Isobaric Height Perturbations Associated with Mountain Waves Measured by Aircraft during the Terrain-Induced Rotor Experiment

THOMAS R. PARISH AND LARRY D. OOLMAN
Department of Atmospheric Science, University of Wyoming, Laramie, Wyoming

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ABSTRACT

It has only been in the last few years that accurate measurement of the horizontal pressure gradient has been possible over complex terrain using an airborne platform. To infer forcing mechanisms for the wind, an independent measure of the height of an isobaric surface is required. Differential GPS analyses have enabled determination of the aircraft height with sufficient accuracy to infer isobaric heights. When coupled with an accurate measurement of static pressure, the horizontal pressure field can be determined. To demonstrate this measurement technique, research flight legs by the University of Wyoming King Air (UWKA) conducted in support of the Terrain-Induced Rotor Experiment (T-REX) in March and April 2006 are examined. UWKA flights conducted on 14 and 25 March and 16 April 2006 encountered strong mountain waves in response to winds directed primarily normal to the Sierra Nevada ridgeline. Winds at flight level showed pronounced variation that suggested topographic influence. The magnitude of isobaric height perturbations along UWKA flight tracks obtained using differential GPS during case study days of 14 and 25 March and 16 April are shown to exceed 70 m, corresponding to horizontal pressure perturbations greater than 4 hPa. Measurements suggest that changes in wind speed are linked primarily to the perturbation height field and that the flow can be classified as Eulerian, implying that Coriolis accelerations are negligible and flows respond to the horizontal pressure gradient force.

1. Introduction

Studies of atmospheric dynamics require information regarding the horizontal pressure gradient force (PGF). It is the dominant force in the horizontal equations of motion and is responsible for nearly all atmospheric flows. Shapiro and Kennedy (1981) were among the first to use an airborne platform to study atmospheric dynamics, measuring the isobaric heights associated with a jet core over the ocean. To determine the PGF, an independent measurement of the height of an isobaric surface above some reference level such as sea level is required. Traditional aircraft altitude measurements rely on static pressure measurements, converted to height assuming the U.S. Standard Atmosphere. Shapiro and Kennedy (1981) used radar altimetry to detect the aircraft elevation above sea level. Later efforts to apply altimetry over irregular terrain (Shapiro and Kennedy 1982; Parish et al. 1988) required precise horizontal positioning of the aircraft to determine the height of the overlying terrain field, which when added to the radar altimeter height yields the isobaric height. Altimetry methods using research aircraft have limitations that have prevented widespread use for studies of atmospheric dynamics. Even when aircraft are equipped with a GPS receiver to refine horizontal positioning, the resulting estimate of the height of the aircraft above a reference level is subject to considerable error. The final isobaric height is the sum of two large terms whose spatial trends are opposed to one another and is inherently noisy (Parish et al. 2007). Recently, differential GPS (dGPS) has been used to refine the three-dimensional positioning of the aircraft (e.g., Jensen et al. 2006; Parish et al. 2007; Parish and Leon 2013). Aircraft altitude as determined through dGPS processing when combined with an accurate measurement of static pressure enables the PGF to be determined.

To demonstrate the application of dGPS technology to the measurement of the horizontal pressure gradient force, aircraft data from the University of Wyoming King Air (UWKA) taken during the Terrain-Induced Rotor Experiment (T-REX) are used. The focus of the...
study will be an examination of perturbations in the isobaric height field that result from flow over the Sierra Nevada.

An impressive body of literature exists regarding flow over mountains and mountain waves. Early work such as Queney (1948) and Scorer (1949) examined linearized models of airflow over idealized terrain and emphasized the roles of wind speed, atmospheric stability, and terrain height in establishing flow streamlines and mountain wave features. Corby (1954) offers a review of early studies of mountain waves. As air is forced over terrain, the restoring force resulting from the difference between an air parcel’s density and that of the ambient environment at the same level will accelerate the air parcel back toward an equilibrium level. The oscillation of disturbed flow in a stable environment has been compared to that of an internal gravity wave. Analyses by Durran (1990) have addressed airflow over a series of sinusoidal ridges to show that the transport of energy associated with waves depends on the inherent frequency of the wave and the Brunt–Väisälä frequency. A summary of mountain wave studies can be found in Wurtele et al. (1996); references contained therein provide an extensive list of contributions on the subject.

