6B.5 ANALYSIS OF COLD POOL BREAKUP IN COMPLEX TOPOGRAPHY AND COMPARISON WITH LABORATORY MODEL

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1. INTRODUCTION

Natural slope flows occurring on complex terrain, and specifically in valleys, have been the focus of numerous studies dating back to the late 19th century. Defant (1951) provides a good review of early research in this area of study up to that time, including some of the first theoretical work performed on slope flow under stable stratification by Prandtl (1952).

Slope flow is of particular importance when studying valley flow regimes, and specifically during the hours of the morning transition, when the stable boundary layer (SBL), with its accompanying temperature inversion, begins to break up due to thermal heating at the surface. At this time the cold pool of air, as it is called, breaks up, resulting in the typical daytime convective boundary layer (CBL) structure with a nearly isothermal potential temperature profile accompanied by a superadiabatic layer very near the ground.

A simpler case to study these events is for circular basin-type topography, which Whiteman et. al. (2003, 2004) have performed. A case of slightly more complexity is that for valley flow, in which there is slope flow in two directions, namely up/down valley (along the valley axis) and up/down slope (perpendicular to valley axis). The current paper focuses on the latter of these two events for a particular case study in Owens Valley California and compares it with some results from laboratory experiments.

1.1 Background

At least four mechanisms of inversion destruction have been proposed, three of which have been directly observed. Whiteman has performed an extensive array of field studies on this topic and developed three of these mechanisms (1982, 1990). Type I occurs when the inversion is destroyed solely by a growing CBL from below. Type II also involves destruction of the inversion from a growing CBL, but is coupled with a descent of the top of the inversion layer, thought to be a result of subsidence of the stable air mass that remains from the evening. In this special case, the growth of the CBL is arrested after a short period of time and remains static for the duration of the morning transition. Finally, type III is defined to be the occurrence of a continually growing CBL coupled with a descending inversion layer top, both lasting until the remnants of the inversion have dissipated.

The fourth mechanism has been more recently defined by Princevac (2008) in laboratory experiments and has been described as a horizontal intrusion-like mechanism, wherein the up-slope flow becomes retarded in a blocking effect by the surrounding stable atmosphere. It was shown that near the point roughly half the height of the inversion, $z = h/2$, if the blocking effect is strong enough, the flow will detrain from the sidewall and flow towards the center of the valley over the top of the upslope flow, presumably cutting into the middle of the remaining stable layer or adding to the height of the CBL. Princevac went on to define the strength of this retarding force by the dimensionless parameter *B* and the upslope angle β, where:

$$B = \frac{N^3 h^2}{q_0}$$

where *N* is the Brunt-Vaisala frequency, *h* is the height of the inversion, and q_0 the buoyancy frequency and estimated the critical value to be ~2000-3000, above which the intrusion mechanism will dominate.

Whiteman's type III inversion destruction, and potentially Princevac's type IV mechanism, are the most pertinent to valley-shaped topography. The following exposition aims to determine the prevailing aforementioned

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mechanisms of destruction during the morning transition in Owens Valley.

2. EXPERIMENTAL METHODS

The Terrain-Induced Rotor Experiment (T-REX) was held in Independence, California in the Owens Valley region during March and April of 2006. Owens Valley is approximately 120km long and lies between the Sierra Nevada mountain range to its west, which has peaks over 4,400m AMSL, and the White and Inyo mountain ranges to its east, reaching heights of 3,300m AMSL. The adjacent valley floor lies at approximately 1,200m AMSL, connecting the two peaks across roughly 30km, making the valley's slope one of the steepest in the world and creating a quasi-two-dimensional terrain. The slopes of Owens Valley are elevated from the horizontal by an angle of $\beta=2.4°$ across ~12km of the main valley floor at which point it meets the very steep-sided faces of the mountain ranges. Figure 1 shows a shaded relief plan view of the region of East-Central California where Owens Valley is located. The valley axis is declined roughly 16° from due north.

