13B.4 WIND PROFILER OBSERVATIONS OF MOUNTAIN WAVES AND ROTORS AT T-REX

Stephen A. Cohn* and William O. J. Brown
National Center for Atmospheric Research, Boulder, CO, USA

1. INTRODUCTION

The National Center for Atmospheric Research (NCAR) deployed a network of three boundary layer wind profilers at T-REX (the Terrain-Induced Rotors Experiment) in the lee of the High Sierras in the Owens Valley, California during the spring of 2006. T-REX studied the structure and evolution of atmospheric rotors and associated phenomena (including lee waves) in complex terrain (Grubišic et al. 2004).

Atmospheric rotors are intense horizontal vortices that form parallel to and downstream of a mountain ridge crest in association with large amplitude mountain waves. They are associated with high levels of turbulence and are a significant hazard to aviation.

The Owens Valley was extensively instrumented for T-REX, with radars, lidars, aircraft, surface towers, and a variety of other sensors. The wind profilers were part of the NCAR ISS (Integrated Sounding Systems, Parsons et.al., 1994) which include the profiler, a surface meteorology station, and at one site, a radiosonde system and sodar.

2. DIAGNOSING WAVE PROPERTIES

The small network of boundary layer wind profilers operated continuously during T-REX and had two primary purposes. The first was to provide general observations of the winds above the valley. These can be used to examine spatial patterns of winds – for example changes in the flow along the valley axis or across the valley during wave and rotor events – and also are valuable for comparison with the T-REX modeling efforts. The second purpose was to examine how wind profilers may be useful in studying waves and rotors.

* Corresponding author address: Stephen A. Cohn, National Center for Atmospheric Research, P.O. Box 3000, Boulder, CO 80307-3000; e-mail: cohn@ucar.edu.

The three ISS included a standard version with a Doppler beam swinging profiler that was sited on the alluvial slope on the west side of the valley; MAPR (Cohn, et.al. 2001), a boundary layer profiler using a spaced-antenna technique which was located in the center of the valley; and a Mobile ISS (MISS) profiler which moved from site to site during the two months of data collection. During IOP 6 of T-REX MISS was located between the ISS and MAPR forming an approximately west-to-east line of observations (Fig. 1). It is rare – perhaps unique – to have a cross section of wave observations over height and time, and we present illustrative observations from this period.

Persistent non-zero vertical motion above a wind profiler is one indication of a lee wave overhead. The strength and even the sign of the motion depends on the phase of the wave and its amplitude. Figure 2 illustrates this for a 12 hour period during IOP 6. Figure 2a-c are a time-height plots of vertical velocity from the west (ISS), central (MISS), and east (MAPR) wind profilers. Areas of blue are updrafts that persist over time and height, while yellow and red show persistent downdrafts. At each site the wave is seen to change significantly over time, with phase changes between updraft and downdraft (for example near 10 UT in the West and Center sites and 11 UT at the East site), and changes in the wave downward penetration into the valley.

In figure 2d we analyze the structure of the wave using vertical velocity from the line of profilers. The abscissa is across-valley distance relative to the western ISS, and the relative terrain profile is shown (thick black line, no scale) for orientation. At 08:30 UT at 4300 m MSL (blue vertical line and circles in 2a-c) the west profiler shows a downdraft while the center and east profilers show updrafts. The blue stars and curve in 2d are these measurements and a least squares sinusoidal fit. Similarly, the red data is for measurements at 13:00 UT, when the western profiler shows an updraft and the center and east profilers observe downdrafts. Finally, the green data (thick line) is for 17:20 UT. Note that these fits do not indicate streamlines, which would be shifted in phase by $\pi/2$. Comparison with the vertical wind measured during a cross-valley leg of a research flight by the University of Wyoming King Air from 17:17 to 17:22 UT (thin green line) shows good agreement. The wave characteristics of the fits are summarized in table 1. We envision analyzing this data in more detail to examine the changing structure of the wave over time and height, comparing with changes in the ambient winds and boundary layer conditions.

