Three-Dimensional Characteristics of Stratospheric Mountain Waves during T-REX

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ABSTRACT

Measurements from the National Science Foundation/National Center for Atmospheric Research (NSF/NCAR) Gulfstream V (G-V) obtained during the recent Terrain-Induced Rotor Experiment (T-REX) indicate marked differences in the character of the wave response between repeated flight tracks across the Sierra Nevada, which were separated by a distance of approximately 50 km. Observations from several of the G-V research flights indicate that the vertical velocities in the primary wave exhibited variations up to a factor of 2 between the southern and northern portions of the racetrack flight segments in the lower stratosphere, with the largest amplitude waves most often occurring over the southern flight leg, which has a terrain maximum that is 800 m lower than the northern leg. Multiple racetracks at 11.7- and 13.1-km altitudes indicate that these differences were repeatable, which is suggestive that the deviations were likely due to vertically propagating mountain waves that varied systematically in amplitude rather than associated with transients. The cross-mountain horizontal velocity perturbations are also a maximum above the southern portion of the Sierra Nevada ridge.

Real data and idealized nonhydrostatic numerical model simulations are used to test the hypothesis that the observed variability in the wave amplitude and characteristics in the along-barrier direction is a consequence of blocking by the three-dimensional Sierra Nevada and the Coriolis effect. The numerical simulation results suggest that wave launching is sensitive to the overall three-dimensional characteristics of the Sierra Nevada barrier, which has an important impact on the wave amplitude and characteristics in the lower stratosphere. Real-time high-resolution Coupled Ocean–Atmosphere Mesoscale Prediction System (COAMPS) forecasts successfully capture the along-barrier variations in the wave amplitude (using vertical velocity as a proxy) as well as skillfully distinguishing between large- and small-amplitude stratospheric wave events during T-REX.

1. Introduction

The Sierra Nevada is a north-northwest–south-southeast-oriented mountain range of approximately 650-km length, 100-km width, and features the tallest peak, Mt. Whitney (4417 m), and the steepest orographic gradient along the eastern slope in the contiguous United States (Fig. 1). The Sierra Nevada is well known for generating large-amplitude mountain waves (i.e., the Sierra Wave). Although topographic ridges such as the Sierra Nevada are often considered a quasi-two-dimensional barrier for flows with a significant crossridge component, the degree to which this is true has yet to be observationally documented. In this study, the three-dimensionality of mountain waves generated by
the Sierra Nevada (hereinafter Sierra) is explored using a set of unique observations from the National Science Foundation/National Center for Atmospheric Research (NSF/NCAR) Gulfstream V (G-V) and the NSF–University of Wyoming King Air (UWKA) research aircraft taken during the Terrain-induced Rotor Experiment (T-REX).

The orographic modification of stably stratified airflow past two- and three-dimensional topography has been the focus of numerous numerical and theoretical investigations. Smith (1980, 1989) and Smolarkiewicz and Rotunno (1989) have explored the dynamical parameter space governing the occurrence of flow stagnation and flow splitting upstream of isolated three-dimensional topography in the absence of rotation. Flow splitting, vortex shedding, and wakes are examples of phenomena that may occur in stratified flows past 3D obstacles (e.g., Smolarkiewicz and Rotunno 1989; Schär and Durran 1997). Likewise, the palette of gravity wave responses is quite complex for stratified flow over 3D mountains, with hydrostatic, nonhydrostatic, and inertia–gravity waves all possible (e.g., see reviews in Smith 1979; Durran 1997). The governing parameters for orographic flow in the nonrotating frame of reference have been identified as the aspect ratio, obstacle shape, and the dimensionless obstacle height (or inverse Froude number), $\hat{h} = Nh_{ma}/U$, where $N$ is the Brunt–Väisälä frequency, $h_{ma}$ is the mountain height, and $U$ is the upstream wind (e.g., Smith 1989; Smith and Grønås 1993). The dimensionless obstacle height is a control parameter, which determines the transition point from flow over the topography to flow around (splitting) the obstacle. The critical value for flow stagnation is $\hat{h}_c \sim 0.85$ for a 2D mountain (Huppert and Miles 1969), while for a symmetric Gaussian obstacle the critical value is larger, $\hat{h}_c \sim 1.1$ (Smith and Grønås 1993). Stratified flow past an obstacle when $\hat{h} < \hat{h}_c$ is generally explained by linear theories (e.g., Smith 1980), while for $\hat{h}_c > \hat{h}$ the nonlinear regime prevails (e.g., Smolarkiewicz and Rotunno 1989; Smith 1989), with the dimensionless obstacle height representing the non-linearity of the flow.

For relatively large-scale mountains, rotation becomes more important and the topographic flow response is governed by $\hat{h}$ and the mountain Rossby number, $Ro = U/fL$, where $f$ is the Coriolis parameter and $L$ is the mountain half-width (e.g., Gill 1982; Pierrehumbert and Wyman 1985; Thorsteinsson 1988). For large $Ro$ ($>10$), rotational effects are weak and the response is primarily governed by vertically propagating gravity waves (Gill 1982). Inertia–gravity waves dominate when $Ro \sim 1$, which are characterized by quasi-horizontal energy propagation and relatively small vertical wavelength (Pierrehumbert 1984; Trüb and Davies 1995). For characteristic cross-mountain wind speeds and length scale for the Sierra Nevada, $Ro$ is typically in the 1–3 range. The flow over synoptic-scale orography ($L > 1000$ km) with strong rotational influence ($Ro < 1$) is characterized by evanescent quasigeostrophic waves (Gill 1982) and the elimination of mountain waves (Queney 1948).

The upstream response to low-level flow blocking is initiated in 2D near $\hat{h} \sim 0.75$ (Pierrehumbert and Wyman 1985). Deceleration upstream of the barrier results in upstream subgeostrophic flow and predominantly leftward deflection around the obstacle (Smith 1982). Pierrehumbert and Wyman (1985) used 2D numerical model simulations to demonstrate that the length scale of the upstream influence for blocked flow is governed by the Rossby radius of deformation, $L_d = Nh_{ma}/f$. Thorsteinsson (1988) applied a three-dimensional isentropic model to flow over and around a symmetric 3D obstacle on an f plane and found that for elongated topography, the lateral airstream deflection is most sensitive to the mountain aspect ratio, $L_y/L_x$, where $L_x$ is the along-stream width and $L_y$ is the width in the cross-stream direction (Thorsteinsson and Sigurdsson 1996). Rotational effects can also modulate the pressure drag (Ólafsson and Bougeault 1997), and downstream conditions through distortion and erosion of leeside vortices and wakes (Peng et al. 1995). Doyle and Shapiro (1999) showed that for stratified flow impinging on a topographic ridge, low-level jets occur along the northern and southern portions of the ridge flanks, which they refer to as tip jets. In the Northern Hemisphere, westerly flow is deflected primarily leftward around the obstacle, which results in strong jets and downslope flows along the...
northern flank. Doyle and Shapiro found that jets along the southern ridge flanks can be prominent as well, and consistent with the principal of conservation of Bernoulli function as parcels accelerate down the large pressure gradient near the southern portion of the ridge.

