Research Proposal

CONVERGENCE AND DIVERGENCE WITHIN A BASIN AND ITS EFFECT ON THE VERTICAL MIXING OF POLLUTANTS

submitted under Program Announcement LAB99-03
in Categories 2, 3, and 4
Environmental Meteorology Program , Vertical Transport and Mixing (VTMX)
to DOE's Office of Science, Germantown, MD

by
Pacific Northwest National Laboratory

Principal Investigator:

Jerome D. Fast, Ph.D.
Senior Research Scientist
(509) 372-6116
(509) 372-6168 fax
Jerome.Fast@pnl.gov

P. O. Box 999
Richland, WA 99352

Official Signing for Laboratory:

W. T. Pennell, Ph.D., Manager
Atmospheric Sciences and Global Change
(509) 372-6256
(509) 372-6153 fax
William.Pennell@pnl.gov

CONVERGENCE AND DIVERGENCE WITHIN A BASIN AND ITS EFFECT OF THE VERTICAL MIXING OF POLLUTANTS

Principal Investigator
Jerome D. Fast
Pacific Northwest National Laboratory

TABLE OF CONTENTS

ABSTRACT 1
NARRATIVE 2
1. Background and Significance 2
   1.1 Basin Meteorological Processes 2
   1.2 Objectives of the Proposed Research 3
   1.3 Relevance of the Proposed Research 4
2. Preliminary Studies 5
   2.1 Completed Studies 6
   2.2 Ongoing Studies 7
3. Research Design and Methods 8
   3.1 Measurements 9
      3.1.1 Existing instrumentation 9
      3.1.2 Field campaign instrumentation 9
   3.2 Analyses 15
      3.2.1 Layering within the basin atmosphere 15
      3.2.2 Convergence and divergence within the basin atmosphere 16
      3.2.3 Multi-scale interactions within the basin atmosphere 18
   3.3 Modeling 19
      3.3.1 Model description 19
      3.3.2 Model experiments 20
   3.4 Project Personnel 24
   3.5 Project Schedule 24
   3.6 Relation to Other Proposals 25
4. Subcontract or Consortium Arrangements 26
5. Summary 26
LITERATURE CITED 27

ABSTRACT

We propose a 4-year program to 1) determine the spatial and temporal distribution of vertical motions resulting from convergence and divergence within a basin and their effect on mixing of near-surface emissions during stably stratified conditions and 2) determine how multi-scale flows interact to either enhance or suppress the mixing of pollutants within a basin. Our hypothesis, which forms the basis of our proposed research, is that *the mean vertical motions within a basin can be large enough to significantly affect the vertical transport and mixing of pollutants in stable conditions and to produce layers of pollutants within the basin atmosphere*. An accurate representation of the four-dimensional dynamic and thermodynamic fields in areas of complex terrain is required to examine this issue. We present an integrated measurements, analysis, and numerical modeling approach that will enable us to describe the characteristics of the convergence and divergence fields and the meteorological processes by which near-surface emissions along the basin floor are transported upwards and downwards within the basin atmosphere during stable conditions. Analyses will performed using measurements obtained from radar wind profilers, sodars, airsondes, backscatter lidar, and perfluorocarbon tracers during a fall or winter field campaign in the Salt Lake City basin. A series of modeling studies, with and without four-dimensional data assimilation, will be performed using a coupled mesoscale meteorological and Lagrangian particle dispersion model to elucidate the interactions of synoptic, mesoscale, microscale, and boundary layer processes responsible for the vertical advection and diffusion of pollutants.

NARRATIVE

1. Background and Significance

1.1 Basin Meteorological Processes

Pollutants released within the stable boundary layer may remain highly concentrated since the strong atmospheric stability and weak turbulent motions significantly reduce the amount of vertical diffusion. Basin topography exacerbates this problem because converging drainage flows will reduce the horizontal advection of pollutants. However, drainage flows may also produce mean vertical motions over the basin floor, vertical wind shears within the basin atmosphere, and turbulence over the basin slopes that can enhance the dispersion of pollutants.