Time (UT)	**08:30**	**13:00**	**17:20**
Amplitude (m/s)	5.4	7.9	5.4
Wavelength (km)	13.4	15.7	17.6
Phase over West ISS (^{o})	333	104	52

Table 1: Wave characteristics derived from sinusoidal fits at 4.3 km MSL at 08:30, 13:00, and 17:20 UT

3. EVIDENCE FOR ROTORS

Although the primary goal of T-REX was observation of rotors, it has been difficult to identify clear cases of textbook large-scale rotors (eg. Fig. 3). In this section we present observations from IOP 3 which provides evidence of rotor circulation. During IOP 3 the west (ISS) and east (MAPR) profilers were located as indicated in Fig. 1, but the Mobile ISS was sited farther north and is not used in this analysis.

One clear signature of rotors in the T-REX domain is reverse flow at the surface identified by a dense surface anemometer network (DRI surface network). In this case reverse flow is approximately easterly during periods of strong westerly winds aloft. Care is needed in identifying reverse flow to avoid including upslope flow. This can occur when the boundary layer is decoupled from flow aloft. The DRI network identified reverse flow with a speed of several m s^{-1} from about 18-19 UT on March 9, during IOP 3. As figure 4 shows, the ISS anemometer at the MAPR site also captured this, with easterly flow from about 16-19 UT. The speed of this easterly flow increases from about 1 m s^{-1} to about 4 m s^{-1} over this period, consistent with the DRI observations. After 19 UT strong westerly winds sweep down the slope and across the valley.

The wind profilers (ISS and MAPR) vertical velocity measurements over this day are shown in figure 5. Earlier in the event, prior to about 19 UT, the western profiler (ISS) measures an updraft aloft and after 19 UT sees a downdraft. Farther east near the center of the valley, MAPR observes a downdraft aloft until about 18 UT followed by an updraft. Note that MAPR data is not available from 20-22 UT due to a malfunction. With only two profilers we cannot fit a sinusoid to this data. However, the pattern is consistent with the western profiler being just east of a trough and the eastern profiler being just east of a crest before about 18 UT (illustrated by W_1 and E_1 on figure 3) and the wave position shifting so that after about 19 UT the western profiler is west of a trough and the eastern profiler (MAPR) is west of a crest (illustrated by W_2 and E_2 on figure 3). If a rotor were indeed present during this shift, MAPR would document the rotor flow.

Figure 6 shows the spectral width from MAPR during the same period as figure 5. Beam-broadening and shear-broadening corrections have been applied (eg. Nastrom 1997) so this width should be proportional to the cube root of turbulent eddy dissipation rate. Notice that the strongly turbulent region descends with time (from 14 to 20 UT). This can be compared with in-situ measurements of the King Air, shown in figure 7. The aircraft conducted transects of the valley, from which streamlines and a cross section of EDR (colored field) are derived. EDR is related to the cube root of eddy dissipation rate and so should be proportional to spectrum width. The King Air measurements show the strongest turbulence on the upwind side of the wave crest. So if the crest were to move eastward from 18-19 UT bringing its upwind side over MAPR we would expect to observe the height of strong turbulence descending over time. This is again consistent with the MAPR observations (Fig. 6).

It is possible that a major outcome of the T-REX project will be a more detailed and complex view of rotors – replacing the current textbook concept.

ACKNOWLEDGEMENTS

The ISS and King Air data were collected as part of the Terrain-induced Rotor Experiment (T-REX). The primary sponsor of T-REX is the US National Science Foundation (NSF). The involvement of the NSF-sponsored Lower Atmospheric Observing Facilities from the University of Wyoming and those managed and operated by the National Center for Atmospheric Research (NCAR) Earth Observing Laboratory (EOL) is acknowledged. The authors appreciate helpful conversations with Vanda Grubišic.

REFERENCES

Cohn, S. A., W. O. J. Brown, C. L. Martin, M. S. Susedik, G. Maclean, and D. B. Parsons, 2001: Clear air boundary layer spaced antenna wind measurements with the Multiple Antenna Profiler (MAPR), *Annales Geophysicae*, **19**, 845-854.

Grubišic, V., J. D. Doyle, J. Kuettner, G. S. Poulos, and C. D. Whiteman, 2004: Terrain-induced Rotor Experiment (T-REX) Overview Document and Experiment Design. 72 pp. Available at http://www.eol.ucar.edu/projects/trex/documents

Grubišić ,V., and S. A. Cohn, 2004: Sierra Rotors Project: Preliminary findings. *Proceedings. 11th Conf. on Mountain Meteorology and the Annual Mesoscale Alpine Programme (MAP) Meeting*. AMS, Bartlett, NH, Online preprint http://ams.confex.com/ams/11Mountain/techprogram/paper_77364.htm

Nastrom, G. D., 1997: Doppler radar spectral width broadening due to beamwidth and wind shear, *Annales Geophysicae*, **15**, 786-796.