Numerical simulations of constant wind speed and static stability flow past elongated three-dimensional (3D) mountains conducted by Epifanio and Durran (2001) suggest that the response can differ significantly relative to flow over two-dimensional (2D) ridges. They found that for ridges with mountain heights smaller than the threshold for wave breaking, 2D theory is valid when the mountain aspect ratio of the ridge is approximately 10 or greater. However, three-dimensional characteristics exist even for aspect ratios of 12 for flows that exhibit wave breaking. The numerical simulations of flow over 3D elliptical topography by Olafsson and Bougeault (1996) indicate that as $N_{\text{h,m}}/U$ increases, wave breaking tends to migrate from above the ridge axis of symmetry to the ridge flanks. The wave breaking regions in their simulations extend as far as a cross-stream half-width on either side of the axis of symmetry.

During T-REX (Grubišić et al. 2008), the NSF/NCAR G-V measured gravity wave properties along repeated transects across the central and southern Sierra Nevada, separated by a distance of approximately 50 km. Race-tracks flight patterns executed across the Sierra ridge at several different stratospheric altitudes, and repeated over a number of different cases, provide a unique opportunity to explore the three-dimensionality of stratospheric gravity waves. Smith et al. (2008) used the T-REX G-V measurements to compute vertical energy fluxes and confirmed the relationship between the momentum and energy flux that Eliassen and Palm (1961) first hypothesized. They found up- and downwelling waves and short wavelength trapped waves in one of the T-REX G-V flights. In a followup study, Woods and Smith (2010) discovered collocated long upgoing and short downwelling waves in the stratosphere in at least four cases and in two other cases noted trapped waves along the tropopause inversion layer. We build on these previous studies through exploration of the three-dimensional characteristics of gravity waves generated by the Sierra using analysis of the G-V and UWKA observations along with nonhydrostatic numerical model simulations. The specific goals of this study are to (i) document the three-dimensional characteristics of stratospheric gravity waves during T-REX, (ii) provide a dynamical understanding of the stratospheric gravity wave characteristics, and (iii) evaluate the ability of high-resolution models to forecast the wave characteristics including three dimensionality. The paper that addresses these points is organized as follows. A description of the numerical model is contained in section 2. The observational analysis is presented in section 3. Numerical simulations results are discussed in section 4 and the summary and conclusions appear in section 5.

2. Numerical model description

The numerical simulations of observed and idealized flows in this study are performed using the atmospheric module of the Coupled Ocean–Atmosphere Mesoscale Prediction System (COAMPS; Hodur 1997). The COAMPS model is based on a finite-difference approximation to the fully compressible, nonhydrostatic equations and uses a terrain-following vertical coordinate transformation. In the real data forecasts, the finite-difference schemes are of second-order accuracy in time and space, while the idealized simulations use a fourth-order accurate horizontal advection. The simulations performed in real time made use of the second-order differing because of computational considerations. The compressible equations are integrated using a time-splitting technique with a semi-implicit formulation for the vertical acoustic modes (Klemp and Wilhelmson 1978).

A prognostic equation for the turbulence kinetic energy (TKE) budget is used to represent the planetary boundary layer and free-atmospheric turbulent mixing and diffusion (Hodur 1997). The Louis (1979) surface layer parameterization, which makes use of a surface energy budget based on the force-restore method, is used to represent the surface fluxes. Subgrid-scale moist convection is represented using the Kain and Fritsch (1993) parameterization. The grid-scale evolution of the moist processes is predicted explicitly from budget equations for cloud water, cloud ice, raindrops, snowflakes, and water vapor (Rutledge and Hobbs 1983). The short- and longwave radiation processes are represented following Harshvardhan et al. (1987). The full suite of physical parameterizations is used in the real data simulation. Results from COAMPS model simulations have been evaluated on numerous occasions using special observations and field campaign datasets and have been demonstrated to accurately simulate topographically forced flows including mountain wave dynamics (e.g., Doyle and Jiang 2006; Doyle et al. 2009; Jiang and Doyle 2009; Eckermann et al. 2006; Doyle and Smith 2003).

The initial fields for the real-data simulation are created from multivariate optimum interpolation (MVOI) analyses of upper-air sounding, surface, commercial aircraft, and satellite data that are quality controlled and blended with the previous 12-h COAMPS forecast fields, which is used as the first guess. An incremental update data assimilation procedure is used in conjunction with the MVOI, which enables mesoscale phenomena to be
Two types of real data forecasts and simulations are performed in this study. The first set of COAMPS forecasts was conducted in real time using three horizontally nested grid meshes of \(91 \times 91, 133 \times 133, \) and \(157 \times 157\) grid points with horizontal grid increments on the computational meshes of 18 km, 6 km, and 2 km, respectively. The real-time COAMPS model contains 40 vertical levels on a nonuniform vertical grid consisting of an increment of 10 m at the lowest level that gradually increases to 700 m at 7 km and continues to increase to the model top at 29 km. A second set of simulations was conducted using a single grid mesh with horizontal grid increments of 27 km, 9 km, 3 km, and 1 km, respectively. In these simulations conducted in the post field campaign stage, 80 vertical levels are used with an increment of 10 m at the lowest level that gradually increases to 250 m at 7 km and continues to increase to the model top at 29 km. The grid meshes are one-way interactive in this application.

In both of the real-data model runs, a sponge upper-boundary condition is applied to mitigate the reflection of vertically propagating gravity waves over the top 10 km of the model. The topographic data are based on the U.S. Defense Mapping Agency (DMA) 100-m resolution dataset that enables the finescale topographic features of the Sierras to be well represented, particularly on the innermost grid mesh shown in Fig. 1.

A series of idealized simulations were conducted using a horizontally homogeneous initial state and a more simplified set up for the model. These simulations were conducted using a single grid mesh with horizontal resolution of 1.5 km consisting of 205 \(\times\) 205 grid points and 80 vertical levels. A radiation condition is used for the lateral boundaries following Orlanski (1976) with the exception that the Doppler-shifted phase speed \((u \pm c)\) is specified and temporally invariant at each boundary (Pearson 1974; Durran et al. 1993). The idealized simulations are dry with a no-slip lower-boundary condition and include a boundary layer parameterization and vertical diffusion in the free atmosphere derived from the explicitly predicted TKE. The experiments are conducted using an \(f\)-plane approximation corresponding to 36.75°N, similar to that of the T-REX observing network location.

