11.7 THE INTERACTION OF THERMALLY-DRIVEN CIRCULATIONS AND THEIR EFFECT ON VERTICAL MIXING PROCESSES IN THE SALT LAKE VALLEY

Jerome D. Fast
Pacific Northwest National Laboratory, Richland, Washington

1. INTRODUCTION

Our understanding of how various meteorological processes redistribute pollutants within basin and valley atmospheres at night has been limited by a lack of observations. Pollutants released within the stable boundary layer may remain highly concentrated since the strong atmospheric stability and weak turbulent motions limit the amount of vertical diffusion. Complex flows associated with basin and valley topography, however, can complicate the vertical distribution of pollutants.

In this study, a mesoscale model, a Lagrangian particle dispersion model, and the extensive observations made during the Vertical Transport and MiXing (VTMX) field campaign are used to examine the interaction of thermally-driven valley, canyon, and slope flows and their effect on tracer transport and turbulent mixing. The mesoscale model predictions have been compared with data from surface stations, sonic anemometers, radiosondes, radar wind profilers, and a Doppler lidar. The predicted mean winds and turbulence quantities from the mesoscale and dispersion models are compared with data from a series of perfluorocarbon tracer (PFT) release experiments that provide quantitative information concerning transport and turbulent mixing patterns during the evening and morning transition periods. The models are also used to describe how mean vertical motions and turbulence associated with converging flows affect the horizontal and vertical distribution of tracers in the Salt Lake Valley. Some of the VTMX measurements are described next, followed by a discussion of the model results.

2. VTMX FIELD CAMPAIGN

2.1 *Instrumentation*

A meteorological field campaign sponsored by the U.S. Department of Energy (DOE) Atmospheric Sciences Program was conducted in the Salt Lake Valley during October 2000 that focused on nocturnal stable periods and morning and evening transition periods. As described by Doran et al. (2002), a wide range of remote sensing and in situ measurements were made including those from surface meteorological stations, sonic anemometers, temperature data loggers, rawinsondes, tethered balloons, radar wind profilers, sodars, and lidars. The NOAA Environmental Technology Laboratory (ETL) Doppler lidar (Banta et al. 2002) and the NOAA Air Resources Laboratory (ARL) radar wind profiler sites are shown in Fig. 1. Ten intensive operational periods (IOPs) were conducted during October 2000. Each IOP began in the late afternoon at 15 MST and ended the following morning at 09 MST. Much of the instrumentation operated continuously, but the rawinsondes, tethered balloons, and lidars were only operated during the IOPs.

The PFT experiments were designed to measure dispersion within the valley on scales of 5 – 50 km during the nighttime stable conditions and the morning transition period to elucidate convergence and divergence patterns in the valley as well as the interactions of slope flows with cold pools for six of the IOPs. The tracer experiments started at 22 MST on 6, 8, 14, 17, 19, and 25 October during IOPs 2, 4, 5, 7, 8, and 10, respectively. Four tracers (PDCB, oPDCH, PMCP, and PMCH) were released, each at a separate location as shown in Fig. 1. Two tracers were released downtown at a constant release rate for 6 h between 00 and 06 MST - one at the surface and the other on the top of a building at 35 m AGL. The other two tracers were released south of downtown at a constant rate for 8 h between 22 and 06 MST. The PDCB and PMCP sites were chosen to release tracers within canyon and down-valley flows, respectively. Two-h samples were collected at 50 sites throughout the valley between 22

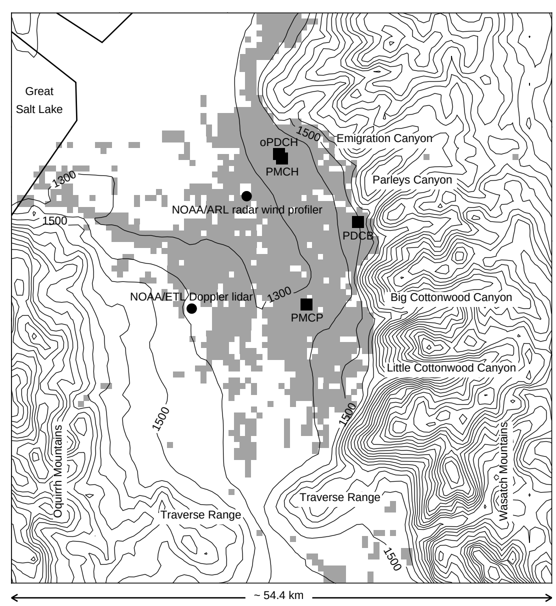

Fig. 1. Topography of the Salt Lake Valley (contour interval of 100 m) from the innermost nested grid of the mesoscale model and the locations of selected instrumentation sites discussed in this paper. Shading denotes residential and commercial urban areas.