Parsons, D. B., and Co-Authors, 1994: The Integrated Sounding System – Description and preliminary observations from Toga-COARE, *Bull. Amer. Meteor. Soc.*, **75**, 553-567.

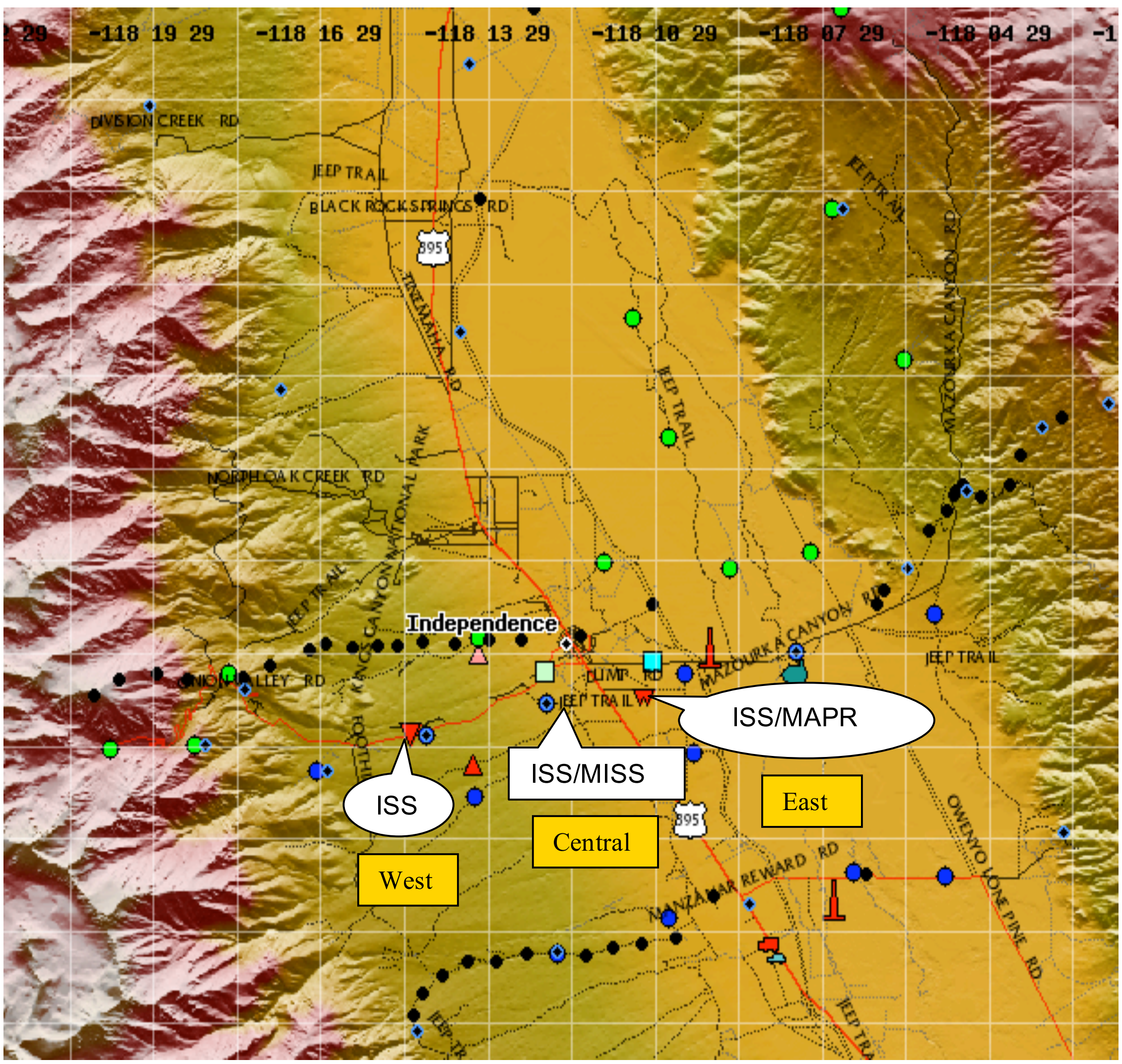

Figure 1: *Map of the Owens Valley showing locations of the west, central, and east wind profilers near Independence, California.*