The topography for some of the idealized simulations is specified as a smooth ridge following the basic shape of Epifanio and Durrant (2001). The long axis is oriented normal to the \(x\) direction and is defined as

\[
h(x, y) = \begin{cases} 
\frac{h_m}{16} \left[1 + \cos(\pi r)\right]^4, & r \leq 1, \\
0, & r > 1,
\end{cases}
\]  

where

\[
r^2 = \begin{cases} 
\left(\frac{x^2}{4a}\right) + \left[\frac{y - (\beta - 1)a}{4a}\right]^2, & |y| > (\beta - 1)a. \\
\left(\frac{x^2}{4a}\right), & |y| \leq (\beta - 1)a.
\end{cases}
\]

The horizontal aspect ratio \(\beta\) is expressed as the ratio of the \(y-x\) dimensions of the ridge. In this formulation for the terrain, \(h(x, y)\) takes the form of a bell-shaped obstacle with length scale \(a\) when \(\beta = 1\). A uniform height section is preserved through the middle of the ridge when \(\beta > 1\). Simulations are conducted with constant \(\beta = 4\), and maximum ridge height \(h_m\) of 3500 m. The simulations with the idealized ridge use an upwind half-width of 15 km and a downwind half-width of 5 km.

3. Observations

The overarching objective of T-REX is to explore rotor and mountain wave dynamics and study the synergistic interaction between rotors, mountain waves, and boundary layer dynamics (Grubišić et al. 2008). One of the primary objectives of T-REX is to gain a better understanding of mountain wave dynamics including the characteristics of wave launching, propagation, and breakdown over the Sierra terrain. The observing period of T-REX took place in March–April 2006 and featured 15 intensive observation periods (IOPs) including 12 G-V flights, as summarized in Table 1.

3.1 Observational platforms and strategy

The G-V platform was instrumented with basic in situ measurement capabilities for the flights during T-REX. The instruments included a gust probe system, static pressure, fast temperature probe, fast tracer system including water vapor, ozone, CO\(_2\), and condensation nuclei. The aircraft was also equipped with cameras and a differential GPS that enables very accurate determination of the geographic location and altitude. The wind speed is determined using a differential pressure on a nose cone or gust probe, together with acceleration sensors and GPS to obtain aircraft position and orientation (Brown et al. 1983) with an accuracy of \(\pm 0.5\) m s\(^{-1}\) for the horizontal wind and \(\pm 0.1\) m s\(^{-1}\) for the vertical wind. Ambient atmospheric pressure is obtained from a static pressure port on the fuselage, corrected for airspeed,
density, and orientation. A shielded Rosemount thermistor is used to measure the air temperature with an accuracy of ±0.5°C. A GPS dropwindsonde system was onboard G-V and more than 300 dropwindsondes were deployed (Table 1). Other aircraft that were available during T-REX include the UWKA and the U.K. Facility for Airborne Atmospheric Measurement (FAAM) BAe146 instrumented jet. In this study, we primarily focus on the measurements from the G-V platform because the aircraft was the only one to perform a racetrack pattern that sampled gravity waves over both the central and southern portions of the Sierras. The King Air and BAe146 operated mainly along the Independence transect.

The T-REX G-V observational strategy consisted of long racetracks to deduce 3D aspects of the wave field and compute circulation statistics, as shown in Fig. 1 (e.g., Smith et al. 2008). This also allowed for upstream and downstream regions to be compared. Multiple racetrack stacks spanning 4 km in altitude were designed to observe how the waves change as they propagate upward into the stratosphere. The racetracks were immediately repeated, as the conditions dictated, to document the steadiness of the wave fields. On each flight, deep aircraft soundings were performed to document the chemistry and basic properties of troposphere and lower stratosphere. The timing of the G-V missions was based on mountain wave activity forecasts from several numerical models including the 2-km-resolution COAMPS (Hodur 1997) and the 4-km resolution Weather Research and Forecasting (WRF) model (Skamarock et al. 2005).

The largest-amplitude mountain waves observed by G-V occurred during the flights of IOP 4 (14 March), IOP 6 (25 March), and IOP 13 (16 April). The maximum vertical velocity observed by the aircraft was over 10 m s$^{-1}$ in each of these flights. All three flights made use of flight track B oriented along 245°, nearly parallel to the large-scale flow. These three IOPs are ideal to contrast the mountain-wave characteristics along the northern and southern flight segments, which were 50 km apart. The Sierra ridge crest beneath the G-V was 500–1000 m higher on the northern flight legs in contrast to the southern transect, as shown in Fig. 2. The mean terrain for a 10-km-wide swath computed along the flight track also indicates that the mean crest beneath the northern transect is substantially higher (Fig. 2).

Radiosondes were launched west of the Sierra in the San Joaquin Valley at the Naval Air Station in Lemoore, California, and from the NCAR Mobile GPS Advanced Upper-Air Sounding System (MGAUS), which was positioned at a latitude that reflected conditions upstream of the central Sierra. Conventional radiosondes from Oakland and Vandenberg Air Force Base were available, as well as supplemental radiosondes launched near Independence.

b. Regional-scale and upstream sounding overview

The synoptic-scale characteristics of interest at 700 hPa for IOPs 4, 6, and 13, are shown in Fig. 3. All three of the intense IOPs feature strong upper-level shortwave troughs

![Fig. 2. Terrain height (m) interpolated to the G-V track “B” flight path for the northern (black) and southern (gray) flight segments. The mean terrain for a 10-km swath along the flight segments are shown by the dashed lines.](image-url)
to the west of the Sierra, which result in strong cross mountain flow near the Sierra crest level. At 1200 UTC 14 March (IOP 4), the 700-hPa flow exceeds 15 m s$^{-1}$ upstream of the Sierras with the incident airflow direction nearly perpendicular to the Sierra ridge (Fig. 3a). Likewise, the 700-hPa flow at 1200 UTC 25 March (IOP 6) exhibits similar characteristics as IOP 4, with strong southwesterly flow in place to the east of the shortwave trough axis (Fig. 3b). The wind speeds are somewhat weaker in IOP 13 with a predominantly westerly wind direction (Fig. 3c). Prominent flow deflection by the Sierra Nevada is apparent near the crest level and below for all three strong IOPs, with the near-surface flow deflected to the left (not shown) consistent with upstream blocking and rotational influence (e.g., Pierrehumbert and Wyman 1985). Enhancement of the flow at 700 hPa is apparent in all three cases in the lee of the northern portion of the Sierra, once again consistent with low-level flow blocking and leftward deflection, which leads to a broad airstream ascending over the northern portion of the ridge. A narrow wind speed maximum is also apparent along the southern flank of the Sierra ridge, particularly for IOPs 4 and 6, which forms in response to a large horizontal pressure gradient present along the southern portion of the ridge, similar to the Doyle and Shapiro (1999) tip jet dynamics. A wind speed minimum at 700 mb occurs in the lee of the central Sierra due to low-level blocking upstream and leeside wave breaking.

