients and positive buoyancy forces may act in concert to make the downslope flow detach from the lee slope, well above the valley floor. This was likely the case in the IOP 13b nighttime event (Fig. 16b). A similar event has also been reported from the persistent cold-air pool study over the Salt Lake valley in 2010 (Lareau and Horel 2015).

To test our hypothesis, we consider the along-slope momentum equation in a Boussinesq and inviscid approximation, appropriate for small vertical displacements (after Haiden 2003):
Here, $s$ is the along-slope coordinate, noughts and primes denote, respectively, reference-state and perturbation variables, and $\alpha$ is the slope angle ($\sim 30^\circ$ for the lee slope of the Sierra Nevada). For IOP 13b, the minimum PGF for separation [Eq. (2)] is estimated as $0.66 \times 10^{-2}$ m$^2$ s$^{-2}$, using $15$ m$^2$ s$^{-1}$ for the wind speed in the downslope flow. However, the maximum along-slope PGF was only $0.07 \times 10^{-1}$ m$^2$ s$^{-2}$ (Fig. 18a). The magnitude of the along-slope buoyancy force [rightmost term in Eq. (3)], instead, was on the order of $0.5 \times 10^{-1}$ m$^2$ s$^{-2}$. The latter estimation assumes a maximum of $\theta'$ of $3$ K between the downslope flow and the cold air in the valley or a maximum excursion of the flow into the low-level inversion of $150$ m (based on both lidar measurements and sounding data). A note of caution applies to the measure of the PGF, which was determined from the surface station pressures, with the closest station available lying downstream of the separation point. Nonetheless, the calculation points to the significant, possibly dominant, role of buoyancy forces for this case. However, to ultimately elucidate the relative importance of pressure gradient, buoyancy, and other forces for flow separation in a range of conditions, a thorough evaluation of the relevant terms in the equations of motion along parcel trajectories would be required. Such an analysis is not possible from observational data alone, motivating the need for high-resolution numerical simulations.

5. Summary and conclusions

Idealized conceptual models of atmospheric rotors in the lee of a mountain range were developed in the 1950s during the Sierra Wave Project (Holmboe and Klieforth 1957) and refined until the 1970s (Lester and Fingerhut 1974). These models, however, prove to be simplistic, in particular in the topographical setting considered in this work, consisting of two parallel mountain ridges separated by a long deep valley. In such an environment, rotor formation may be influenced by thermally driven slope and valley flows, pressure-driven flow channeling, or by the modulation of lee-wave characteristics in the presence of the second ridge.

In this study, we have considered observations of large-amplitude waves, low-level rotors, and severe turbulence made during IOPs 1, 2, 3, 4, 6, and 13 of T-REX. We have examined commonalities and differences in the rotor morphology and the spatial and temporal patterns of turbulence within Owens Valley, downstream of the southern Sierra Nevada. Four case studies reveal the rich variety of flow responses and turbulent structures during periods with strong mountain-wave activity. Schematic diagrams, highlighting typical flow scenarios and pointing to the mechanisms of turbulence generation in the valley, have been distilled (Fig. 16). These include the elevated turbulence zone (A), separation of downslope flow at a low-level valley inversion (B), turbulent interactions of in-valley westerlies with channeled along-valley flows (C), and transient mountain waves and rotors (D).
The scenarios and their comparison show that the elements of the classic rotor concept are greatly enriched and, at times, largely offset by dynamically and thermally induced processes in the valley. For instance, flow reversal downstream of the separation point was rarely observed because of channeled along-valley flows prevailing in the valley, downwind of the separated surface westerlies. Conversely, individual aspects of the rotor concept may coexist even in the absence of a fully developed rotor. For example, roll clouds parallel to the mountain ridge appear to form even without a rotor (scenarios A and C). Moderate to severe turbulence may be generated in the valley through other processes, such as shear instability at the interface between the separated westerlies and the up-valley flow underneath (scenarios B and C). However, in the strongest cases, all ingredients may be in place to give rise to a vigorous rotor flow and attendant severe turbulence (scenario D). While in scenarios A, B, and C, turbulence structures can deviate substantially from those associated with a classic rotor, scenario D underlines that the rotor concept may apply even in a valley, given a suitable set of conditions.

The four flow scenarios can be related to different stages of frontal passage over the valley. The evolution of individual events often runs through a sequence of these stages (Table 2) and is governed by the interaction of the large-scale to small-scale processes, occurring at temporal scales from 1 day to 10 min (Table 3). The scenarios do not seem to be constrained to the Sierra Nevada and Owens Valley, as indicated by reports of similar observations in the Alps.

Despite the presence of large-amplitude waves and rotorlike structures, horizontal pressure gradients at the valley floor were often relatively weak. It is hypothesized that wave-induced pressure perturbations are subject to critical-level absorption and/or turbulent diffusion of wave energy in the boundary layer, preventing them from extending to the valley bottom. Under certain conditions, the resistance of the stably stratified valley atmosphere to the incoming dynamically forced flow seems to be important for flow separation and turbulence generation.

In conclusion, while some of the observations presented in this work appear to call into question the concept of the rotor flow as a whole, its strongest occurrences do contain most of the defining elements suggested in previous studies. Even its nonideal variants, here referred to as rotorlike turbulent structures, seem to bear sufficient similarity to deserve the name—not least because the term is well known in the aviation community, where it stands for the likely encounter with severe low-level turbulence underneath lenticular wave clouds.

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REFERENCES