The Sierra Nevada is well known for the generation of large amplitude mountain waves. Results from the Sierra Wave Project first documented the structure of strong mountain waves with attendant rotors (i.e., Grubišić and Lewis 2004). An integrated examination of the Sierra Nevada mountain wave/rotor circulation was conducted during T-REX. Goals of this project were to explore the structure and evolution of mountain wave features and attendant rotors using an extensive array of surface-based instrumentation, remote sensing platforms, and multiple research aircraft, supported by extensive real-time numerical simulation. A comprehensive overview of T-REX is found in Grubišić et al. (2008). It was the task of the UWKA to conduct measurements within the lowest 8 km of the atmosphere to directly monitor rotor development. UWKA flight legs frequently passed through large amplitude mountain waves. Those airborne measurements provide some of the most detailed data from tropospheric mountain wave phenomena.

The fundamental goal of this study is to present analyses of UWKA wind and pressure measurements to assess the forcing of the airflow associated with mountain waves. A focus here is on the relationship between observed tropospheric isobaric height perturbations, obtained using dGPS processing, and the wind field. Observations of isobaric height perturbation fields are among the first of its kind to be presented and complement analyses presented in Smith et al. (2008) for the National Center for Atmospheric Research (NCAR) Gulfstream V (GV) flights in the upper troposphere and lower stratosphere on the same case study days.

2. Considerations regarding airborne measurement of atmospheric dynamics

Legs conducted by the UWKA during T-REX and most other field projects commonly follow isobaric surfaces. Given the task of understanding the dynamics of the motion field, it is logical to inquire what information can be obtained from isobaric flight data. The simplest approach is to examine the equation of motion. The inviscid momentum equation for the motion component along an axis \( x \) following the isobaric flight leg can be written:

\[
\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + \omega \frac{\partial u}{\partial p} = -g \frac{\partial z}{\partial x} + f v, \tag{1}
\]

where \( u \) refers to the along-track wind component, \( v \) is the cross-track component in \( y \), \( \omega \) is the vertical component in pressure \( p \), \( g \) is the acceleration due to gravity, \( z \) is the height above some reference level, and \( f \) is the Coriolis parameter. In the case of T-REX, UWKA flight legs were conducted along the axis of the wind and thus cross-track wind components are typically small. If it is assumed that steady conditions prevail over the duration of the flight leg, Coriolis effects are small and that advection by the cross-track wind component \( v \) can be neglected, (1) can be rewritten as

\[
\frac{\partial u}{\partial x} + \omega \frac{\partial u}{\partial p} = -g \frac{\partial z}{\partial x}. \tag{2}
\]

Simple scale analysis shows that the above assumptions are appropriate for T-REX legs discussed here. Physically (2) implies that changes in the along-track component of the wind during a flight leg result from vertical advection in the presence of mean wind shear and/or accelerations induced by the horizontal pressure gradient force. If, as will be shown later, the vertical advection term is smaller than the horizontal pressure gradient force, (2) can be integrated along a pressure surface to yield the following expression:

\[
\left( \frac{u^2}{2} + gz \right) = \text{constant}. \tag{3}
\]

This diagnostic form of the isobaric momentum equation contains key components that are seen in the atmospheric form of the Bernoulli equation. It is important to note that variables in (3) must be evaluated on an isobaric surface. In particular, the height \( z \) must be
precisely determined on an isobaric surface if (3) is to be applied. From (3) deviations of the isobaric height are directly related to wind speed such that higher wind speeds are associated with lower isobaric heights.