Upstream profiles from the Oakland radiosonde and the MGAUS sounding are shown in Figs. 4 and 5, respectively (locations shown in Fig. 3a). The Oakland soundings exhibit several relatively shallow inversion layers for IOPs 4 and 6 (Figs. 4a,b), while a prominent marine inversion is present for IOP 13 (Fig. 4c). All three cases exhibit moist conditions below 700 hPa and are relatively dryer above the Sierras. The upstream MGAUS soundings shown in Fig. 5a indicate weaker stability within the boundary layer in the lowest 1–1.5 km. The IOP 13b profile indicates an inversion in the 3.1–3.4-km layer, while the other IOPs do not exhibit enhanced stability near the mountain crest. The cross-mountain wind speed component is the strongest below the 3-km level for IOP 6, while at 4 km near the Sierra crest the cross mountain winds were strongest for IOPs 4 and 13.

Estimates of the dimensionless mountain height (or inverse Fr), $\hat{h} = Nh_m U$, for the three strong IOPs is shown in Table 2. The upstream MGAUS soundings averaged in the 2–4-km layer are used to compute the Brunt–Väisälä frequency, $N$, and cross-mountain wind component, $U$. The approximate mean ridge height of the Sierra Nevada, 3500 m, is used for $h_m$ in the calculation. All three IOPs are characterized by an $\hat{h}$ that is

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**Fig. 3.** Analyses of 700-hPa winds from COAMPS for (a) 1200 UTC 14 Mar (IOP 4), (b) 1200 UTC 25 Mar (IOP 6), and (c) 0000 UTC 16 Apr (IOP 13). The isotach interval is 5 m s$^{-1}$ with gray shading above 15 m s$^{-1}$ in (a) and (b) and 10 m s$^{-1}$ in (c). Wind vectors are shown every 5 grid points [scale shown in (c)]. The 700-hPa radiosonde winds are shown with a full barb corresponding to 5 m s$^{-1}$. Sounding locations of interest are shown in (a). The solid lines indicate the state boundaries. The G-V flight track B is shown in (a).
FIG. 4. Skew T–logp soundings for the Oakland radiosonde corresponding to (a) 1200 UTC 14 Mar (IOP 4), (b) 1200 UTC 25 Mar (IOP 6), and (c) 0000 UTC 16 Apr (IOP 13). The observed soundings are shown in black and the model soundings in gray. The winds (m s$^{-1}$) are shown along the right sides with the model winds shown to the left of the observations. A full barb corresponds to 5 m s$^{-1}$. The location of the sounding is shown in Fig. 3a.

FIG. 5. Radiosonde MGAUS profiles of (a) potential temperature ($\theta$, K) and (b) cross-mountain wind speed (m s$^{-1}$) corresponding to 1800 UTC 14 Mar (IOP 4), 2100 UTC 25 Mar (IOP 6), and 2100 UTC 16 Apr (IOP 13). The location of the sounding is shown in Fig. 3a.
significantly larger than unity indicative of upstream blocking conditions. The upstream profile in IOP 4 exhibits the largest $\hat{h}$, in contrast to IOPs 6 and 13, which have $\hat{h}$ that are smaller, but still greater than 2.

c. Research aircraft measurements

A large-scale trough approached the West Coast and strong southwesterly flow impinged on the Sierra Nevada on 14 March during IOP 4. A G-V flight was executed along track B. A summary of the flight level data from the 13.1-km level for the 4 northern and southern flight segments are shown in Figs. 6a,b, respectively. There are a number of gross similarities between the northern and southern flight segments in IOP 4. For example, large-amplitude waves in the lower stratosphere are apparent in both sections with maximum vertical velocities in excess of 6 m s$^{-1}$ and potential temperature perturbations greater than 10 K. However, clearly there are a number of differences between the sections. The maximum wind speed and potential temperature perturbations are 15 m s$^{-1}$ and 18 K, respectively, along the northern section and 20 m s$^{-1}$ and 16 K along the southern route. The primary vertical velocity wave signature has a longer wavelength to the north and shorter to the south. Note that the primary long wave is steady during the G-V measurement period. The wave amplitude (crest to trough) of the primary wave is 12 m s$^{-1}$ to the south and 6 m s$^{-1}$ to the north. In the lee of the primary wave, short, small-amplitude, unsteady waves are present to the north, in contrast to the south where larger amplitude and somewhat more steady waves are apparent. The strongest descent occurs above the Inyo range in the northern segment and in the mid-Owens valley to the south. The southern section contains at least three short and small-amplitude waves upstream of the primary wave, while little wave activity is apparent in the northern segment. It is noteworthy that a series of large-amplitude waves are present in the southern flight segment well downstream of the Sierra crest and characterized by similar amplitudes as the primary wave. Smith et al. (2008) noted the existence of shorter trapped waves for several of the T-REX IOPs with secondary generation emanating from near the tropopause and reflection or secondary generation occurring in the lower stratosphere.

### Table 2. Estimation of the bulk $N$, $U$, and $Nhm/U$ for IOPs 4, 6, and 13, based on the upstream MGAUS soundings averaged in the 2–4-km MSL layer.