As a supplement to the primary investigation of wave activity over the Sierra's, periods of relative quiescent conditions were studied during Enhanced Observational Periods. Table 1 defines the time periods of these EOPs during T-REX. The aim of these EOPs was to gather insight into boundary-layer structure and evolution in the absence of synoptic scale interaction/interference. During these quiescent periods, it is hoped that the diurnal boundary layer cycles, including the destruction of the nighttime SBL via those mechanisms mentioned above, can be more clearly observed since thermal forcing can be expected to have a significant impact on NBLs (Grubisic, 2004).

Most importantly, it is hoped that the erosion of cold pool inversion layers can be clearly observed in this deep valley due to the nature of its topography. It has been shown for a variety of valleys and basins that the primary source of cold pool erosion is from thermal forcing (Whiteman et. al., 2004; Clements, et. al., 2003) and that along-valley air flow has a negligible effect on the breakup of cold pools (Whiteman et. al., 2004).

Arizona State University's Center for Environmental Fluid Dynamics brought numerous instruments to the experimental site in Independence, CA. Among them were a WindTracer Doppler Lidar (from Coherent Technologies) and a Scintec sodar/RASS profiler from which observations presented here were acquired through. Figure 2 is a plan view of the layout of the instruments along the valley floor, just south and east of the town of Independence. The GPS coordinates of the lidar and sodar were 36.79753 N/118.17578 W and 36.787983 N/118.178417 W, respectively.

Lidar scans were used to detect wind fields at the crests of the Sierra Nevada range in an attempt to determine whether the dominant overhead airflow over the mountains was able to penetrate the valley and thus disrupt the nocturnal boundary layer. The sodar/RASS was able to provide vertical temperature profiles and wind velocity fields to determine the presence or absence of the inversion layer and to visualize the progression of its destruction and thus determine which destruction mechanism dominates in Owens Valley. The profiles of the sodar ranged from about 30 m to 600 m, with the lidar providing coverage up to 4 km radially, including the level of peaks of the Sierras.

ASU's Lidar was running both RHI and PPI scans continuously during EOPs 2-5 and the sodar/RASS unit was running continuously during EOPs 2-4, calculating 30-minute averages for each variable. Of the five EOP periods, EOP 2 was notably the best (most synoptically inactive) period to observe boundary layer transitions, and so only EOP 2 is presented here for detailed analysis. Though each EOP lasted 21 hours, the focus will remain on the hours from approximately 0500 LT until 1100 LT of the second day of each EOP, as this is the period during which the NBL initially forms its most distinctive features and continues on to its dissipated state.

3. RESULTS

The nocturnal boundary layer with its associated cold pool was successfully visualized during EOP 2. Conditions favored well-developed NBL formation, as winds were extremely light to calm from 2300 to 1000 LT during the night and morning of 30 March at heights from 30 m to 500 m as seen in Figure 3. More importantly, the prevailing synoptic scale winds were extremely light and westerly, preventing them from interfering with the velocity structure within the valley. EOPs 3 and 4 did not provide good observations primarily because the synoptic winds contained partial-to-significant along-valley components and were significantly stronger than those during EOP 2. Noticeable in Figure 3 is that the lightest winds during the morning transition of EOP 2 occur from 0830-0900 LT, during which time the down-valley wind reverses to up-valley flow. For this reason, and because cross-valley flow is significantly weaker than along-valley flow, one must recognize that the best opportunity to observe any cross-valley flow is during the 0830-0900 LT averaging period (denoted as the 0900 average period).