In terms of energy, it is appropriate to start with the equation of motion expressed on an isentropic surface again along an axis $x$ following the flight leg (e.g., Holton 1979):

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + \frac{dS}{dt} \frac{\partial u}{\partial \theta} = -\frac{\partial (\rho c_p T + g z)}{\partial x} + f v,$$

(4)

where the term in parenthesis is the so-called Montgomery streamfunction. Again, if it is assumed that steady conditions prevail and that the flow is adiabatic with a negligible Coriolis force, (4) can be rewritten as

$$\frac{\partial u}{\partial x} = -\frac{\partial (\rho c_p T + g z)}{\partial x}.$$

(5)

Integrating (5) with $x$ yields a form of the Bernoulli equation:

$$\frac{u^2}{2} + c_p T + g z = \text{constant}.$$

(6)

Again, it is important to note that evaluation of the Bernoulli function in (6) must be performed on an isentropic surface. Evaluation of (6) on an isobaric surface, for example, removes the energy constraints between the terms and thus the sum of $(u^2/2) + c_p T + g z$ is not conserved. To use (6) based on isobaric data only, correct interpolation of the Montgomery streamfunction to an isentropic surface is first necessary. Prater (1996) provides a concise summary of issues involved in making such calculations. He notes that interpolation of isobaric data to an isentropic surface has a history of misuse and suggests that errors in the streamfunction calculation may have contributed to the neglect of isentropic analyses until about the 1960s. For purposes here, it is important to note that the enthalpy and geopotential terms in the streamfunction are not independent and must be calculated together such that the hydrostatic relationship is satisfied when transforming from isobaric to isentropic coordinates. Calculation of (6) for typical isobaric flight legs can be shown (e.g., Smith et al. 2008) to be a function of potential temperature, illustrating only the hydrostatic nature of the atmosphere.

Analyses shown here will focus on the isobaric evaluation of winds measured by the UWKA. From elementary atmospheric dynamics, the horizontal pressure gradient force can be expressed as either the variation of the height of an isobaric surface or the variation of pressure in a horizontal plane. Here the height variation of an isobaric surface will be used primarily.

3. UWKA measurements of atmospheric forcing during mountain wave events

T-REX was conducted during March and April 2006 with the center of operations in the Owens Valley in eastern California. The valley floor extends along a primarily north–south axis stretching over 100 km and is approximately 20–30 km in width and is surrounding by the nearly 4000-m Sierra Nevada crest to the west and the White-Inyo Range to the east. Vertical relief between the Sierra ridgeline to the Owens Valley floor is typically in excess of 3000 m. Terrain slopes rise to the west of the Owens Valley in excess of 2000 m in less than 10 km making this stretch one of the steepest sections in the continental United States (Fig. 1).

Configuration of the Owens Valley played a major role in UWKA flight strategy. UWKA flight lines considered in this study were conducted along an axis parallel to the wind, which during strong wind conditions shown here had a dominant component of the wind aligned perpendicular to the Sierra ridgeline. During an intensive observing period (IOP), the UWKA conducted a stair-step profiling mission beginning first with legs of 70 km or so in length at 8000 m, which is well above the crest of adjacent mountain peaks. Legs were flown on isobaric surfaces. Successive legs were conducted by dropping in elevation roughly 500 m. Once the ridgeline level of the Sierras was reached, leg lengths decreased considerably as flight legs were confined to the Owens Valley. UWKA flights were conducted on 22 days during the March–April 2006 period in support of T-REX. Smith et al. (2008) note that T-REX flights conducted on 14 and 25 March and 16 April (UWKA Research Flights 4, 5, 10; IOP 4, 6, 13, respectively) encountered strongest wave activity based on observations using the GV. Not surprisingly, synoptic conditions during each of those periods consisted of strong 500-mb winds directed normal to the Sierra crest. Two UWKA flights were conducted on each day with the first flight takeoff about 1600 UTC and the second flight launched about 2200 UTC. Measured winds speeds at the highest flight level (~8000 m) were in excess of 30 m s$^{-1}$ for each case.