<table>
<thead>
<tr>
<th>IOP</th>
<th>Time and date</th>
<th>$N$ (s$^{-1}$)</th>
<th>$U$ (m s$^{-1}$)</th>
<th>$Nhm/U$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>1800 UTC 14 Mar</td>
<td>0.0116</td>
<td>11.3</td>
<td>3.6</td>
</tr>
<tr>
<td>6</td>
<td>2100 UTC 25 Mar</td>
<td>0.0125</td>
<td>20.0</td>
<td>2.2</td>
</tr>
<tr>
<td>13</td>
<td>2100 UTC 16 Apr</td>
<td>0.0120</td>
<td>15.0</td>
<td>2.8</td>
</tr>
</tbody>
</table>

FIG. 6. Flight-level data from the G-V at 13.1 km on 14 Mar (IOP 4). (from top to bottom) The wind speed (m s$^{-1}$), $\theta$ (K), vertical velocity (w; m s$^{-1}$), and terrain along the flight path (m) for the (a) northern and (b) southern flight segments are shown.
The second case considered here is IOP 6, which took place on 25 March 2006. This event featured very strong cross Sierra flow associated with a large-scale trough and a midtropospheric short wave. In many respects, IOP 6 was the most intense event measured during T-REX. Once again the mountain wave characteristics over the northern and southern sections are quite different as illustrated by the flight level data for 13.1 km shown in Figs. 7a,b. The amplitudes of the potential temperature and horizontal and vertical velocity perturbations are larger on the southern legs than the northern, and the primary wave structure appears to be more steady and repeatable. The perturbation potential temperature is 50% larger on the southern section than the northern leg. Likewise, the crest-to-trough maximum vertical velocity is 18 m s$^{-1}$ for the southern leg and 13 m s$^{-1}$ for the northern leg. Note that in both of the segments, the first strong downward vertical velocity “plunge” is displaced away from the highest terrain and lee slopes likely due to nonlinear effects (e.g., Durran 1986; Grubišić and Stiperski 2009).

The wave amplitudes for both segments showed significant differences at lower levels. In IOP 6 and a number of other events, the vertical velocity and wave amplitudes were largest in the highest levels of the stratosphere that were sampled. For example, Fig. 8 shows data from two southern flight segments during IOP 6, which were separated by only 30 min. Much larger vertical velocities were present at 13.1 km than at 11.9 km, likely related to the decrease of density with height and background shear effects. The decrease of wind speed with altitude above the jet (Fig. 4) may have amplified the waves in the lower stratosphere (e.g., 13.1-km level). Plausible mechanisms include nonlinear wave steepening associated with backward wind shear and wave reflection from the wave breaking zone aloft (i.e., near the critical level at ~20 km MSL; Smith et al. 2008).

The final G-V flight leg for IOP 6 was flown at 45 kft (13.7 km) over the southern portion of the B racetrack. A large-amplitude wave was encountered on this segment as illustrated in Fig. 9. The perturbation wind speed and potential temperature was 35 m s$^{-1}$ and 30 K, respectively, and the length of this wave is very large. The vertical velocity time series shows a broad downward-directed minimum followed by a very sharp upward vertical velocity spike of 12 m s$^{-1}$ (18 m s$^{-1}$ in the 25-Hz high-rate dataset). It is noteworthy that the aircraft experienced rather strong turbulence during this encounter with the sharp vertical velocity consistent with gravity wave breaking. The location of the strongest ascent was well east of the Sierra slopes, perhaps attributable to nonlinear effects (Durran 1986; Grubišić and Stiperski 2009). A broader maximum in the potential
temperature is coincident with a sharp vertical velocity maximum and a small-amplitude spike in the horizontal wind speed. Also, a sharp ozone concentration maximum of 500 ppb, which is 350 ppb greater than the ambient background values, occurred nearly coincident with the vertical velocity maximum. The ozone maximum undoubtedly is related to advection of higher ozone concentration from other levels. As part of the turbulent event, the aircraft Mach number changed rapidly from 0.74 to 0.85 and then returned to 0.74 over a longer time period corresponding to the larger-scale wave (wavelength 20–25 km). The location of the turbulent event occurred near the eastern portion of the valley well downstream of the Sierra crest. Unfortunately, companion measurements along the northern section at 13.7 km were not performed. The wave amplitudes were significantly larger on the southern section at 13.1 km.

Strong cross-Sierra flow at crest level occurred during IOP 13 on 15–16 April 2006 associated with a large-amplitude midtropospheric trough and jet stream synoptic-scale system. The G-V flight-level data for the northern and southern legs at the 13.1- and 11.3-km altitudes are shown in Fig. 10. The largest-amplitude waves were observed at the 11.3-km level, in contrast to IOP 6. The short-wavelength unsteady mountain waves are apparent downstream in the southern segment at 13.1 km, unlike IOP 4 that featured similar characteristics along the northern segment (Fig. 6). The largest-amplitude waves at 13.1 km in terms of vertical velocity occur along the northern flight segment, in contrast to IOP 4 and IOP 6. The wave characteristics are quite different between the two altitudes. For example, note that the vertical velocities tend to differ more between altitudes than between the north and south segments. Overall, IOP 13 seemed to show smaller differences between the vertical velocity observed in the north and south legs, relative to IOPs 4 and 6. The wave generation may be more uniform along the Sierra crest since IOP 13 featured less of a tendency for a strong asymmetric response in the low-level winds (e.g., lack of jet near the southern portion of the Sierra apparent in Fig. 2c).

d. Vertical flux of horizontal momentum

The cross-mountain component of the vertical flux of horizontal momentum can be defined as
where $\rho$ is the density, $u'$ is the cross-mountain perturbation wind component, $w'$ is the perturbation vertical velocity, and $d$ is the distance along the flight leg. The vertical flux of horizontal momentum has been computed for each of the IOPs following Smith et al. (2008) and stratified between the northern and southern flight legs. Significant differences exist in the vertical flux of horizontal momentum between these southern and northern legs. The vertical flux of horizontal momentum derived
from the G-V and King Air measurements are shown in Fig. 11 for 14 March (IOP 4), 25 March (IOP 6), and 16 April (IOP 13). Each of the cases exhibit considerable scatter. In IOP 4, the southern leg has approximately 3 times larger momentum flux than the northern leg, and is nearly constant with height on the northern leg (Fig. 11a). The King Air, which was flown along the northern segment, shows similar scatter. In IOP 6, the southern leg momentum flux is once again approximately 3 times larger than the northern leg. The momentum flux characteristics for IOP 13 are quite different from the other two strong cases. The scatter is quite large for both the northern and southern legs, and above 12 km the momentum flux becomes positive. A further discussion of the momentum and energy flux can be found in Smith et al. (2008) and Woods and Smith (2010).