Virtual potential temperature profiles and cross-valley flow for the morning hours between 0500 LT and 0800 LT (primarily before the transition occurs during EOP 2) are shown in Figures 4 and 5. A well-developed ground-based inversion of roughly 500m height and 6.5°K strength already exists at 0530 LT and appears to be the maximum strength of the inversion during this nocturnal setting. The form or extent of the inversion does not change significantly through the 0800 LT period, but noticeable is the lower 200m of the inversion, which is nearly isothermal in nature and heats slowly by less than 2 degrees. This feature is not commonly seen in valley-like settings, but may, in this case, be due to the larger-than-normal dimensions of Owens Valley, which could provide enough turbulent mixing of the down-valley flow to create a mixed lower layer of air. The upper levels of air begin to warm, and while it is somewhat difficult to define a well-marked inversion top during the earlier hours, by 0800 LT the inversion top has both warmed and subsided to about 450m, in accord with the Type III destruction mechanism defined by Whiteman.

It is readily seen that the early-morning cross-valley wind profiles show a well-developed low-level down slope flow during the 0530, 0600, and 0630 LT average periods. Interestingly, there is an elevated up-slope flow at approximately 150-325m during this time as well. This could possibly be the result of larger scale eddies in the turbulence of the down slope flow. However, this turbulence would require a timescale of at least the 30-minute average periods, which may not be reasonable. Alternatively, being that sunrise at valley bottom occurs at 0541, it may be possible that heating along the upper elevations of the valley sidewall earlier than this time induces a point of divergence above which air flows upslope and below which down slope flow continues. As this point slowly travels down slope, it would pass the instrument location, and may be what appears during the 0530, 0600, and 0630 periods. At 0730 an upslope flow becomes well defined in the lower 100m of the boundary layer while winds 0-1m/s remain flowing down slope from 100-280m. This trend continues through the 0800 period and, while diminished, is still visible as a very light down slope wind during the 0830 period.

After the early morning hours, the temperature profiles begin to change significantly, as shown in Figures 6 and 7. A significant change occurs from 0800 to 0830 during which time the lower well-mixed layer of air with near-constant potential temperature appears to collapse, or possibly diffuse, into a smoothly and stably stratified layer of 500m depth and 3°K strength. After this time the potential temperature gradient remains very nearly constant across the entire boundary layer but slowly decreases to isothermal conditions at 0930. After this time, however, a superadiabatic layer forms from 100-300m, in the same region where the down-slope air had continued until much later than sunrise. This type of motion is rather indicative of what one might expect in the type IV inversion destruction, where intrusion type flows exist atop the already-induced upslope flows. This could also explain how a superadiabatic layer can form in the upper levels of a valley. The air which is continually heated as it travels along the slope becomes detrained at a particular point and begins to move toward valley center, carrying some of that heat with it. If this process continues for a long enough time period, it may be capable of producing an elevated region of relatively hotter air as is seen.

Moreover, an intrusion process may justifiably explain this situation since the air in contact with the ground, which would normally transport heat upward, heats neither as fast nor as much as the elevated region from 100-200m. As such, some other source and direction of heat would be required to accomplish this situation. Heated horizontal intrusions from the sidewalls would accomplish just that.

Figures 8 and 9 are included for completeness here and show the evolution of the along-valley wind component. There are no particularly striking anomalies occurring during this morning, where an apparent log-law profile blows down valley with an elevated jet at 200m. The form of the profile remains similar through 0800 at which time there is a transition from down valley flow to up valley flow in the upper reaches of the boundary layer. This coincides with the position of the top of the inversion and was a condition observed to occur in the inversion breakups studied by Whiteman (1982). In these cases the return valley flow occurs first at the top of the inversion, but because of its stable nature will not penetrate it significantly. As the inversion subsides into the valley, these up-valley winds grow to a deeper level, until at 0930 here, when the boundary layer becomes isothermal, a layer of up-slope flow the depth of the boundary layer persists and henceforth continues to increase in strength.