**Corresponding author address:* Jerome D. Fast, Pacific Northwest National Laboratory, P.O. Box 999, K9-30, Richland, WA 99352, e-mail:jerome.fast@pnl.gov

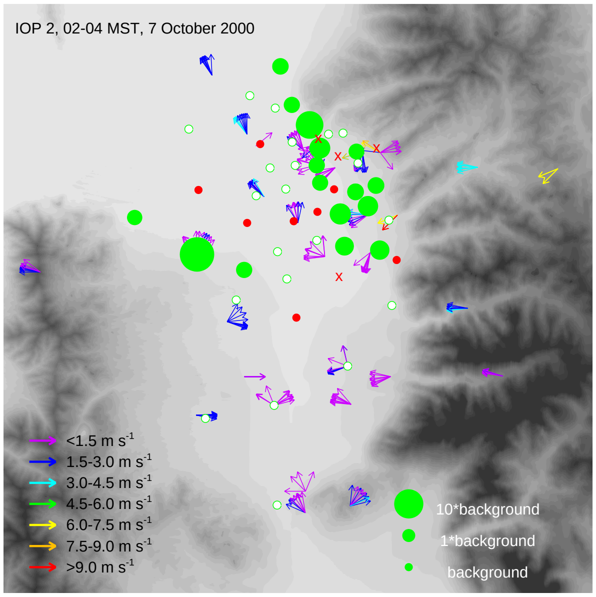

Fig. 2. Contours of topography (shaded,) near-surface observations of winds at 15-min intervals, and concentrations of PDCB for 02-04 MST during IOP 2. White filled circles denote samplers measuring background concentration and red filled circles denote missing data.

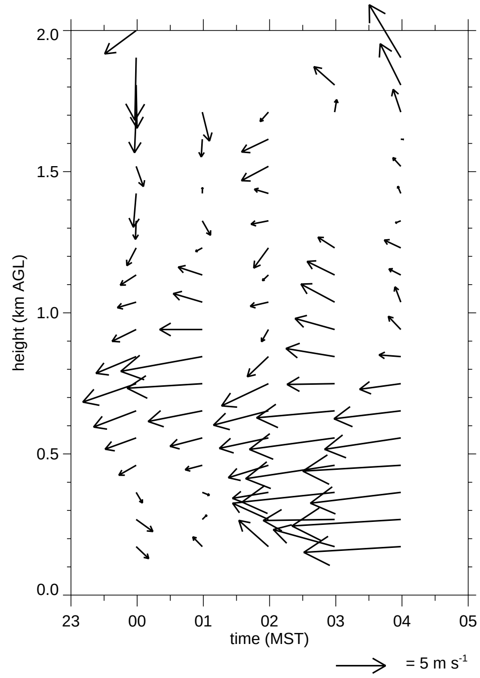

Fig. 3 Wind profiles from the NOAA / ARL radar wind profiler between 00 and 04 MST during IOP 2.

and 12 MST the following day. Most of the samplers were located at 3 m AGL; however, four samplers were located on building tops at elevations of 27, 36, 56, and 121 m AGL (http://www.pnl.gov/atmos_sciences/Jdf/design.html). Data from the building top samplers and the samplers located along the slopes provide information on the vertical extent of mixing above the valley floor. In addition to providing the PFT tracers and samplers, scientists at Brookhaven National Laboratory (BNL) analyzed approximately 2000 samples after the field campaign (Dietz 1986).

Thermally-driven circulations, including nocturnal down-slope, down-valley, and canyon flows, were observed by VTMX instrumentation when the synoptic forcing was weak. The winds at the surface were usually characterized by drainage flows during the entire evening; however, the winds a few hundred meters AGL were more variable. At times, southerly down-valley flow occurred throughout most of the valley atmosphere with the strongest wind speeds in the valley center. At other times the down-valley flow was weak and strong canyon flows propagated across the valley. Meteorological and tracer data from two contrasting IOPs are presented next to illustrate the dispersion patterns associated with canyon and down-valley flows.