Diagnosis of the isobaric forcing of the wind requires an understanding of the horizontal pressure gradient. Combined with an accurate measurement of static pressure, dGPS heights permit accurate assessment of the height of an isobaric surface and hence the horizontal pressure gradient force can be evaluated. This dGPS measurement technology requires deployment of one
or more reference GPS stations with a precisely determined location that can be used to refine position estimates for a rover GPS receiver, here being the UWKA. For T-REX applications, a GPS base station receiver was deployed at the hangar that housed the UWKA at Bishop, California. GPS data were recorded at 10-Hz from the base station for the duration of the project and the position of this reference GPS receiver was known to within a few centimeters. GrafNav Version 8.1 from Waypoint Consulting was used in a postprocessing mode to providing enhanced UWKA vertical position solutions. Details of the dGPS technique, sources of error, and limitations to the measurement accuracy are given in Parish et al. (2007) and Parish and Leon (2013). Although the height of an isobaric surface above a reference level has been the limiting aircraft measurement for decades, dGPS technology now enables the height of the aircraft to be determined with precision. Analyses described in Parish et al. (2007) and Parish and Leon (2013) suggest an accuracy of the height of the aircraft to within a few decimeters. The fidelity of the static pressure measurement is now thought to be the fundamental limitation to detection of the isobaric height field (Rodi and Leon 2012). All dGPS-derived heights presented here use the static pressure corrections discussed in Rodi and Leon (2012).

Figure 2 illustrates results from three UWKA legs conducted from 1656–1720 UTC on the first flight of 14 March 2006. Legs shown (Fig. 2a) are about 60 km in length, extending across the Owens Valley, and stacked vertically with a separation of roughly 900 m. Winds at flight level were from $240^\circ$ and the aircraft track followed the axis of the wind. Of prime importance are the isobaric perturbation heights along the leg (Fig. 2b). These heights were determined by first conducting the differential GPS processing of the aircraft heights. Then, the minor deviations of the UWKA from the isobaric surface are hydrostatically corrected following Parish et al. (2007) and Parish and Leon (2013). To produce the final perturbation heights, the mean isobaric height for the entire leg is subtracted from the corrected dGPS heights. The perturbation height gradient thus is proportional to the horizontal pressure gradient force. It is estimated that the cumulative height error is significantly less than 1 m and thus there seems no doubt that the 70-m amplitude perturbation heights dwarf possible errors in the measurement. When examining such isobaric height traces, it must be noted that only the relative changes are of interest in determining the horizontal pressure gradient. For all three legs, isobaric height perturbations show a minimum over the highest peaks of the Sierra Nevada followed by a sharp increase with a maximum over the central Owens Valley, a secondary minimum near the crest of the White-Inyo Mountains and a minor secondary maximum immediately to the east. Note that isobaric perturbation heights rise by nearly 50 m over a horizontal distance of about 13 km that, from an atmospheric perspective, is a huge horizontal pressure gradient of 0.03 m s$^{-2}$. This is equivalent to a horizontal pressure difference of 3.5 hPa, corresponding to a geostrophic wind of about 400 m s$^{-1}$. Winds at flight level thus experience a strong adverse pressure gradient force above the western half of the Owens Valley and, consequently, should experience rapid deceleration. Isobaric height perturbations are similar in amplitude and phase for each of the three legs shown.

As stably stratified air is forced over a topographic obstacle, it undergoes an oscillation at the Brunt–Väisälä
frequency. To a first approximation, the buoyancy oscillation has a characteristic wavelength \( L \) equal to
\[
L = \frac{2\pi U}{N}
\]
(7)
where \( N \) is the Brunt–Väisälä frequency. Smith et al. (2008) have evaluated vertical profiles of \( N \) based on upwind soundings. Typical \( N \) values are 0.01 \( \text{s}^{-1} \), corresponding to a wavelength of about 25 km for a mean wind of 40 m \( \text{s}^{-1} \). Vertical velocities as measured by the UWKA (Fig. 2c) are consistent with this wavelength and display a lee-side sinking motion of about 3 m \( \text{s}^{-1} \) followed by weak rising motion over the center of the Owens Valley. Close inspection suggests some westward shift of the vertical velocity pattern with height, consistent with classic mountain wave solutions (e.g., Holton 1979). Comparing Figs. 2b and 2c, it is apparent that, while wavelengths of both are similar, vertical velocities are out of phase with the perturbation heights, again consistent with internal gravity waves (e.g., Holton 1979). Flux calculations (not shown), however, indicate a positive correlation indicating upward wave propagation similar to results of Smith et al. (2008).