4. CONCLUSIONS

Some of the results found during the T-REX campaign concerning cold pool destruction are in accord with previous studies, however, there are results that support new theory as well. The depth and topography of Owens Valley was of great benefit in studying valley flow characteristics as isolated from synoptic scale forces and the sodar/RASS was able to gather useful data during EOP 2 in support of three different mechanisms that destroyed the nocturnal inversion during this time. These included a growing convective boundary layer with a subsiding stable boundary layer (as is the case in Whiteman's type III destruction) and also additional data to support the presence of intrusions as a mechanism that dominantly dictates how the stable boundary layer evolves.

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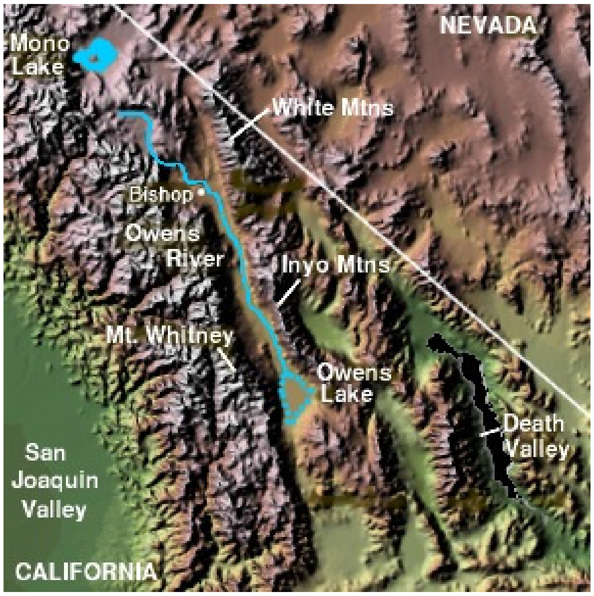


Figure 1: Shaded relief map of the region of interest during the T-REX campaign. Indpendence, CA is located 66km southeast of Bishop and is where the ASU instrumentation was located. The scale of the image is approximately 350km across.