2.2 *Observations during IOP 2*

During IOP 2, a strong outbreak of cold air east of the Continental Divide in Wyoming that propagated westward 2 (Doran et al. 2002; Holland 2002). Strong easterly flow developed through gaps in the Wasatch Mountains and spilled into the valley by midnight.

Concentrations of PDCB between 02 and 04 MST and the winds at 15-min intervals during the 2-h period are shown in Fig. 2. Prior to 02 MST, PDCB tracer released from the base of Parleys Canyon at an elevation of about 150 m above the valley floor was transported to the northwest as the northeasterly canyon outflow merged with the down-valley flow (not shown). Between 02 and 04 MST, concentrations of PDCB were observed at three sampler sites on the west side of the valley even though most of the tracer was transported to the northwest. Near-surface winds in the central valley were southerly and less than 2 m s^{-1}, but the winds measured by the NOAA radar wind profiler (Fig. 3) became easterly between 150 and 800 m AGL with a sharp increase in wind speeds to around 10 m s^{-1}. The meteorological observations suggest that PDCB was transported across the valley over the cold pool and then mixed to the surface. An increasing number of samplers in the valley center measured PDCB after 04 MST as the easterly flow continued (not shown). The strong vertical wind shears likely produced mechanical turbulence that mixed the tracer downwards.

2.3 Observations during IOP 4

Prior to 05 MST during IOP 4, clear skies, weak winds aloft, and strong surface-based radiation inversions prevailed. As a result of an approaching upper-level trough, southerly winds aloft became stronger and modified the valley winds and eroded the nocturnal inversions.

While the near surface winds between 02 and 04 MST shown in Fig. 4 were similar to those during IOP 2, the wind speeds at the base of Parleys Canyon were

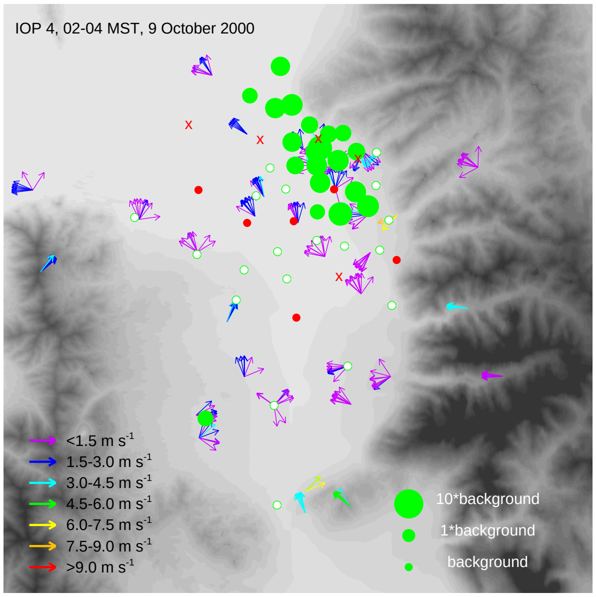

Fig. 4. Same as Fig. 2, except during IOP 4.

about 2 m s^{-1} lower. In contrast with IOP 2, no cross-valley transport of PDCB occurred between 02 and 04 MST. None of the samplers located over the western valley measured PDCB during the entire evening. Tracer distribution at the surface extended further north and west than the tracer plume during IOP 2.

The wind speeds at the base of Parleys Canyon were as high as 9 m s^{-1}, but the strength of the outflow diminished over the valley center as indicated by the southeasterly wind speeds less than 5 m s^{-1} between 150 and 500 m AGL at the NOAA radar wind profiler (Fig. 5). Above 500 m AGL, the moderate southerly winds were associated with the upper-level trough and the wind speeds became stronger after 05 MST. Apparently, the weaker canyon outflow prevented PDCB from being advected to the western side of the valley. Instead, PDCB was transported to the northwest within the down-valley flow the entire evening.

3. MODELING

It is not clear from the data alone what are all of the processes responsible for the PDCB distribution shown in Figs. 2 and 4. For example, samplers located 100 to 200 m above the valley floor along the northeast slopes of the valley measured PDCB. One possibility is that the tracer remained lofted above the stable layer so that the plume intersected the valley slope sites and turbulent processes mixed a portion of the plume downward to the valley floor. Another possibility is that PDCB was transport by canyon outflow as it descended into the valley and was subsequently mixed upward to the valley slope sites. Samplers along the valley slopes and downtown building tops during all the IOPs frequently measured high concentrations of one or more of the tracers, indicating that they were not trapped within the shallow very stable layer. Two models are therefore employed to provide additional information on the horizontal and vertical wind and tracer distributions.

