Final Report for U.S. Department of Energy
Grant DE-FG02-04ER63717

Submitted by
University Corporation for Atmospheric Research
Boulder, Colorado

Final Report on the NCAR VTMX Effort

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NCAR/EOL

13 February 2007

Overview: The NCAR effort is primarily focused on the analysis of a diverse suite of measurements taken at the southern end of the Salt Lake City Valley within the Jordan Narrows. These measurements include wind profiler, surface, lidar, radiosonde, multi-layered tether-sonde and sodar measurements. We are also collaborating with other VTMX investigators through linking our measurements within the Jordan Narrows with their investigations. The instrumentation was provided to interested VTMX investigators and was used extensively (e.g., Doran et al. 2002; Monti et al. 2002; Zhong and Fast, *Mon. Wea. Rev.*, 2003; Fast, *Wea and Forecasting*, 2003; Banta et al., *J. Appl. Meteor.*, 2004; Ludwig et al., *J. Appl. Meteor*., 2004; Chen et al., *J. Appl. Meteor*., 2004; Banta et al*., J. Atmos. Sci*., 2006). Thus the NCAR data set played a large role in the results of the overall experiment.

Our work under this proposal includes analysis of the observations, mesoscale modeling efforts in support of our VTMX analysis and general instrumentation development aimed at improving the measurement of vertical transport and mixing under stable conditions. This report is subdivided by research objectives.

Research questions addressed by the NCAR effort:

1. Can wind profiler technology and processing techniques be improved to make profiler observations more relevant to measurements in stable, calm environments?

Conventional wind profilers measure wind speed and direction by scanning in three to five beam directions and assuming spatial and temporal homogeneity. Thus, direct measurements of the vertical motion occur intermittently (roughly 1/3 to 1/5 of the time) and the observations of winds require significant averaging time (typically every 30 mins). We have extended our efforts to refine our spaced antenna wind profiler techniques under this proposal. The advantage of such a system is that the profiler remains continually in a vertical pointing mode so that a high temporal-resolution record of vertical motions can be obtained. At the same time, the tracking of eddies across the spaced-antenna array allow for the retrieval of high rate (typically every 1-5 mins) horizontal wind vectors as well. Cohn et al. (2000) demonstrated the utility of this technique in getting BL winds using data collected near Boulder prior to the 2000 VTMX field experiment. Cohn et al. (2001b) show examples of the continuous measurement of vertical motions by this technique, but primarily deals with the validation of relatively rapid sampling of the horizontal winds. Additional work is currently being carried out to explore the ability of a spaced antenna system to measure the vertical motions and momentum flux in a dry, cool season environment (Parsons et al. 1999; Parsons et al. 2004).

One of the primary problems with profiler data is that the systems do not have the vertical resolution to capture the fine-layered structures in the stable boundary layer. A new high resolution imaging technique called RIM or Range IMaging (Palmer et al. 1999) has been applied to MAPR with encouraging results (Yu et al. 2002, Yu and Brown, 2003). This algorithm make it possible to obtain profiles of horizontal and vertical winds that are accurate and much higher resolution than that possible with the unprocessed MAPR data. This is evident in the increased range resolution which improved from 100 meters to around 10-20 meters using RIM. The resolution of the resulting reflectivity fields approaches that seen in FMCW radar backscatter data (Brown et al. 2003). Yu et al. (2003) have shown that implementing a Full Correlation Analysis (FCA) to RIM enables the retrieval of high resolution winds. The use of RIM-FCA provides a promising solution to the bird clutter contamination problem encountered during VTMX because with such high vertical resolution, spatial filtering techniques can be applied to extract the atmospheric echoes from the highly intermittent clutter caused by bird echoes as discussed by Brown et al. (2004). The application of RIM does lead to some loss in sensitivity; however, this has been mitigated by using a transmitter that is ten times more powerful than that used on standard UHF wind profilers. These advances in both hardware and data processing techniques since the VTMX field deployment in October 2000 make the NCAR MAPR a promising system for the study of stable boundary layers in mountainous terrain in the future.