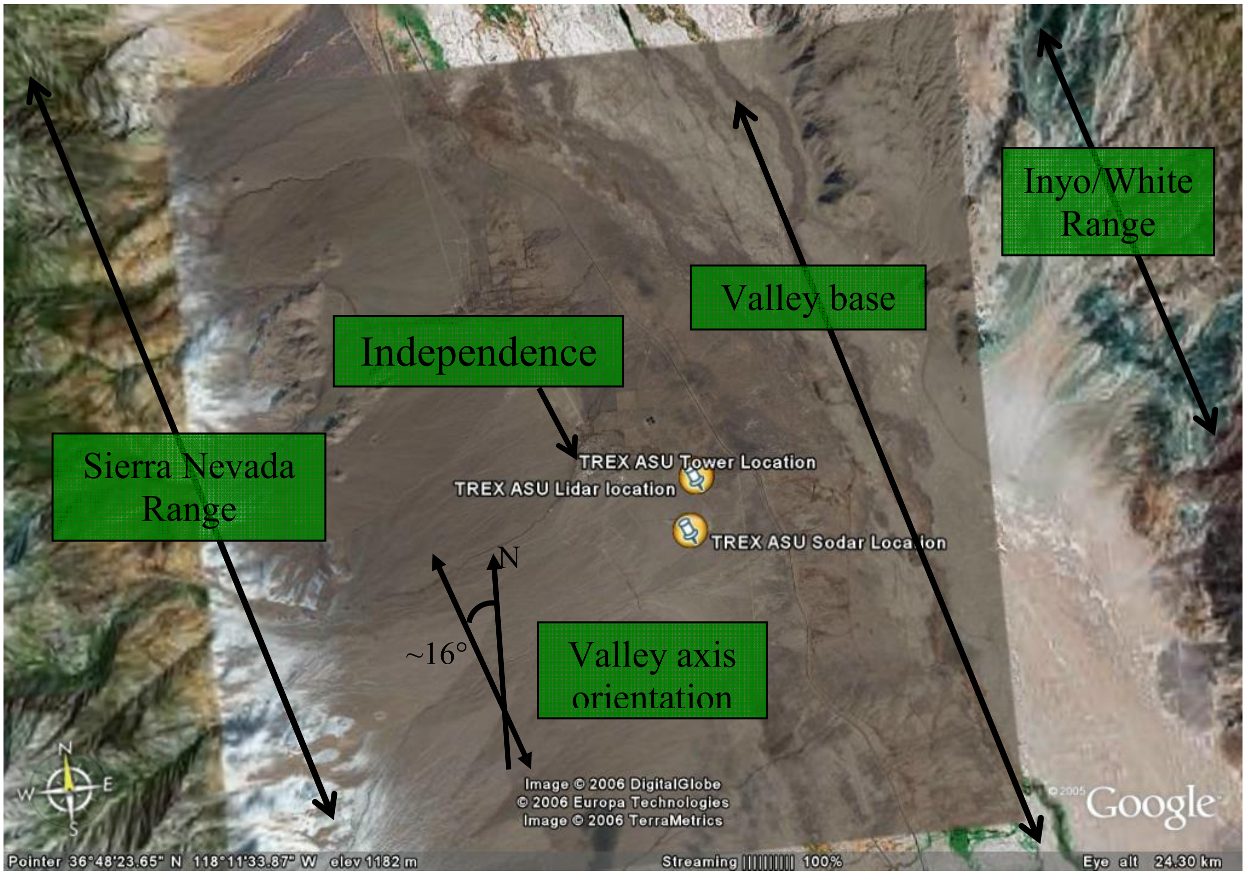


Figure 2: Plan view of Owens Valley showing pertinent features of the valley along with instrument location.