Our understanding of how various meteorological processes redistribute pollutants within the basin atmosphere is limited by a lack of observations. Even though many large metropolitan areas in the intermountain region of the western U.S. are located in basins, few meteorological observations are routinely available. The twice-daily rawinsondes are the only routine upper-air measurements for Salt Lake City, Reno, Las Vegas, Boise, Tucson, Flagstaff, Albuquerque, and El Paso. These upper-air measurements, however, are insufficient to characterize the temporal and spatial variations in wind, temperature, and humidity that affect local air quality in mountainous regions. While the largest cities usually have a network of surface observations, the station density and distribution is still not adequate to fully describe the near-surface flows. Nor are these observations representative of conditions above the surface, especially during the evening when strong vertical gradients in wind and temperature may be present.

Field campaigns have been conducted in the western U.S., primarily during the summer months, to obtain additional meteorological observations necessary for local air-quality studies. Several of these field campaigns have been performed in California to investigate high ozone episodes in the Los Angeles Basin (Fujita et al. 1998; Lawson 1990; Lu et al., 1997) and San Joaquin Valley (Blumental and Watson 1991; Seaman et al. 1995). A series of studies, most recently during summer and winter periods of 1996 and 1997, have been performed along the Front Range of the Rocky Mountains in Colorado to characterize horizontal transport and vertical mixing associated with particulates in the vicinity of Denver (Neff 1994, 1997a,b). Meteorological measurements and aircraft measurements of trace gas species were recently made in Phoenix during the early summer of 1998 (Doran et al. 1999) to investigate vertical mixing of trace gas species in the mixed layer. Other air-quality studies, such as MOHAVE (Gaynor and Ping 1992, Uliasz and Pielke 1998) and SCENES (Davies and Gay 1998), have been conducted to examine the effect of regional-scale pollutant transport on visibility in national parks located in the southwestern U.S. Field campaigns have also been conducted in Vancouver during the summer of 1993 (Banta et al. 1997; Hayden et al. 1997; McKendry et al. 1997; Steyn et al. 1997) and Mexico City during the spring of 1997 (Doran et al. 1998) to examine the meteorological processes associated with the formation, transport, and fate of ozone.

While these studies have improved our understanding of how convective boundary layer processes affect pollutant transport in areas of complex terrain, relatively little is known about circulations that develop within basins during stably stratified conditions. Some of the vertical exchange processes resulting from dynamic and thermodynamic influences of basin topographies are depicted in Fig. 1. Thermally-driven flows due to the heating or cooling of terrain slopes are predictable features in the absence of large-scale forcing; however, multi-scale interactions of the

local winds and regional and synoptic-scale flows may produce complicated circulations. Mean vertical motions associated with slope flows, terrain-related convergence and divergence, gravity waves, and subsidence will all affect the vertical transport of pollutants in a basin. Small-scale processes such as intermittent turbulence and gravity wave breaking increase the vertical mixing of pollutants under stable conditions. Large-scale processes that contribute to the formation, persistence, and breakdown of cold pools over multi-day periods affect the ventilation rate of pollutants from the basin to the free atmosphere.

Our hypothesis, which forms the basis of our proposed research, is that *the mean vertical motions within a basin can be large enough to significantly affect the vertical transport and mixing of pollutants in stable conditions and to produce layers of pollutants within the basin atmosphere*. While it is likely that many meteorological processes may contribute to the vertical mixing of pollutants, we intend to focus our efforts on understanding of transport associated with the detailed structure of the three-dimensional mean flow field. Over flat terrain, mean vertical motions are important for long-range transport of pollutants over relatively long time periods. Conversely, the effects of mean vertical motions are likely to be significant for short-range transport and short time periods within urban basins.

Fig. 1 Conceptual diagram that illustrates vertical exchange processes within a basin during (a) nighttime and (b) daytime conditions where 1 is drainage flow, 2 slope flow detrainment, 3 urban heat island divergence, 4 terrain-related divergence, 5 subsidence, 6 synoptic scouring, 7 waves, 8 intermittent turbulence, 9 convective mixing, 10 entrainment, 11 upslope flow, 12 mountain venting, and 13 cloud entrainment.