e. Wave characteristics

Scatter diagrams are presented in Fig. 12 based on each northern and southern flight leg pairs for the maximum magnitude of the vertical velocity (Fig. 12a) and cross-mountain wind speed (Fig. 12b) perturbations, and the vertical velocity variance (Fig. 12c). The perturbation magnitudes for the cross-mountain and vertical wind speed (Figs. 12a,b) are computed using the G-V measurements over a window that extends from the Sierra crest to 40 km downstream. The G-V data were only displayed in this narrow portion of the flight leg so that the characteristics of the long-wavelength primary wave can be distinguished from the short-wavelength waves apparent downstream of the primary wave. The shorter secondary waves may be trapped or downward propagating (e.g., Smith et al. 2008; Woods and Smith 2010) and the characteristics of these waves may not be intimately related to the terrain below. In general, the maximum horizontal and vertical velocity magnitude lies close to the diagonal, especially for the weaker cases. However, a number of the IOPs indicate horizontal and vertical velocity maxima that occur preferentially along the southern leg, consider, for example, the strongest IOPs 4, 6, and 13. The stronger IOPs have velocity perturbations that are significantly greater on the southern leg than for the corresponding northern flight segment. Note the systematically larger vertical velocity maxima on the southern legs for IOPs 4, 6, and 13b and the horizontal velocity perturbations for IOPs 4 and 13b. An exception to the southern leg dominance occurs for horizontal velocity perturbations during IOP 6 (Fig. 7), which are complex and quite unsteady along the northern segment and may be influenced by transient waves or vertical shear. On one of the flight legs during IOP 3, the G-V measured anomalously large horizontal and vertical velocity maxima with short wavelengths that may have been influenced by moist processes.

The vertical velocity variance at the 13.1-km flight level indicates a maximum along the southern flight legs for IOP 4 and considerable scatter for IOPs 6 and 13. The large vertical velocity variances in IOP 4 computed for the southern leg are qualitatively consistent with vertical velocity from the G-V shown in Fig. 6. Interestingly, the potential temperature variance (not shown) is greater along the northern flight segments for several IOPs (e.g., IOP 4 and IOP 13).
4. Numerical simulations

An analysis of a series of numerical simulations is presented in this section in order to further explore the three-dimensional waves emanating from flow over the Sierra. The COAMPS forecasts conducted in real time during T-REX are evaluated using the G-V flight-level data. Simulations performed in an idealized configuration are used to gain further insight into the three-dimensional wave characteristics generated by both an idealized ridge and realistic terrain.

a. Real-data simulations

During T-REX, the COAMPS model was executed in real time with three nested grids, with a horizontal grid increment on the finest mesh of 2 km and 40 vertical levels. A comparison of the model-forecasted and observed upstream soundings at Oakland for IOPs 4, 6, and 13, shown in Fig. 4, indicate a generally good agreement between the observed soundings and model initial state. However, it should be noted that the model analysis fails to capture shallow inversions near 740 hPa in IOP 4 and near 700 hPa in IOP 6. These inversions may have some importance for the downstream wave field. Also, some minor differences between the observations and analyses are apparent in the low-level winds. Overall, the model forecasted winds at 700 hPa and the available radiosondes at Oakland, California, and Reno and Vandenberg, Nevada, are in good agreement at the model initialization for IOPs 4, 6, and 13 (Fig. 3). The horizontal winds at the 300-m level (AGL) (model sigma layer 7) for the three strongest IOPs, 4, 6, and 13, are shown in Fig. 13 for three representative times corresponding to the 24-h forecast time. There are some noteworthy common characteristics for all three IOPs. All three cases exhibit deep blocking upstream of the Sierra crest through approximately the lowest 2–3 km MSL (Fig. 5), which also is apparent in the simulated winds at the 300-m level shown in Fig. 13. The deflection of the low-level winds in part associated with the blocking and Coriolis effect is consistent with previous studies of blocked flows (e.g., Ólafsson and Bougeault 1996, 1997). The low-level flow in the California Central Valley is deflected preferentially to the left in IOP 13 in agreement with theoretical considerations, unlike the low-level flow in IOPs 4 and 6, which are more influenced by the larger-scale pressure gradient. The 300-m wind speed reaches a maximum in excess of 30 m $s^{-1}$ in all three strong IOPs along the steep leeside slopes downstream of the Sierra crest. Wind speed maxima occur along the northern and southern flanks of the Sierra ridge for all three IOPs, as shown in Fig. 13, consistent with the idealized simulations of Doyle and Shapiro (1999). It is noteworthy that the

![Fig. 12. Scatter diagram showing (a) vertical velocity maximum magnitude, (b) maximum magnitude of the perturbation crossmountain wind speed, and (c) vertical velocity variance for northern and southern leg pairs at 13.1 km for each G-V flight.](image)
low-level winds along the southern portion of the Sierra ridge are stronger than in the lee of the highest terrain in the central Sierra as a result of low-level wave breaking over the highest terrain and a strong east–west-oriented pressure gradient along the southern flank. The G-V sampled over portions of the central Sierra and the relatively lower southern flank of the ridge. The flow upstream of the higher central portion of the Sierra is predominantly blocked and deflected to the north, and to a lesser degree to the south due to the Coriolis effect. Both the northern and southern portions may launch larger-amplitude waves than the central part of the ridge due to the response to the blocking. Generation of larger-amplitude waves by the southern portion of the ridge relative to the central section of the Sierra is consistent with the established theory.

Vertical cross sections of vertical velocity and potential temperature normal to Sierra ridge with an orientation along the northern G-V flight segment (for location see Fig. 1) are shown in Fig. 14 for the three IOPs. All three of the strong IOPs exhibit a tropospheric lee wave characterized by relatively long wavelengths (~20–35 km), similar to the low-level observations of the King Air (Grubišić et al. 2008), with smaller-amplitude waves in the lee of the Inyo Mountains. Shorter wavelengths are apparent in the stratosphere. The three IOPs also exhibit enhanced stability near the Sierra crest, which is conducive for downslope windstorms and gravity wave generation (e.g., Durran 1990). The gravity wave phase lines suggest that the energy is predominantly trapped below the tropopause with vertical energy propagation leaking into the stratosphere at altitudes sampled by the G-V (e.g., Smith et al. 2008; Woods and Smith 2010). Reverse wind shear above the jet stream leads to wave steepening aloft above 15 km and deformed isentropes.

The real-time 2-km horizontal-resolution COAMPS 18–24-h forecasts were interpolated to the flight paths for IOPs 4, 6, and 13b. A comparison of the flight level observations and numerical model data for the northern and southern flight legs is shown in Figs. 15a,b, respectively. Overall, the model captures the basic character of the differences between the northern and southern flight segments. The model is able to distinguish the
FIG. 14. Vertical cross section of the model-simulated vertical velocity shaded in color (every 0.5 m s\(^{-1}\)) and potential temperature (every 3 K) for the 24-h forecast times valid at (a) 0000 UTC 15 Mar, (b) 0000 UTC 26 Mar, and (c) 0000 UTC 17 Apr. The vertical cross section is oriented along the northern flight segment of the B racetrack (Fig. 1).