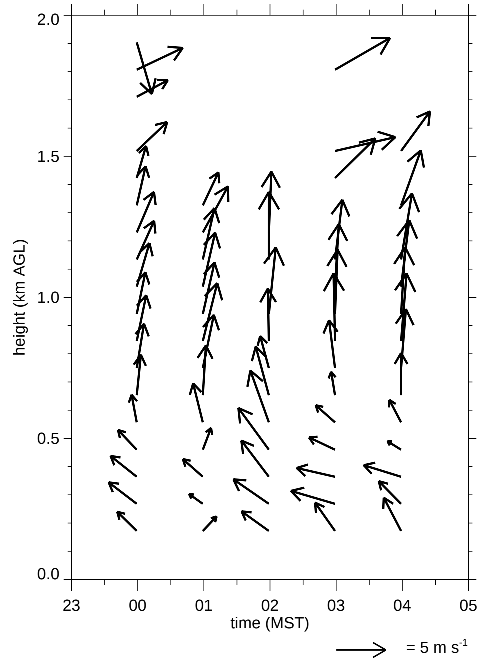

Fig. 5. Same as Fig. 3, except during IOP 4.

3.1 Model Description

The RAMS mesoscale model (Pielke et al. 1992) was run for eight of the ten VTMX IOPs to simulate the boundary layer structure and circulations in the valley. Five nested grids were used with grid spacings of 45, 15, 5, 1.7, and 0.56 km. The outer grid encompassed the western U.S. while the inner grid encompassed the Salt Lake Valley and the surrounding mountains and was the same size as the region shown in Fig. 1. The model employs a terrain-following vertical coordinate and in this study the vertical grid spacing gradually increased from 15 m adjacent to the surface to 500 m near the model top at 12 km MSL. Due to the staggered vertical coordinate, the first grid point was 7.5 m AGL.

The turbulence parameterization consists of a simplified second-order closure method that employs a prognostic turbulence kinetic energy (TKE) equation. Cumulus and cloud microphysics parameterizations were not activated because of the mostly clear conditions observed during the VTMX IOPs. For the outer grids, vegetation type was based on a 1-km U.S. Geological Survey (USGS) data set, while a higher resolution USGS data set was used that also had a more realistic distribution of urban land use for the inner grid. The temperature of the Great Salt Lake was set to 14 C, based on observations made during October. Initial and boundary conditions were based on the NCEP's AVN model and operational upper-air soundings.

The HYPACT Lagrangian particle dispersion model (Tremback et al. 1994) was run for the six tracer experiments to simulate the tracer distribution using the predicted wind fields. Particles were released at a constant rate at the PFT release sites shown in Fig. 1

during the release periods. By scaling the number of particles released with the PFT release rates, observed and simulated concentrations can be directly compared in units of femtoliters per liter (fL L^{-1}).

3.2 Model Results

A comprehensive evaluation of the wind, temperature, and humidity fields predicted by RAMS using data from surface meteorological stations, radiosondes, and radar wind profilers is given in Zhong and Fast (2003). More recently, Fast and Darby (2003) have evaluated the spatial characteristics of the predicted wind fields using Doppler lidar measurements made over the valley.

Scans from the Doppler lidar for IOPs 2 and 4 are shown in Figs. 6a and 7a. The figures depict the radial wind velocities along a 1.0^{o} elevation scan close to 03 MST, the mid point of the tracer measurements between 02 and 04 MST (Figs. 2 and 4). Red and blue denotes flow towards and away from the lidar, respectively. Note that data near the lidar are close to the surface, while the data near the valley center are about 250 m AGL. During IOP 2, wind speeds as high as 12 m s^{-1} were observed near the base of the Wasatch Mountains and the flow exiting Parleys and Emigration Canyons propagated over the valley center. The lidar scan during IOP 4 indicated weaker northeasterly canyon outflow that converged with strong southerly down-valley flow 5 to 7 km northeast of the lidar.

The simulated radial velocities shown in Figs. 6b and 7b are obtained by first computing the radial velocities on each model grid point based on the lidar location. Then, the velocities are interpolated vertically to correspond to the elevation scans made by the lidar between 0.5 and 3 degrees. Also shown are the horizontal winds that depict the actual simulated wind direction. The model predicted radial velocities are qualitatively similar to the lidar measurements. During IOP 2, the model predicted distinct outflows from Parleys and Emigration Canyons, and to a lesser extent Big Cottonwood Canyon. The simulated northwesterly flow south of the lidar was stronger than the observations, indicating that the down-slope winds over the lower slopes of the Oquirrh Mountains were too strong. During IOP 4, the down-valley flow was similar to observed, but the convergence of the canyon and down-valley flows occurred a few km northeast of the observed convergence zone.