1.2 Objectives of the Proposed Research

We propose a 4-year program of measurements, analysis, and modeling to

1) *determine the spatial and temporal distribution of vertical motions resulting from convergence and divergence patterns in a basin and their effect on mixing of near-surface emissions during stably stratified conditions, and*

2) *determine how multi-scale flows interact to either enhance or suppress the mixing of pollutants within a basin*.

These objectives will be achieved by obtaining and analyzing surface and upper-air meteorological measurements within a basin in the western U.S. during a fall or a winter period.

The observations will be supplemented with mesoscale model simulations, since we expect that even the field campaign measurements will be insufficient to fully describe the vertical velocities and multi-scale flow interactions within the basin. Four-dimensional data assimilation will be employed to provide a physically consistent analyses of the meteorological fields in space and time. A four-dimensional interpretation of the meteorology, based on both the observations and the mesoscale model, will be needed to understand how complex circulations form and affect vertical advection.

In addition to meteorological measurements, information on the particulate distribution will be obtained using a backscatter lidar to determine the vertical extent of mixing within the nocturnal boundary layer (NBL) and the presence of layers above the NBL that may be due to recirculating flows. Perfluorocarbon tracer experiments will be conducted to quantify how convergence and divergence patterns in the basin affect vertical transport. The tracer data will also provide a time history of vertical and horizontal transport that can be used to infer the winds between the observation locations. In conjunction with the particulate and tracer data, a Lagrangian particle dispersion model will be used to simulate the vertical transport and diffusion of near-surface emissions to identify and illustrate the processes associated with vertical mixing within the basin atmosphere.

Some of the scientific questions we intend to investigate include:

- *What are the meteorological mechanisms contributing to near-surface convergence and divergence over the basin floor during stable conditions?*

- *What are the spatial and temporal variations of the convergence and divergence zones over the basin floor? Are there preferred regions of the basin where rising or sinking motions occur or where pollutants tend to accumulate? Do local terrain variations significantly affect the location of the convergence and divergence zones?*

- *What is the magnitude of upward and downward motions caused by surface convergence and divergence zones over the basin flow during stable conditions? Where are the mean vertical motions large enough to increase the effective vertical mixing?*

- *How does the interaction of synoptic, mesoscale, and boundary layer processes affect the vertical mixing of pollutants within the basin atmosphere during stable conditions?*

- *To what degree does the effects of the urban canopy perturb basin-scale circulations and convergence and divergence patterns that affect the vertical mixing of pollutants?*

- *How much data does a mesoscale model need to assimilate to adequately represent the wind and temperature fields in a basin?*

1.3 Relevance of the Proposed Research

The objectives and scientific questions to be addressed by our research correspond to those outlined in the Environmental Meteorology Program's (EMP) science plan on Vertical Transport and Mixing (VTMX). Because of the broad scope of measurements and modeling, the proposal falls under category 2 "Field Experiments", category 3 "Improvement and Applications

of Numerical and Conceptual Modeling Approaches", and category 4 "Development and Application of Tracer Technology". We will participate in the field campaign by deploying a backscatter lidar, a radar wind profiler, and several surface meteorological stations as part of category 2. Since we will employ models and field campaign observations to determine the processes that affect mean vertical motions within a basin, most of the proposed research falls under category 3. Model simulations will also be performed prior to the field campaign to determine the optimal sites for the available meteorological instrumentation as part of categories 2 and 3. Although no development of tracer technology is proposed, perfluorocarbon tracer experiments will be performed to help determine horizontal and vertical transport pathways of pollutants within the basin as part of category 4.