FIG. 15. Vertical velocity (m s\(^{-1}\)) at 13.1 km derived from the G-V (solid) and model forecasts (dashed) for (from top to bottom) IOP 4, IOP 6, and IOP 13b for the (a) northern and (b) southern segments of the flight racetracks (Fig. 1). The terrain interpolated to the G-V position from a 1-km digital elevation model is shown in the bottom panels (solid) along with the interpolated model terrain (dashed).
magnitude of the wave response between the northern and southern flight legs. For example, the large-amplitude waves are predicted for IOPs 4 and 6 on the southern legs, which is in broad agreement with the G-V observations. However, the model overpredicts the vertical velocity minimum associated with the primary wave in both IOPs 4 and 6 for the southern leg. Also, phase errors are apparent in the primary wave and particularly in the secondary waves downstream from the primary wave. The model predicts moderate wave activity downstream of the Sierra crest during IOP 4 along the southern flight segments (Fig. 15b), although the wave amplitudes are not as large as observed (Fig. 6b).

The real-time 2-km horizontal-resolution COAMPS forecasts were interpolated to the flight paths for IOPs 9, 10, and 13a. The flight level observations and numerical model comparison for the northern and southern flight legs is shown in Fig. 16. The comparison highlights the model capability to adequately forecast the occurrence of weak amplitude cases. However, accurate simulation of the wave characteristics for these small-amplitude cases is clearly a challenge.

The real-time forecasts are unable to resolve some of the shorter wavelength structures observed because of the horizontal resolution of 2 km (and 40 vertical levels). A higher-resolution simulation of the IOP 6 wave event has been conducted using 4 nested grid meshes with a horizontal resolution of 1 km on the finest grid mesh and 80 vertical levels. A vertical cross section of the crossmountain wind component and potential temperature oriented along the southern leg is shown in Figs. 17a–c, which correspond to the 2100 UTC (21-h forecast), 2200 UTC (22-h forecast), and 2300 UTC (23-h forecast) on 25 March. The simulation contains a region of wave steepening, positioned above the jet in a reversed shear region, indicated by the hatched region in Fig. 17 corresponding to areas with turbulence kinetic energy greater than 20 m² s⁻². The region of wave steepening increases in amplitude and area, and progressively occurs at lower altitudes in the 2100–2300 UTC time period. The simulation is consistent with the timing and spatial location above Owens Valley and downstream from the Sierra crest in which the G-V encountered turbulence and a large-amplitude mountain wave (Fig. 9). It is noteworthy that the other flight legs at the 13.1-km altitude indicated the presence of large amplitude waves, but the signatures of wave breaking were only observed at the 13.7-km level.

b. Idealized simulations

Idealized simulations are performed to provide further insight into the three-dimensional nature of the waves generated by the Sierra ridge. The idealized simulations
FIG. 17. Vertical cross section of the model-simulated along-section wind speed component shaded in color (every 2.5 m s$^{-1}$) and potential temperature (every 8 K) valid at (a) 2100 UTC 25 Mar, (b) 2200 UTC 25 Mar, and (c) 2300 UTC 25 Mar. The vertical cross section is oriented along the southern flight segment of the B racetrack (Fig. 1). TKE in excess of 20 m$^2$ s$^{-2}$ is shown by the hatched regions.
are conducted with a 1.5-km horizontal grid increment and 80 vertical layers and make use of surface friction, a boundary layer parameterization, and rotation. A single grid mesh is used in these idealized experiments, with a horizontal resolution that is slightly coarser than the IOP 6 simulation (i.e., $\Delta x = 1$ km) to allow the lateral boundaries to be sufficiently far away from the mountains and to minimize reflections from the boundaries. The initial potential temperature and winds for the idealized simulations are based on the static stability and cross-mountain wind speed profiles derived from the 2100 UTC 25 March 2006 MGAUS sounding (Fig. 5) and comprise a horizontally homogeneous initial state. The simulations are integrated to 4 h, which allows the wave fields to become fully evolved and reach a quasi-steady character.

Simulation results conducted with the idealized three-dimensional ridge described above are shown in Figs. 18a,b. The vertical velocity at the 5-km level (Fig. 18a), indicates the largest-amplitude waves are launched near the ridge flanks. Because of the topographic blocking and Coriolis effect (Olafsson and Bougeault 1997), the flow is preferentially deflected northward upstream of the elliptical barrier with greater mass passing over the northern portion of the barrier than the southern portion. The asymmetry of the flow passing over the barrier results in stronger wave launching along the northern portion of the ridge (Fig. 18a), although a smaller and localized vertical velocity maximum exists in the lee of the southern portion of the ridge as well. Enhanced trapping of the wave energy is also apparent near the ridge flanks. The flow fields indicate northward flow below the ridge crest.

FIG. 18. Model-simulated vertical velocity at the 4-h time using an idealized ridge at (a) 5 and (b) 13 km MSL, and Sierra terrain at (c) 5 and (d) 13 km MSL. The vertical velocity is shaded in color every 0.5 m s$^{-1}$. The 2500- and 3500-m terrain contours are shown in thin and bold contours, respectively. The distance between the small tick marks is 1.5 km, and 6 km for the larger tick marks. The wind vectors at 2500 m are shown in (a) at an interval of every eight grid points. The locations of the north and south flight legs for the track B pattern are shown in (c).
due to the blocking and Coriolis effect, and are broadly similar to the real data simulations of IOP 6. At the 13-km level (Fig. 18b), the vertical velocity is a maximum near the southern portion of the ridge. According to linear theory, vertical velocity induced by the interaction between a geostrophically balanced unidirectional flow and a finite-symmetric ridge-oriented perpendicular to the flow direction should remain left–right symmetric in the absence of surface friction. This result was obtained through a semianalytic linear computation (e.g., Smith et al. 2002; Doyle and Jiang 2006) for a uniform flow over a three-dimensional ridge. The left–right (i.e., north–south) asymmetry in the simulated wave patterns (Figs. 18a,b) results from the interplay of surface friction, nonlinear blocking and the Coriolis effect. The primary wave immediately in the lee of the ridge is relatively long, although waves downstream of the primary wave along the southern flank have a shorter horizontal wavelength and therefore are more dispersive, too. It is interesting to note that the G-V observations for IOPs 4 and 13 indicate the propensity for shortwave components on the southern-most legs (Figs. 6 and 10), however, the IOP 6 observations indicate more shortwave energy along the northern legs (Fig. 7), which may arise from either nonlinear steepening or secondary generation in the lower stratosphere (e.g., Woods and Smith 2010).