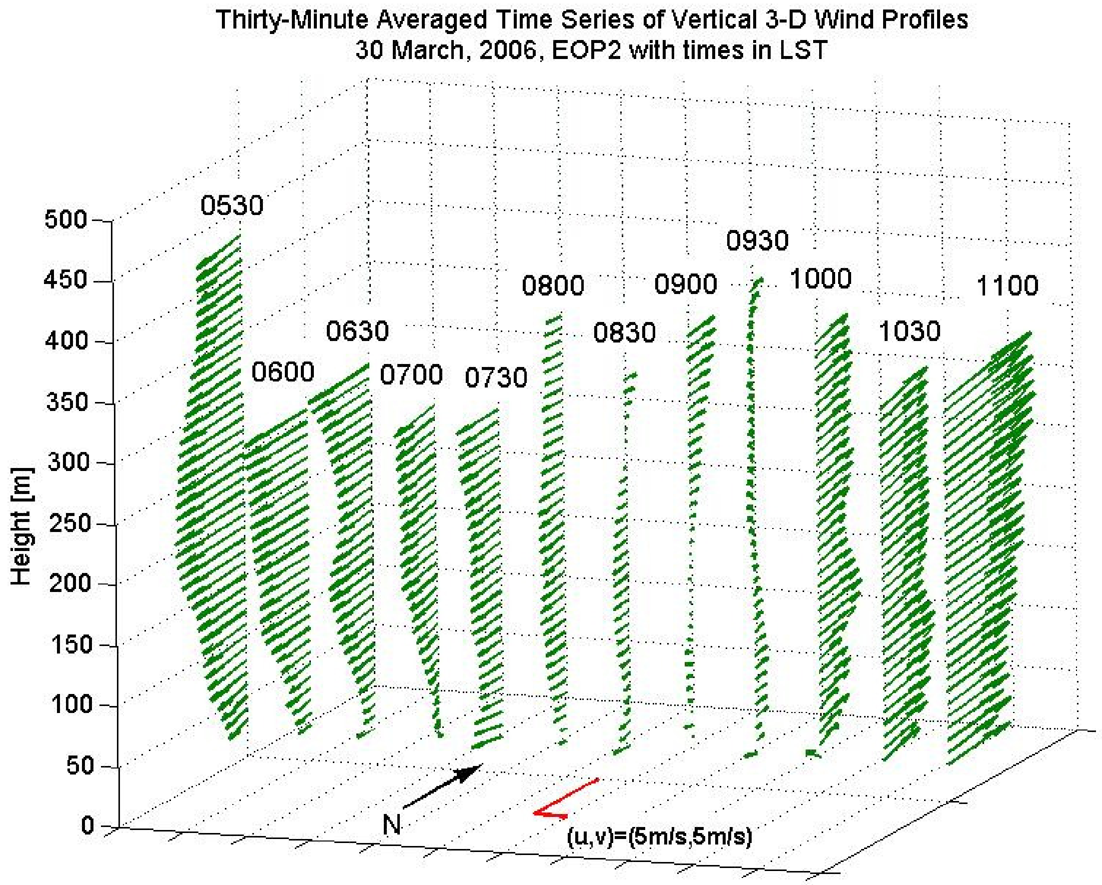
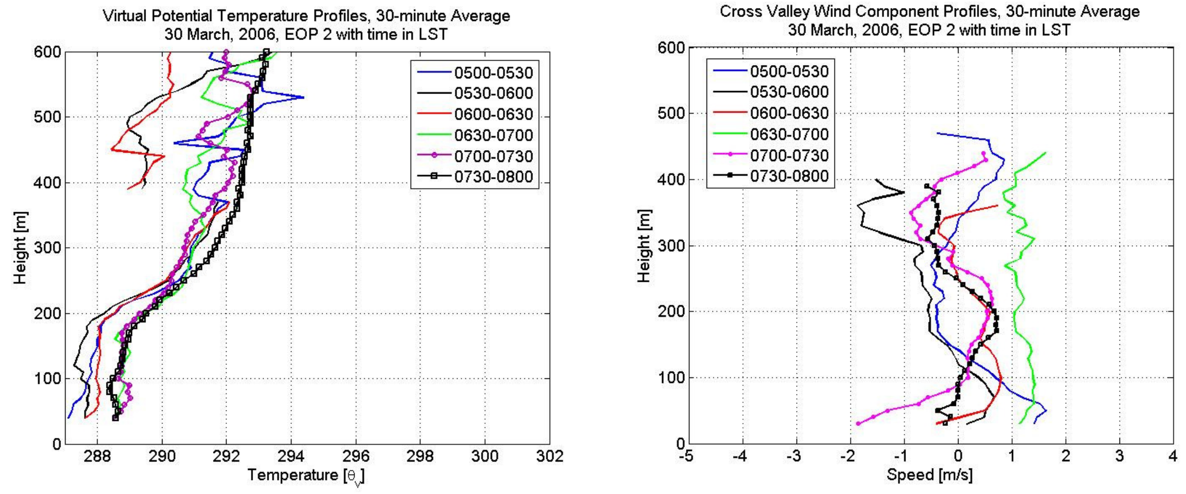
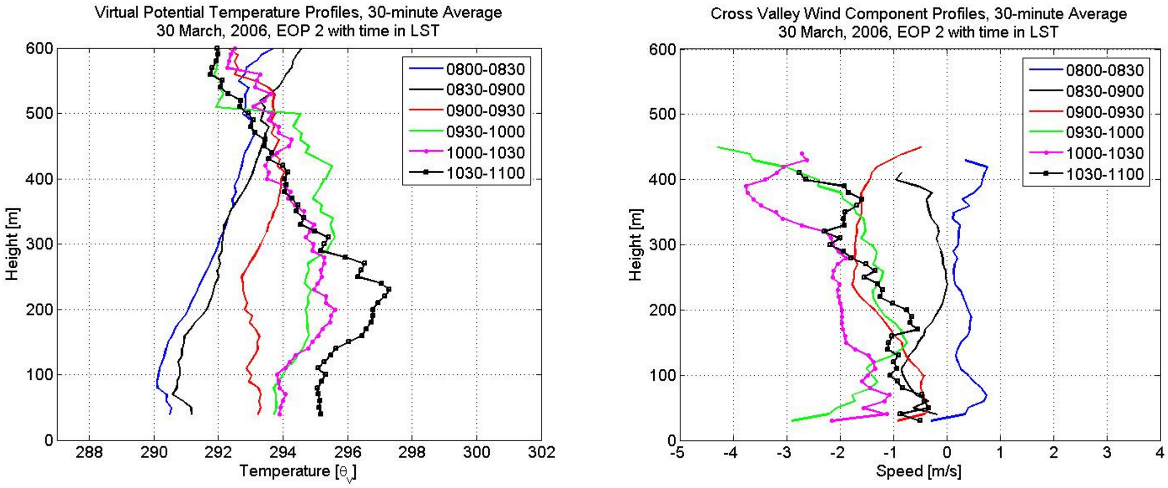