2. How do terrain-induced circulations pattern mixing and vertical transport during the VTMX field phase?

ATD scientists have collaborated with NOAA/ETL and DOE/Pacific Northwest National Laboratories to document and understand how nocturnal flow evolves across the Great Salt Lake (GSL) Valley (Banta et al. 2004) with particular interest in how nocturnal flows initiate vertical transport and mixing in the stable boundary layer (Pinto et al. 20004). Data collected with the NCAR/ATD Integrated Sounding System (ISS), which was deployed at the southern end of the GSLV and the NOAA/ETL Doppler lidar (TEACO2) revealed the presence of a low-level downvalley jet (DVJ) on 50% of the nights during a 3.5 week period in October. The jet tended to occur under clear skies and during periods of weak synoptic-scale forcing. Data collected with TEACO2 and the ISS indicated that the DVJ emerged fully formed from the Utah Lake Basin to the south and usually spanned the entire north-south length of the GSL valley. The jet typically developed by 0600 UTC (2300 MST) or about 5 hours after sunset, and continued well into the next morning, often persisting until passage of a lake breeze front generated by the GSL between 1400 and 1700 UTC.

Banta et al. (2004) hypothesized that the system of basins was acting like a large-scale valley allowing deep nocturnal flows to span wide regions of the intermountain west. Data from the ATD observation site revealed that maximum jet winds occurred between 100 and 300 m with the depth of the DVJ often spanning the depth of the entire basin. The wind profile often revealed interesting structure with multiple jet layers often being observed as well as the presence of small scale micro-jet features or regions of enhance horizontal winds in the layer of maximum jet winds. Comparisons of wind profiles from the ATD ISS and TEACO2, located 20 km to the north revealed similar flow speeds indicating little flow distortion at the ATD site by the valley side walls.

The DVJ was also observed the pulse in strength over the course of the night with period ranging from 1 to 3 hours. The low frequency pulses tended to extend through the entire depth of the jet and were observed to occur across the basin. Higher frequency pulses were only observed in the data collected at the ATD site. These pulses were smaller in amplitude and confined to the lowest few hundred meters of the jet. These pulses in wind speed are important because they are responsible for the evolution of vertical mixing in stable the nocturnal boundary. The deeper pulses are also potentially important for the vertical transport of pollutants out of the stable boundary layer, though this has not been proven.

Pinto developed a conceptual model describing how the DVJ impacted vertical mixing in the region where flow emerges from the Utah Lake Basin. The conceptual model was developed using data collected with the enhanced ISS deployed by NCAR/ATD (sodar, SABL, TAOS, and radiosondes) and PNNL sonic anemometers located at the southern end of the Great Salt Lake Basin. Offline radiative transfer calculations were made to quantify radiative cooling rate profiles. Initially, radiative cooling of the surface and turbulent diffusion dominate the heat budget resulting in strong cooling at low levels of the atmosphere and formation of a shallow cold pool in the Jordan Narrows. Flow is generally weak during this time and shifts from northerly to southerly as local terrain-induced circulations set up. Eventually, cold air building up in the Utah Lake Basin spills over the gap in the Traverse Range resulting in a rapid increase in winds in the Narrows region and setting up inter-basin exchange and a large-scale DVJ.

The formation of the DVJ results in warming at low levels (predominantly through vertical mixing of inversion layer air) and cooling aloft (via mesoscale horizontal advection). Budget analyses reveal that longwave cooling accounts for only 10-25% of the cooling observed above the inversion layer. The rest must be accounted for by the upward vertical transport and mixing of air in the cold pool and the horizontal advection of cold air. Vertical mixing of the heat deficit associated with the cold pool out of the stable boundary layer could only account for about 40% of the observed cooling aloft. Thus, at least 35-50% of the cooling observed above the surface-based inversion must have been caused by mesoscale advection of cold air associated with the DVJ. The combined effect of these processes is to reduce the stability of the NBL and to aid in its ventilation.

The pulsing flow further complicates the picture resulting in local areas of low-level convergence and periodic episodes of mixing events. It was found that pulsing flows only occurred when the surface energy budget remained negative through the night. Pinto et al. (2004b) theorized that on these nights, lulls in the winds (caused by low-level friction or drag) allowed the surface-based inversion to reform via radiative cooling, thereby decoupling the flow from the surface once again. The pulsing flow itself results in local areas of convergence which may help to ventilate the NBL during brief episodes.

Mesoscale modeling studies using the Penn State/NCAR mesoscale model (MM5) have revealed that the circulations span multiple basins, making it a very non-local problem. While the general structure and timing of the nocturnal downvalley jet were handled by its modeled depth, intensity and temporal evolution were poorly simulated indicating the difficulties inherent in simulating nocturnal circulations characterized by high stability in regions of complex terrain (Pinto et al. 2002).