The location of the maximum vertical velocity on the flanks of the ridge is primarily a consequence of the upstream flow blocking and the Coriolis effect as noted previously. The simulations indicate that only a relatively thin layer is energetic enough to pass over the highest portion of the terrain, while a relatively thicker layer ascends over the lower terrain of the ridge flanks. Additionally, low-level jets located near the flanks of the ridge form due to upstream blocking and flow down the pressure gradient on the southern flank (e.g., Smith and Grønås 1993; Doyle and Shapiro 1999) and may provide additional enhancements to the wave launching. It is noteworthy that the steeper terrain slope along the southern flank also contributes to the formation of the stronger surface jet near the southern flank, and accordingly, stronger waves aloft. The results of these idealized simulations are consistent with the results of Öffsson and Bougeault (1996). Simulations conducted with lower terrain (e.g., $h_m = 100$ m), indicate that the maximum vertical velocity is generated over the terrain ridge crest rather than the ridge ends, further underscoring the importance of flow blocking. The results of the low-terrain simulations are similar to linear theory solutions obtained using a fast Fourier transform method following Smith et al. (2002) and Doyle and Jiang (2006).

Idealized simulations conducted with the identical initial state and using the Sierra terrain show similar tendencies to develop larger-amplitude vertical velocities near the shoulders of the Sierra ridge. The simulated vertical velocity at 5 and 13 km MSL after 4 h of integration is shown in Figs. 18c,d. Maximum vertical velocities occur to the north and south of the highest terrain (Fig. 18c). At the 13-km level, the largest-amplitude waves are located south of the crest and consistent with the G-V observations and the simulation with the idealized ridge (Fig. 18b).

A simulation conducted without the Inyo and White Mountain ranges, which are downstream from the Sierra, shows less mountain wave activity in the lower levels (Fig. 19) relative to the simulations with the full terrain (e.g., Fig. 18c). This suggests that the Inyo range does contribute some to the downstream wave energy and may reinforce the waves downstream through lee-wave resonance in concert with the Sierra (Grubišić and Stiperski 2009).

5. Summary and conclusions

The largest-amplitude mountain waves observed by G-V during the T-REX field campaign occurred during the flights corresponding to IOPs 4, 6, and 13. The large-scale conditions were generally similar for all three strong IOPs characterized by strong cross-mountain flow associated with an approaching synoptic-scale trough. All three IOPs were characterized by an upstream $\hat{h}$ that ranged from 2.2 to 3.6, consistent with strong upstream flow blocking.

Although the Sierra Nevada range is considered nearly a two-dimensional barrier to southwesterly flow, G-V
observations and numerical model results from T-REX indicate that the mountain waves generated by the Sierra and Inyo ranges exhibited substantial three-dimensionality. Racetrack pattern flight legs across the Sierra crest were flown with the G-V approximately 50 km apart. The terrain beneath the northern flight segment is 500–1000 m higher than the southern segment; however, a number of the IOPs featured larger-amplitude waves on the southern leg. The maximum vertical velocity at the 13.1-km altitude observed by the aircraft was over 10 m s\(^{-1}\) in each of these flights and occurred primarily on the southern flight segment. Vertical velocities in the primary wave exhibited variations up to a factor of 2 between the southern and northern portion of the racetracks in the lower stratosphere.

Multiple racetracks at several stratospheric altitudes indicated that these differences were repeatable for the primary wave signature, which is suggestive that the deviations were likely due to mountain waves that varied systematically in amplitude rather than associated with transients. The vertical velocity power spectrum for the southern legs exhibit greater energy at shorter wavelengths than for the northern segments. The origin of the short waves in the lower stratosphere has been addressed in other studies (e.g., Smith et al. 2008; Woods and Smith 2010). The characteristics of the vertical flux of horizontal momentum vary greatly between the northern and southern flight segments, with the southern leg having up to 3 times larger momentum flux than the northern leg.

Real-time high-resolution numerical model forecasts were evaluated using the G-V flight level measurements. All three strong IOP events exhibit deep blocking and flow deflections upstream of the Sierra crest through approximately the lowest 2–3 km MSL. Also, all three of the strong IOPs exhibit a tropospheric lee wave characterized by relatively long wavelengths (~20–35 km), similar to the low-level observations of the King Air, with a second set of waves in the lee of the Inyo Mountains. The real-time 2-km horizontal resolution COAMPS interpolated to the flight paths for IOP 4, 6, and 13 indicate that the model is able to distinguish the magnitude of the wave response between the northern and southern flight legs, although the magnitude of the vertical velocity minimum associated with the primary wave in both IOPs 4 and 6 for the southern leg is overpredicted.

A large-amplitude wave was encountered on the final G-V flight leg for IOP 6, which was flown at 45 kft (13.7 km) over the southern portion of the B racetrack. Perturbation wind speed and potential temperature were 35 m s\(^{-1}\) and 30 K, respectively, and the vertical velocity time series exhibited an upward vertical velocity spike of 12 m s\(^{-1}\) along with observations of moderate turbulence consistent with wave breaking. A high-resolution model simulation successfully captures a region of wave steepening and turbulence, which is positioned above the jet in a reversed shear region that progressively advances to lower altitudes in the stratosphere.

Simulations conducted with a horizontally homogeneous initial state and an idealized three-dimensional ridge indicates that the largest-amplitude waves are launched near the ridge flanks. The vertical velocity maxima along the flanks of the ridge are primarily a consequence of the upstream flow blocking. The strongest wave launching appears to occur over the northern portion of the barrier, although a secondary maximum is present along the southern ridge flank, which is the region where the G-V operated. Simulations conducted with a realistic Sierra terrain show similar tendencies to develop larger amplitude vertical velocities near the shoulders of the Sierra ridge due to low-level blocking.

The implications of the three-dimensionality of mountain waves observed and simulated over the Sierra Nevada may be significant for several reasons. First, the inclusion of nonlocal effects in gravity wave drag parameterizations may be needed to represent the momentum flux maxima that occur along the ridge flanks. Second, observing strategies such as the racetrack flight pattern adopted during T-REX may be needed in future field campaigns to properly observe gravity waves generated by elongated ridges. Additionally, the observations presented provide confirmation for the simulations performed in this study and previous simulations (e.g., Ölafrsson and Bougeault 1996, 1997) that under some conditions wave amplification may be more likely over lower terrain, rather than the highest terrain. Finally, it should be noted that mountain-wave induced turbulence may not be just confined to regions over the highest terrain. In situations with severely blocked upstream flow, wave breaking and turbulence may be more likely over the ridge flanks, which may have important implications for aviation safety.

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