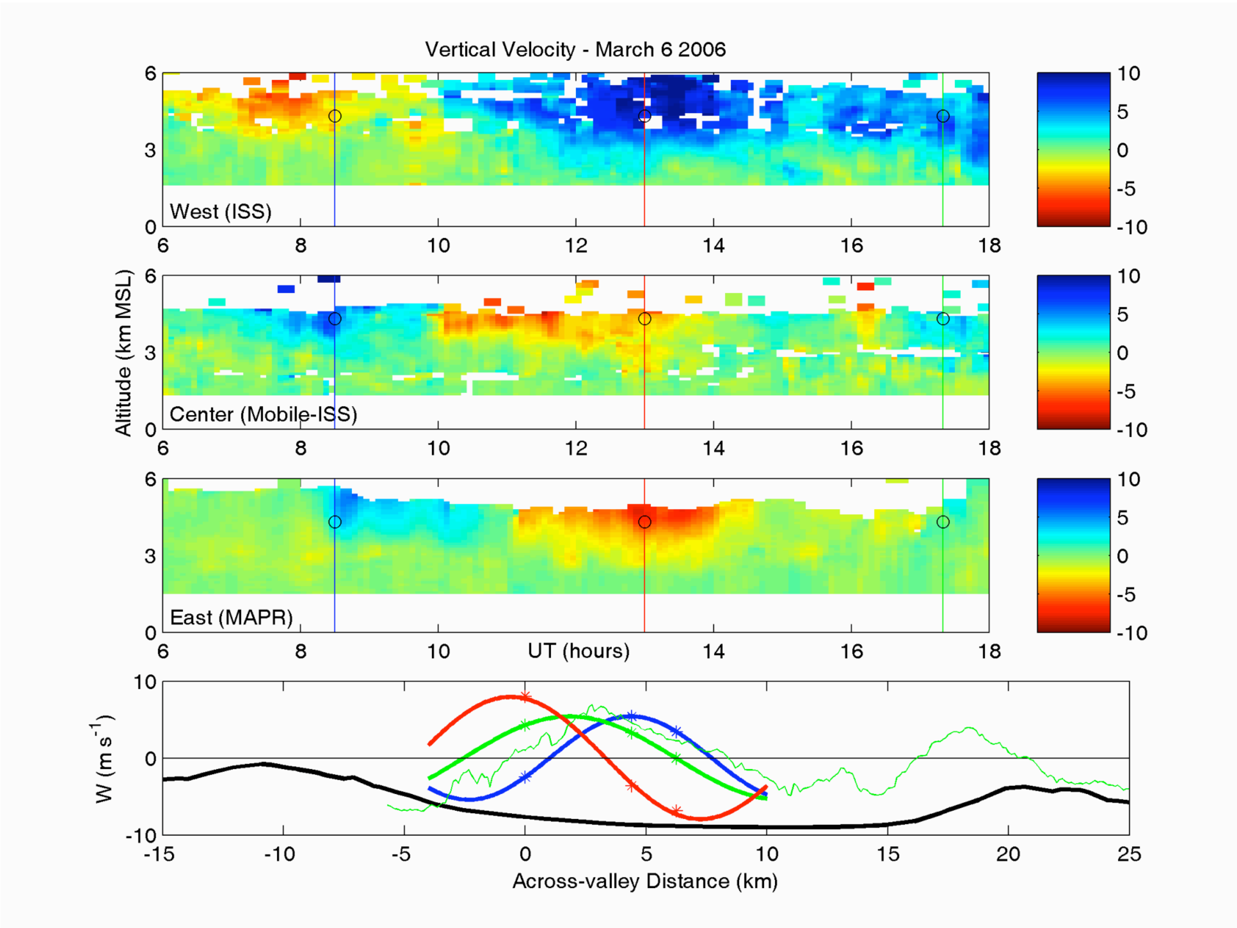

Figure 2: *Vertical wind measurements and inferred wave structure during IOP 6. (a) Time-height plot of vertical wind measured with the western-most ISS wind profiler on the valley's alluvial slope. This data was smoothed using a running 10-minute and 150-m window. Areas of white are low signal strength or below the first sample height of the profiler. Vertical lines and circles highlight times to be shown in (d). (b) as in (a) but for the Mobile ISS (center) wind profiler. (c) as in (a) but for the MAPR (east) wind profiler in the center of the valley. (d) Vertical wind observations from the King Air and inferred wave structure from the profiler network at 4300 m MSL at 08:30 UT, 13:00 UT, and 17:20 UT (corresponding to vertical lines and circles in (a-c). See text for further explanation.*