The jounral article on this effort was “Coevolution of Down-Valley Flow and the Nocturnal Boundary Layer in Complex Terrain” by Pinto et al., *Journal of Applied Meteorology and Climatology* (2006). This article showed that the organized mixing that is associated with down valley flow due to Kelvin-Helmholtz waves at the interface between the downvalley flow and flow within the basin. This non-linear mixing is treated inadequately in current model parameterizations utilized for stable flows with Monin-Obukhov similarity theory which has major implications for treating nocturbal boundary layers in stable terrain. This work has led us to one more investigation on the impacts of radiational cooling vs drainage and downvalley flows on the depth and intensity of the inversion.

3. How do we best measure mixing and vertical transport in stable nocturnal environments?

The NCAR/ATD instrumentation included lidar, acoustic, in-situ, radar (i.e., profiler) and surface techniques into a single integrated sounding system allowing us to provide some insight into the best techniques for observing vertical transport and mixing in a shallow stable boundary layer. The findings can be summarized as follows:

a) The environmental conditions that produce the strong inversions (a very dry boundary layer with light winds) make it challenging to use active profiler techniques as the same conditions are associated with low values of backscatter (Cohn et al. 2001a). In addition, the mountain valleys are known to serve as migration routes for birds which tend to flock at night in numbers large enough to make it nearly impossible to recover clear air signals throughout the night. The application of RIM and a spatial filter may allow for retrieval of clear air signal at night; however, this remains to be demonstrated. To address the problem of low backscatter in the inversion environments, the power of MAPR’s transmitter can be increased, (we now use a new stronger transmitter in MAPR) and use either pulse coding (this was not available during VTMX) or the acoustic shell generated by continuous operation of RASS (we have begun to test such an approach).

b) The lidar techniques provide numerous qualitative images of mixing and vertical transport when there are gradients in the aerosol backscatter. These conditions often occur near the top of the nocturnal boundary layer. We have found one case where we believe we have recovered quantitative mixing with breaking waves at the top of the down-valley flow through making several reasonable assumptions. One of these assumptions is that the overall time tendency in the backscatter is removed as the mixing event is associated with an increase of wind speed and a general change in the backscatter values apart from the mixing.

c) In-situ sensors work well, including our TAOS multi-level tether system, for mean values. Tower based measurements or sonics on a tethered system would obtain some provides some direct measurement of mixing. Since we show mixing occurs in the lowest 100 m, towers and tethers are possible approaches.

d) Acoustic techniques showed reliable performance with some increase in backscatter as the inversion strength increases in contrast to the difficulties with profiler measurements. We have observed some direct increase in the variance in the acoustic vertical velocity when we believe mixing is taking place in the lower levels of the nocturnal down-valley flow as well as direct measurement of vertical motions associated with waves or mesoscale flow features. Lidar and sodar measurements have also been combined to show vertical transport of aerosol (Brown et al. 2000, Brown et al. 2002).

4. Collaborations

a) James Pinto collaborated with the NOAA/ETL group on placing our local measurements within the context of the basin-wide lidar observations. It was found that the downvalley flow emerged fully formed from the Utah Lake Basin on a number of occasions with large amplitude variations in the downvalley flow strength occurring nearly simultaneously across the basin. On these nights the interconnected basins appear to behave as a long valley with the gap in the Tranverse Mountain Range acting to accelerate the flow through Jordan Narrows. James Pinto has also begun collaborating with K. Costigan (Los Alamos National Labs) on the origins of cold air in the connected basin system.

b) David Parsons is collaborating with Will Shaw and Rich Coulter providing lidar estimations of boundary layer depth. Our measurements also show that a collapse of the boundary layer often occurs during the afternoon hours even at the NCAR site in the narrows. The measurements suggest a coupling of the two valleys with the possibility that both basins show a subsidence response to upslope ascent in response to heating. The third site near the slope [Rich Coulter's data] shows a weaker collapse. The findings indicate pollution will reside within a shallower layer during the afternoon than originally thought.

c) Numerous VTMX groups have used the ATD data sets in their process study research and model initialization/validation work.

d) David Parsons has had discussions with several VTMX investigators about coordinating research for processes in the vicinity of the Jordan narrows.

Products delivered:

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