In general, there were periods during the other IOPs when the model performance was better and worse than shown in Figs. 6 and 7. Most of the errors were associated with the timing of the down-valley flow onset and the magnitude of the canyon wind speeds that affected the location of the convergence in the valley.

The predicted tracer concentration fields that correspond to the PDCB measurements between 02 and 04 MST are shown in Figs. 8 and 9. The model qualitatively reproduced the observed spatial tracer distributions for both periods. During IOP 2 (Fig. 8), particles were transported within the near-surface down-valley flow; however, a fraction of the particles were also transported across the valley by the easterly Parleys Canyon outflow. The vertical cross section

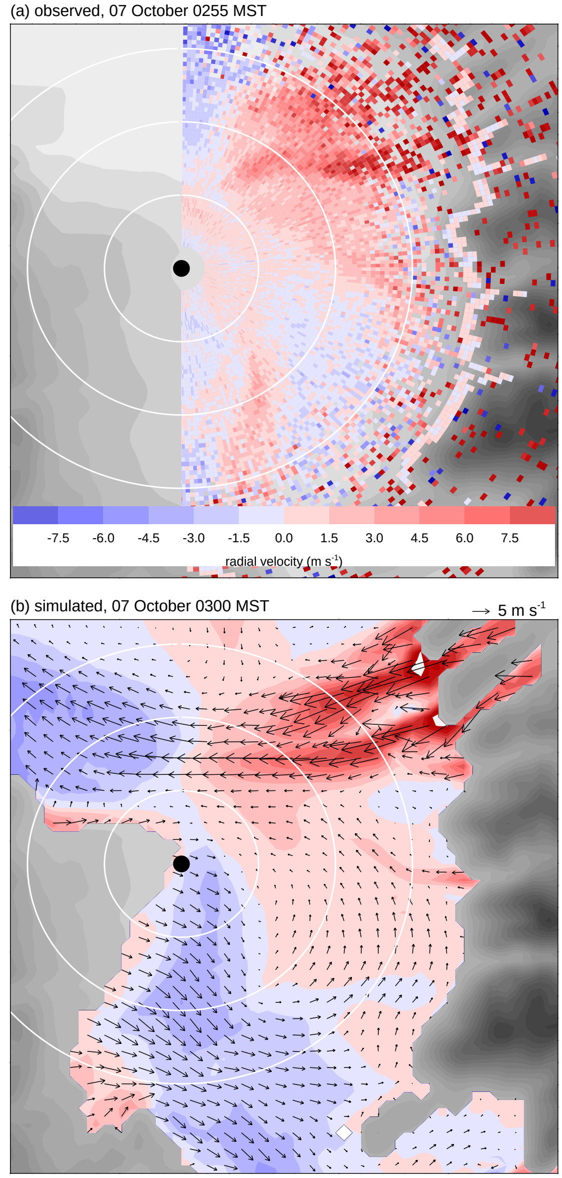

Fig. 6. (a) Observed and (b) simulated radial velocities along a 1.0^{o} elevation scan at 03 MST during IOP 2. Red and blue indicates flow towards and away from the lidar, respectively. Arrow denote simulated horizontal wind direction and speed and circles denote distances of 5, 10, and 15 km from the lidar.

shows that particles released at the base of Parleys Canyon were mixed vertically several hundred meters above the surface by positive vertical velocities as large as 40 cm s^{-1} and TKE as large as 1 m^{2} s^{-2} associated with a hydraulic jump. The relatively large TKE values are generated by the large vertical wind shears. Easterly winds between 200 and 500 m AGL, consistent with the profiler data, transported a portion of the particle plume over the very stable layer in the valley center. Note that rising motions between 1 and 5 cm s^{-1} were simulated over the western valley; however, downward transport of particles began 1-2 h earlier when