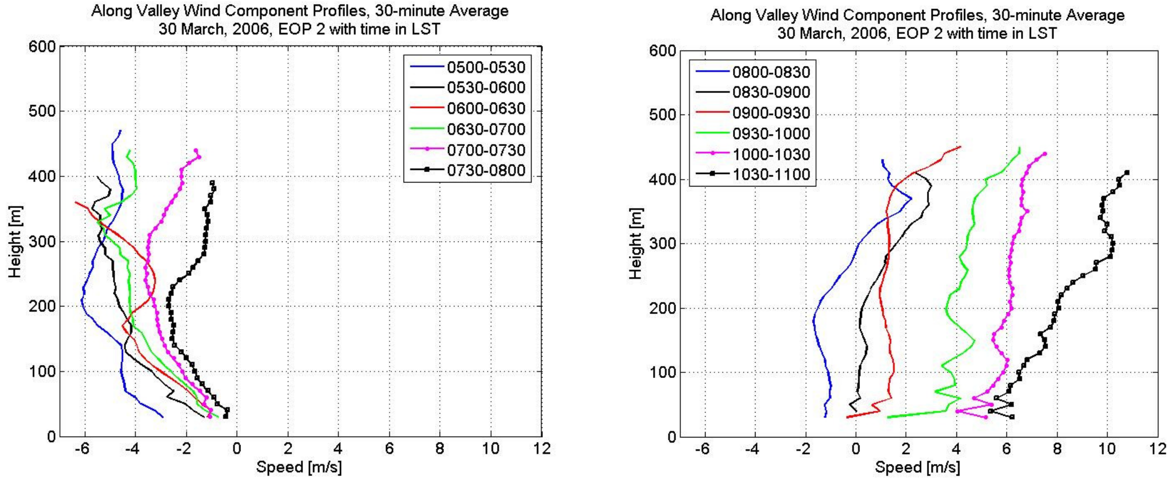
Figure 3: Three-dimensional vertical wind profiles averaged over 30 minutes from 0530-1100 on 30 March, 2006, EOP 2.



Figures 4-5: 30-minute averaged virtual potential temperature profiles from 0500-0800 with concurrent cross-valley wind profiles during EOP 2. Note that a positive cross-valley wind component is down slope.



Figures 6-7: 30-minute averaged virtual potential temperature profiles from 0800-1100 with concurrent cross-valley wind profiles during EOP 2. Note that a positive cross-valley wind component is down slope.



Figures 8-9: 30-minute averaged along-valley wind profiles from 0500-1100 during the morning transition of EOP 2. Note that a positive along-valley wind component is up valley.

EOP No.	Start Date/Time (LST)	End Date/Time (LST)	Actual Sunrise (LT)
2	29 March 2006 1500	30 March 2006 1200	0541
3	18 April 2006 1500	19 April 2006 1200	0613
4	28 April 2006 1500	28 April 2006 1200	0600

Table 1: EOP number and its corresponding start and end date/time, with accompanying sunrise times.