Along-track wind speeds display marked variation along the flight legs (Fig. 2d). Maximum speeds near 50 m \( \text{s}^{-1} \) at the UWKA upper level are situated over the crest of the Sierra Nevada; minimum wind speeds are seen over the center of the Owens Valley. Deceleration of the flow is tied to the horizontal pressure gradient of the isobaric perturbation heights illustrated in Fig. 2b. Wind speeds are lower for the lowest leg, in response at least in part due to enhanced levels of turbulence experienced by the UWKA. Note that the wind speed is anticorrelated to the isobaric perturbation height field and also out of phase with the vertical velocity. Potential temperatures along the flight legs show surprising little evidence of significant wave activity for the upper two levels.

Given the isobaric height pattern in Fig. 2b and the vertical velocity trace in Fig. 2c, an examination can be made into the forcing of the winds in Fig. 2d. Two physical mechanisms, the vertical advection of along-track winds and horizontal pressure gradients, have been noted in (2). Data shown in Fig. 2 convincingly show that the vertical advection term in (2) is not responsible for pronounced changes in the along-track winds in Fig. 2d. From the two upper legs an estimate can be made of the vertical wind shear of roughly 1.3 m \( \text{s}^{-1} \) km\(^{-1} \) for this flight. Assuming a vertical velocity of 3 m \( \text{s}^{-1} \), the vertical advection term scales about 0.004 m \( \text{s}^{-2} \). This is about an order of magnitude less than the horizontal pressure gradient force. Further, and most telling, the decrease in along-track winds in Fig. 2d is associated with sinking motion. If the vertical advection of momentum term would be dominant, downward vertical velocity should transport higher momentum air and along-track winds should increase in response. It is concluded that along-track changes in wind for this flight are fundamentally the result of the horizontal pressure gradient force and that the assumption made to arrive at (3) is appropriate for this flight.

If the flow is steady, the isentropic form of the equation of motion (4) can be used to depict a streamline. Multiple isobaric legs are required to perform calculations of the Montgomery streamfunction as suggested in Prater (1996). For this flight a 314-K potential temperature surface was selected for analysis; the upper two legs are used to define the spatial variation of the potential temperature vertical gradient. In a practical sense,
The calculation of the Montgomery streamfunction ($M$) based on aircraft data is sensitive to the steady-state assumption. Figure 3a illustrates the horizontal variation of the perturbation $M$ field for the 314-K isentropic surface. Here, $M$ plays the same role as pressure along a horizontal surface or height along an isobaric surface; the horizontal variation of $M$ is thus similar to that seen in Fig. 2b. Once a correct $M$ is computed, the height of the isentropic surface can be determined. Smith et al. (2008) have used motion components along the leg to define a vertical streamline displacement, which is a proxy for streamline height. Figure 3b illustrates vertical streamline displacement for the two upper legs, compared with actual 314-K streamline height.

That energy is conserved along an $M$ surface can be confirmed by plotting perturbation values of the Bernoulli function, $B = (u^2/2) + (w^2/2) + c_p T + gz$, versus distance along the streamline (Fig. 3c) for this case. In terms of forcing of the horizontal wind, (3) can be evaluated in a similar manner along the two upper legs. While not displaying the constancy of the Bernoulli function, the isobaric energy term, $I = (u^2/2) + gz$, shows little variation along the leg and again suggests that (3) is an appropriate approximation to the horizontal equation of motion and that the horizontal wind is responding primarily to horizontal pressure changes.

Legs shown in Fig. 2 were conducted above the boundary layer and data displayed only minor evidence of turbulence. UWKA flight plans for that day included legs along a similar, albeit shortened, track within the boundary layer. Turbulent intensities experienced by the UWKA during these boundary layer legs were among the strongest ever recorded on that research platform. Isobaric height perturbations and wind speeds showed a profound influence of the boundary layer turbulence. Figure 4 illustrates results from three vertically stacked isobaric legs, the first leg above the boundary layer and
the lower legs within the highly turbulent boundary layer above the Owens Valley. Legs were conducted at levels vertically separated by about 1100 m (Fig. 4a). Amplitudes of the isobaric height perturbations (Fig. 4b) decrease significantly with height across the boundary layer interface such that at the 3000-m level, no significant horizontal pressure gradient remains. The vertical velocity field (Fig. 4c) retains elements similar to the upper level legs illustrated in Fig. 2c; the along-track horizontal velocity component (Fig. 4d) decreases rapidly with height. It can be concluded from the large vertical changes in the isobaric height perturbation amplitudes that the wind and pressure fields are linked in the free atmosphere. The isobaric height perturbations in Fig. 2b are not representative of larger-scale horizontal pressure field. This is confirmed by automatic weather station data along the Owens Valley (not shown) that shows no evidence of the profound isobaric height perturbations shown in Fig. 2b. It can be inferred from the airborne observations that the horizontal pressure field in the free atmosphere illustrated in Fig. 2b is a function of the airstream which while passing over elevated terrain is similar to the dynamics of a nozzle (e.g., Fox and McDonald 1985).