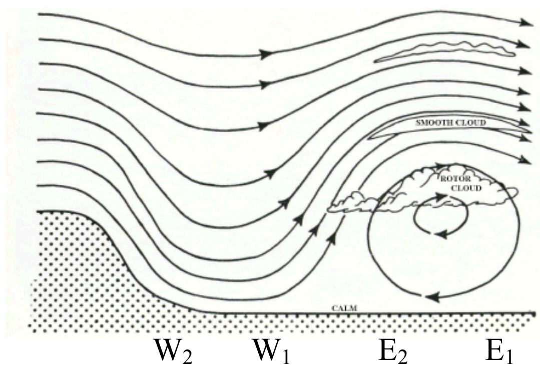

Figure 3: *The schematic diagram of the two dimensional airflow pattern with waves and rotors downwind of a ridge. (from Grubišic and Cohn, 2004). E1, E2 and W1, W2 are illustrative positions of the East and West profilers relative to the wave crest and trough at times before about 18 UT and after about 19 UT on March 9, 2006 (IOP 3).*

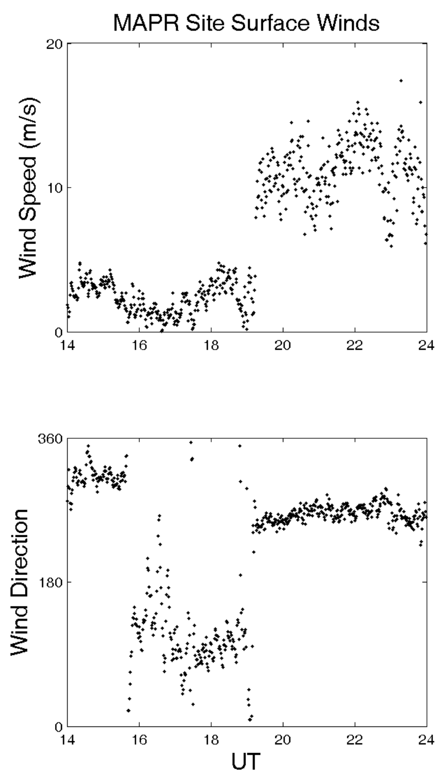

Figure 4: *Surface wind speed and direction at the MAPR site from 14-24 UT on March 9, 2006.*