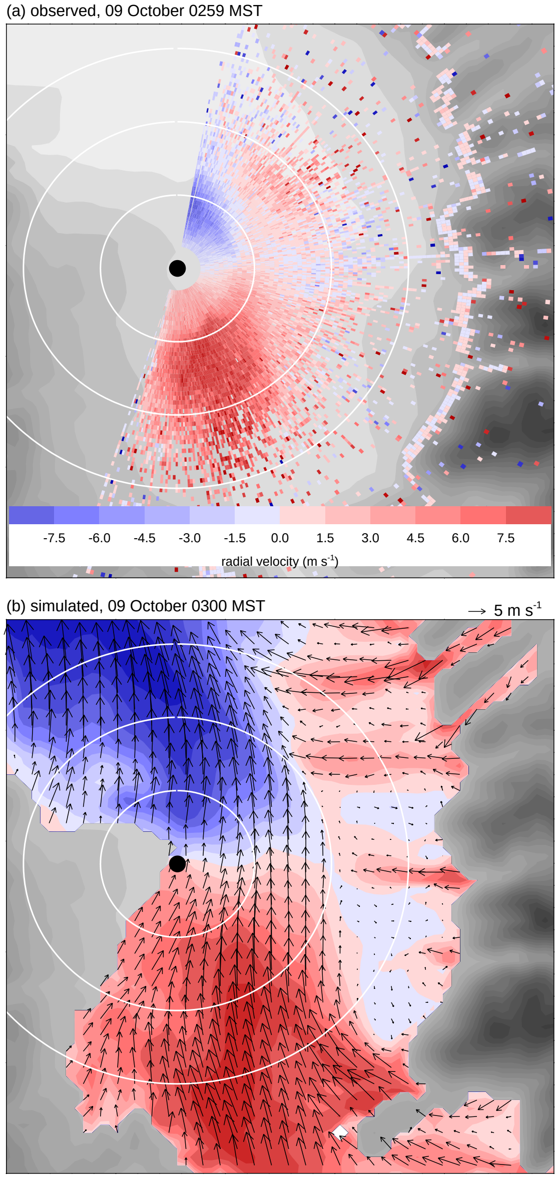

Fig. 7. Same as Fig. 6, except for IOP 4.

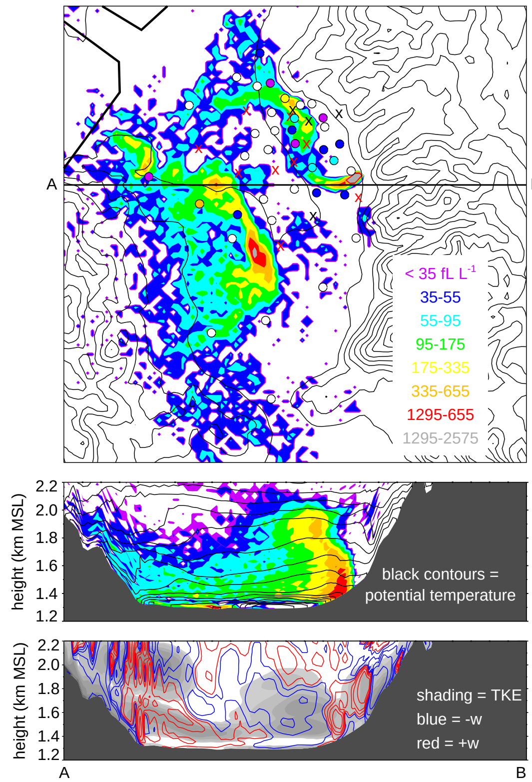

Fig. 8 Observed and simulated surface PDCB distribution between 02 and 04 MST and vertical cross-section of predicted concentrations, TKE, and vertical velocities (contours of 1, 5, 10, 20, and 50 cm s^{-1}).

sinking motions occurred over a large area of the northwestern valley. Mean sinking motions and turbulent mixing were both responsible for the downward transport. The simulated peak concentrations of 335-655 fL L^{-1} along the lower slopes of the Oquirrh Mountains were only a few km northeast of a sampler that measured similar concentrations. While there were no particles at the surface in the valley center consistent with the observations, the model transported particles to the southern end of the valley where no PDCB was measured at this time.

During IOP 4 (Fig. 9), the simulated tracer plume remained over the eastern side of the valley the entire evening, consistent with the PFT measurements. Although the magnitude of the predicted concentration was too high between 02 and 04 MST at a couple of samplers close to the release site, the concentrations at the other samplers were similar to the observations. Outflow from Parleys canyon vertically mixed particles a few hundred meters above the ground, but the vertical extent was lower than during IOP 2. The vertical velocity pattern along the slopes of the Wasatch Mountains was similar to IOP 2, but the amount of predicted TKE was much smaller as a result of the weaker canyon outflow.