Findings from the first flight on 14 March could also be seen in analyses from the flight later that day. Results from the second flight for the two highest legs on 14 March 2006 from 2305–2343 UTC are shown in Fig. 5. Wind direction at the flight level was approximately 235° and as in the first flight set the track angle for the legs. The highest leg (Fig. 5a) was about 1000 m above the highest leg of the first flight. Some of the largest measured perturbation heights (Fig. 5b) were observed during this flight with deviations in excess of 70 m. This corresponds to a horizontal pressure change for the uppermost leg of nearly 5 hPa and a pressure gradient force of 0.04 m s⁻². The position of the perturbation heights is similar to that seen earlier with the suggestion that the maximum may be displaced a few kilometers to the east, consistent with the stronger winds. UWKA measured vertical velocities (Fig. 5c) were surprisingly weak with maximum sinking motions reaching only about 3 m s⁻¹ for the lower leg. Again vertical velocity is out of phase with the isobaric height perturbation field; vertical velocity displays a westward shift from the lower to upper levels. As with the earlier flight, large changes in the horizontal wind speeds were observed (Fig. 5d) that are anticorrelated with the isobaric height perturbations and isobaric energy terms are roughly constant for both legs (not shown), again confirming assumptions made to arrive at (3). Potential temperature measurements suggest better developed waves as compared to the earlier flight. Again, a westward shift with height is seen in the potential temperature field and a phase difference with the wind speed is evident. Close inspection suggests the vertical velocity field is nearly in phase with potential temperature. Smith et al. (2008) defined dominant waves for their analyses of the GV flights that same day. The shorter lengths of the UWKA legs limited similar spectral analyses although phase differences are apparent for legs shown.

Evidence shown from the 14 March 2006 UWKA flights strongly suggests that the motion field is Eulerian (e.g., Haltiner and Martin 1957), in which winds respond directly to the horizontal pressure gradient force. Magnitudes of acceleration of the wind field match measurements of the horizontal pressure gradient. For example, the decrease in wind from 58 to 44 m s⁻¹, illustrated in Fig. 5c, matches precisely with the corresponding 72-m height rise in Fig. 5b. For this case the vertical advection term is at least an order of magnitude smaller than the horizontal pressure gradient force and hence plays an insignificant role in the observed deceleration of the wind above the Owens Valley. Tropospheric flows are
constricted by the Sierra Nevada, leading to flow acceleration, followed by a rapid deceleration as the tropospheric column increases over the Owens Valley. A subsequent secondary increase in wind speed is observed over the peak of the White-Inyo Range.

A case can be made that given similarities in large-scale atmospheric conditions, results from 14 March 2006 should be similar to that seen from other flights during strong wind conditions. Two other study days of note for T-REX were 25 March and 16 April 2006, the former being the most intensely studied of all T-REX cases (e.g., Grubišić et al. 2008; Smith et al. 2008; Woods and Smith 2010; Cohn et al. 2011; Doyle et al. 2011a,b and references contained therein). For brevity, only the second UWKA flights on 25 March and 16 April will be examined.