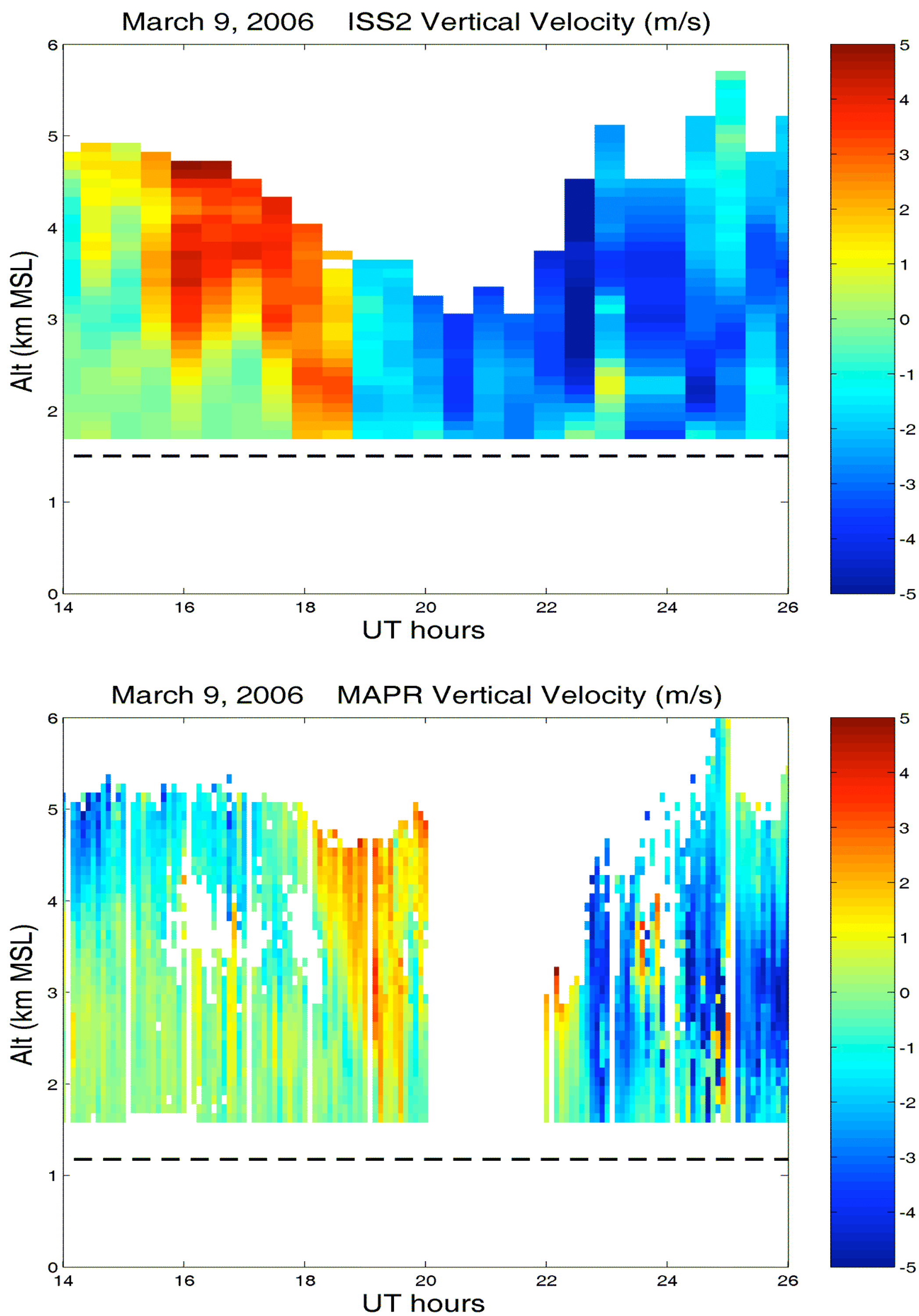

Figure 5: *Time-height plot of vertical wind measured with the western-most ISS wind profiler on the valley's alluvial slope (top) and with the eastern-most wind profiler (MAPR) near the center of the valley (bottom). Areas of white are low signal strength or below the first sample height of the profiler. MAPR data from 20-22 UT is unavailable due to a malfunction.*