To examine the ventilation rates in the valley, another set of HYPACT simulations were performed for eight of the VTMX IOPs. In these simulations, particles were released continuously from the area over the valley center denoted by the gray shading in Fig. 10 between 19 and 07 MST. The fraction of particles remaining over the valley (within the larger box) was lowest during IOPs 4, 7, and 10. These IOPs were characterized by Doran et al. (2002) as having the strongest synoptic influence and, therefore, the highest wind speeds in the mid-valley atmosphere. IOP 2, with the down-slope windstorm event, had the highest particle fraction. Despite the high wind speeds associated with the canyon outflow (Fig. 6), it was the least ventilated evening. The down-slope winds started earlier in the evening during IOP 3 than IOP 2; therefore, the ventilation rates was higher prior to midnight. For both IOP 2 and 3, particles were transported south across the Traverse Range into the Provo Valley around midnight. Particle fraction for IOPs 5, 6, and 8 with well-developed drainage circulations had particle fractions

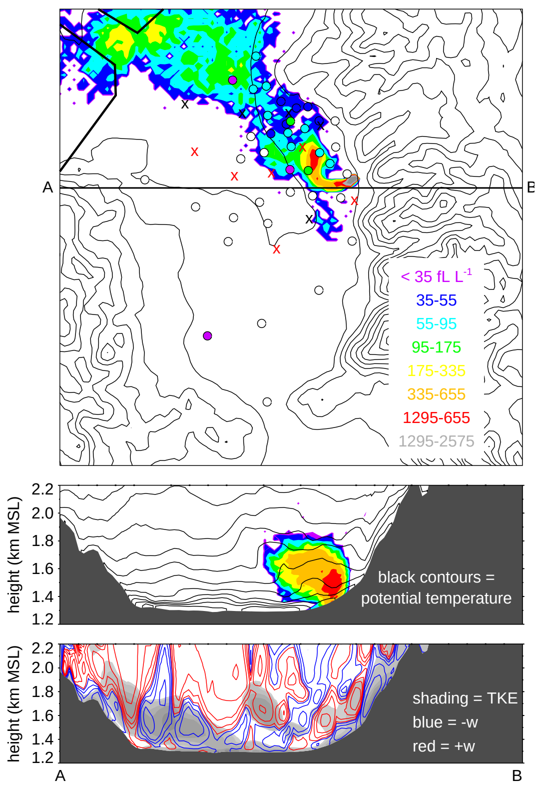

Fig. 9. Same as Fig. 8, except for IOP 4.

between those of the down-slope windstorm and synoptic IOPs. The light winds during the transition period between the up-valley and down-valley flows produced lower ventilation rates than the synoptic IOPs. IOP 8 had a lower ventilation rate than IOPs 5 and 6 because the down-valley flow began several hours later during that evening.

To examine the relative contribution of mean vertical motions and turbulent mixing on the distribution of particles, additional HYPACT simulations were performed that set the mean vertical velocities to zero. The resulting dispersion patterns were similar to those in Figs. 8 and 9, but the magnitudes of the concentrations were significantly different. Removing vertical motions changed the particle fraction in Fig. 10 by as much as 5% because the neglect of vertical velocity changed the only the vertical distribution.

4. SUMMARY

As expected, the tracer distributions were largely determined by the horizontal transport within nocturnal drainage circulations, however the data and model results also illustrated the effects of vertical mixing processes. Some of the findings so far include:

- simulated tracer concentrations were often consistent with the PFT data, suggesting that the model produced most of the observed features of the valley circulations during those times
- despite the strong near-surface stability and low wind speeds, the PFTs were often well dispersed in the horizontal and vertical
- tracers were confined to the eastern valley during typical canyon outflow conditions; conversely, strong canyon outflow produced cross-valley transport and downward mixing
- through a series of sensitivity simulations it was found that turbulence was largely responsible for transporting tracer above the very stable layer; still, the magnitude of the predicted vertical velocities (often > 5 cm s^{-1} as a result of converging flows) was large enough to significantly modulate vertical dispersion and change tracer concentrations

The findings concerning the relative importance of turbulent mixing and mean vertical motions depend on the performance of the mesoscale model. While the model reproduced most of the observed features of the mean flow, it is not perfect and does not adequately simulate turbulence within the stable boundary layer (Fast and Shaw 2002). It is widely known that the turbulence parameterizations in mesoscale models are not adequate during these conditions, which is a subject of on-going research.