Figure 6 illustrates conditions for the 25 March 2006 case with three legs taken from the UWKA record during the period 2234–2303 UTC. As in the 14 March case, the UWKA track followed the axis of the wind, which on this day was from 250° (Fig. 6a). Isobaric height perturbations as measured by the UWKA (Fig. 6b) approach 70 m for the upper two legs. Significant vertical velocities were measured by the UWKA with strongest subsiding motion of 6 m s⁻¹ at 6500 m above ground level in the lee of the Sierras and extending over the Owens Valley. Oscillations of vertical velocity can be traced all along the UWKA legs. Again for this case, inspection of the UWKA record shows the vertical velocity is out of phase with the isobaric height perturbations. Further, the periodic behavior in the vertical velocity field is not seen in the isobaric height field implying that two signals are not tightly coupled. Along-track winds as measured by UWKA show a similar pattern to the 14 March case in that winds decrease significantly in response to the adverse pressure gradient illustrated in Fig. 6b. Again the wind speed is anticorrelated with the isobaric height perturbations. A large amplitude oscillation is seen in the potential temperature field at all three levels implying that isentropes must show a significant downward trend in the lee of the Sierra Nevada.

For the second flight on 16 April 2006, similar patterns emerge in terms of the forcing of the horizontal wind. Figure 7 illustrates flight tracks (Fig. 7a) that were aligned along the axis of the wind, which was from 250° at flight level. As with previous cases, isobaric height perturbations (Fig. 7b) show a minimum over the crest of the Sierra Nevada and a large increase of over 70 m over the Owens Valley. A secondary decrease in isobaric height perturbations is seen directly over the White-Inyo Range and downstream increase. Vertical velocities (Fig. 7c) are weak east of the Sierra Nevada and it appears as though downstream wave amplification is occurring as vertical velocities increase. UWKA data suggests that the phase relationship between isobaric perturbation height and vertical velocity varies with height. Close inspection shows that vertical velocity is roughly in phase with isobaric perturbation height at the uppermost flight level yet appears less so at lower levels. As before, wind speeds (Fig. 7b) appear tied to the isobaric height perturbations, decreasing in response to the adverse pressure gradient force over the western Owens Valley. For the most part, wind speeds are anticorrelated with isobaric perturbation heights at all levels and secondary wind speed minima and maxima have corresponding maxima and minima height perturbations. For both 25 March and 16 April cases, the large isobaric height perturbations are damped rapidly within the highly turbulent boundary layer (not shown) similar to that observed in the 14 March case. Large amplitude height perturbations thus are confined to the free atmosphere, suggesting that the local pressure field is determined from the flow itself rather than reflecting the large-scale environment.
4. Summary

Observations conducted by the UWKA during the T-REX field study are some of the most detailed airborne datasets ever taken during strong mountain wave episodes. Among the most compelling of the UWKA measurements from the T-REX campaign are the isobaric height perturbations. Differential processing of raw data collected by an airborne GPS platform with GPS data from a fixed base station provides a means by which the vertical position of the aircraft can be detected to within a decimeter or so. Combined with accurate measurement of static pressure, height perturbations along an isobaric surface or, equivalently, horizontal variations of pressure can be detected along a flight track. Such measurements are required to evaluate atmospheric dynamics that are responsible for abrupt wind changes associated with mountain wave features along a flight line. Height perturbations in excess of 70 m have been measured along UWKA tracks, comparable to a horizontal change of over 4 hPa. Along-track winds associated with mountain waves are sensitive to variations in isobaric heights and a relatively simple analysis suggests Eulerian accelerations can provide an answer as to the observed wind changes. Evidence shown from the 14 March 2006 UWKA flights strongly suggests that the motion field is Eulerian, in which winds respond directly to the horizontal pressure gradient force similar to that seen in an idealized Bernoulli flow. From an energy perspective, flow behaves similar to that from the simple Bernoulli equation and matches that seen in Smith et al. (2008). Wind speeds seem less tied to mountain wave features and more to simple conservation of mass and Bernoulli concepts based of UWKA data for this day.

Isobaric height perturbations are damped rapidly within the boundary layer. Analyses of flight legs conducted in the highly turbulent layers below maximum crest level of the Sierra Nevada display a remarkable decrease in the height perturbations. Such measurements are confirmed by surface automatic weather station records (not shown) that reveal little detectable pressure perturbations associated with mountains waves. Application of the dGPS technique is thought to be a critical new tool in assessing dynamics of a wide variety of atmospheric motions using an airborne platform.

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REFERENCES