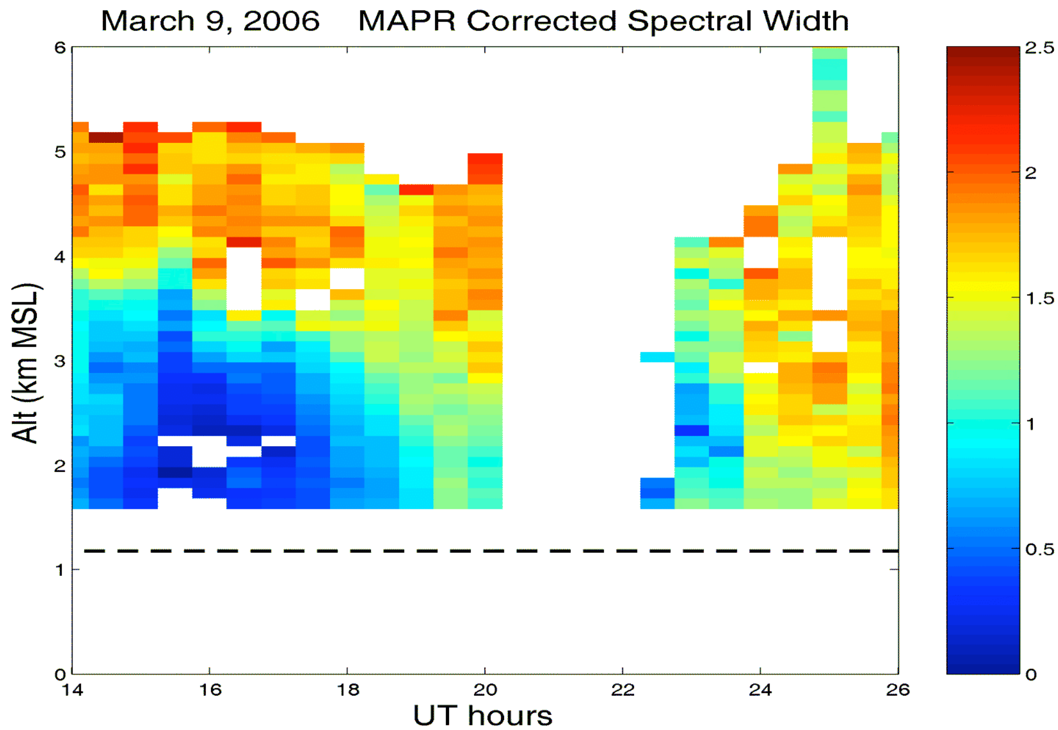

Figure 6: *Time-height plot of corrected spectral width from MAPR. Data from 20-22 UT is unavailable due to a malfunction.*

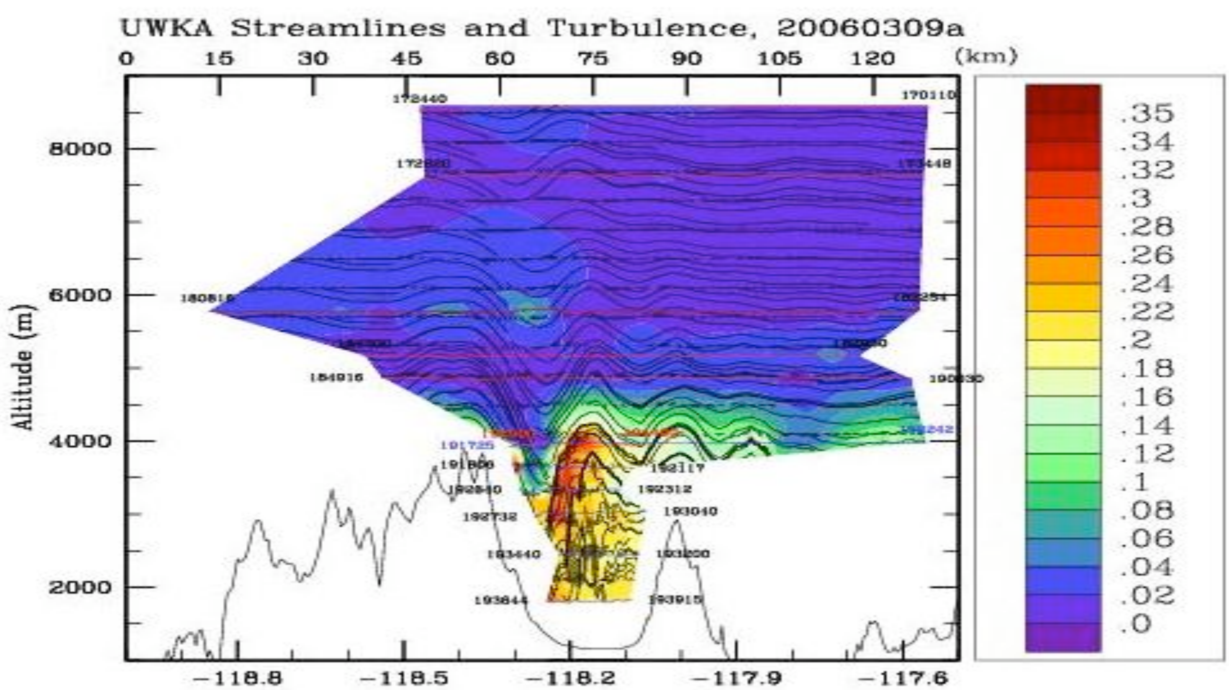

Figure 7: *Streamlines and turbulence from the Univ. of Wyoming King Air flight (first T-REX IOP 3 flight on March 9, 2006). Turbulence (EDR, proportional to the cube root of eddy dissipation rate) is colored.*