Acknowledgments. I would like to than Lisa Darby and Bob Banta (NOAA/ETL) for providing the Doppler lidar data and Kirk Clawson (NOAA/ETL) for providing the radar wind profiler data. The assistance of Jerry Allwine (PNNL), Joel Torcolini, and Russell Dietz (BNL) was critical during the PFT experiments and is greatly appreciated. This work was supported by the U.S. Department of Energy, under the auspices of the Atmospheric Sciences Program of the Office of Biological and Environmental Research. Pacific Northwest National Laboratory is operated for the U.S. DOE by Battelle Memorial Institute.

REFERENCES

Banta, R.M., L.S. Darby, B.W. Orr, and C.-J. Zhu, 2002: Down-basin drainage jet observed during VTMX: Large-scale controls and effects on local-scale flows. Preprints, *10th Conference on Mountain Meteorology and MAP Meeting*. Amer. Meteor. Soc., Park City, UT, 1.

Dietz, R.N., 1986: Perfluorocarbon tracer technology. *Regional and Long-Range Transport of Air Pollution*, Elsevier Science Publishers, 215-247.

Doran, J.C., J.D. Fast, and J. Horel, 2002: The VTMX 2000 campaign. *Bull. Amer. Meteor. Soc*. 83, 537-551.

Fast, J.D., and L.S. Darby, 2003: The interaction of down-valley and canyon flows and their effects on mean vertical motions and ventilation during stable conditions. To be submitted to J. *Appl. Meteor.*

Fast J.D., and W.J. Shaw, 2002: Observed and simulated turbulence kinetic energy and dissipation profiles in an urban valley during VTMX 2000. Preprints, *15th Symposium on Boundary*

Layers and Turbulence. Wageningen, Netherlands, Amer. Meteor. Soc., 638-641.

Fast, J.D., K.J. Allwine, J.C. Torcolini, and R.N. Dietz, 2002: Perfluorocarbon tracer experiments during VTMX 2000. Preprints, *10th Conference on Mountain Meteorology and MAP Meeting*. Amer. Meteor. Soc., Park City, UT, 42-45.

Holland, L.D., 2002: Downslope windstorms along the Wasatch Front. M.S. Thesis, Univ. of Utah, 86 pp.

Pielke, R. A., W. R. Cotton, R. L. Walko, C. J. Tremback, W. A. Lyons, L. D. Grasso, M. E. Nicholls, M. D. Moran, D. A. Wesley, T. J .Lee, and J. H. Copeland, 1992: A comprehensive meteorological modeling system – RAMS. *Meteor. Atmos. Phys.*, 49, 69-91.

Tremback C.J., W.A. Lyons, W.P. Thorson, R.L. and Walko, 1994: An emergency response and local weather forecasting software system. Preprints, *Eighth Joint Conference on the Applications of Air Pollution*, Nashville, TN, Amer. Meteor. Soc., 219-233.

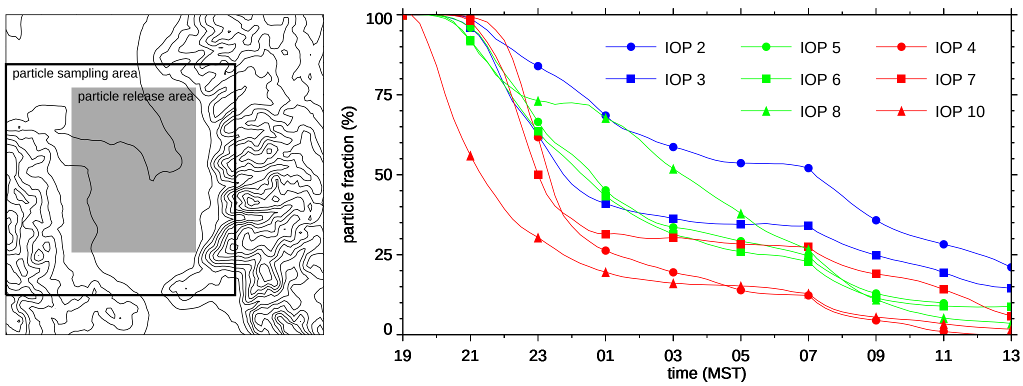

Fig. 10. Percent of particles released continuously between 19 and 07 MST (shading) that remain over the Salt Lake Valley (black box) for eight IOPs. Blue, green, and red denote IOPs characterized by down-slope windstorms, well-developed thermally-driven circulations, and thermally-driven circulations modified by synoptic forcing, respectively.