By addressing the specific scientific questions list in the previous section, we can contribute to answering the more general questions listed in the VTMX science plan that include:

- *What are the fundamental processes that control vertical transport for stable and transition boundary layers?*

- *How do pollutants move through residual layers above a stable or convective surface layer and to what extent can pollutants penetrate stable and residual layers aloft ?*

- *What is the nature of the interaction of terrain-induced flows with cold air pools in basins, and how do such flows affect the formation and erosion of those pools and the dispersion of pollutants in them?*

- *How do traveling weather systems remove stable stagnant air out of a basin, and under what conditions do these removal mechanisms fail?*

If our hypothesis is correct, then an understanding of the mean vertical motions associated with the local thermally-driven circulations and multi-scale interactions with larger-scale flows will be essential to address each of these questions.

Basins and valleys are common topographic features over western North America and throughout the world. Many of the major cities in the western U.S. also suffer from poor air quality caused, in part, by the meteorological conditions found in basins or valleys. Air-quality modeling studies for cities in the western U.S., such as the Wasatch Front Ozone Study in the summer of 1988 in the vicinity of Salt Lake City (Barickman and Swart 1997), often lack an accurate representation of the wind field. The knowledge we gain from the proposed research will lead to a detailed understanding of the three-dimensional flows within an urban basin and their effect on the vertical transport and mixing of pollutants, which will also benefit the U.S. Environmental Protection Agency's (EPA) air-quality modeling efforts.

2. Preliminary Studies

Over the past several years, several mesoscale modeling studies have been completed by Jerome D. Fast and other PNNL scientists as part of the U.S. Department of Energy's (DOE) Atmospheric Studies in Complex Terrain (ASCOT) and Atmospheric Chemistry (ACP) programs. Some of the findings associated with vertical exchange processes that are relevant to the objectives of this proposal are discussed next.

2.1 Completed Studies

We have described meteorological processes responsible for inhomogeneous ozone concentrations in the Mexico City basin (Fast and Zhong 1998a) as part of the IMADA-AVER field campaign (Doran et al. 1998) during the spring of 1997. This was achieved by analyzing the field campaign observations and employing the RAMS mesoscale model (Pielke et al. 1992), with and without four-dimensional data assimilation. Radar wind profiler measurements indicated the presence of local and regional thermally-driven circulations influenced by the basin topography. The highest wind speeds usually occurred in late afternoon and the wind directions suggested the presence of strong convergence over the basin floor.

The mesoscale model results demonstrated that this convergence was due to the heating of the elevated basin that produced a deep convective boundary layer (CBL) significantly warmer than the surrounding environment. By using a Lagrangian particle dispersion model, we showed that the vertical motions associated with convergence in the CBL may be strong enough to ventilate pollutants out the basin atmosphere into the free atmosphere. This vertical exchange process, also known as "basin venting" (Jauregui 1988), efficiently reduced near-surface particle concentrations late in the afternoon. During the late morning and early afternoon, another vertical exchange process known as "mountain venting" or the "mountain-chimney effect" (Bossert 1997; Lu and Turco 1994) ventilated particles from the basin atmosphere into the free atmosphere over the mountains to the west and south of the city. On some days, southwesterly winds aloft advected a fraction of these particles back over the basin that were subsequently entrained in the growing CBL during the early afternoon. Recirculation patterns also formed at night due to drainage flows that formed over the basin sidewalls and propagated over the basin floor (Fast and Zhong 1998b). Particles released at the surface did not remain within the NBL; instead, they were advected by mean vertical motions into the residual layer and up to elevations as high as the basin rim, 800 m above the basin floor. Particles were not always trapped within the basin by the converging drainage flows. Periodically, they were advected to the north, suggesting that the nighttime circulations were sometimes similar to those found in valleys.

The model has also been used to simulate how regional-scale flows, such as winds that develop in a gap in the terrain southeast of the city (Zhong and Doran 1998) and shallow flows that propagate from the Gulf of Mexico into the central plateau (Shaw et al. 1999a), affect the basin atmosphere. Both of these regional-scale flows have characteristics similar to propagating density currents (Bossert and Cotton 1994; de Wekker et al. 1998a; Doran and Zhong 1994).

RAMS has also been applied to simulate the development of the NBL in the Sinbad Basin, a small canyonland basin in western Colorado (Fast et al. 1996). The model results were compared with observed profiles of wind, temperature, and humidity made near the center of the basin and within a narrow canyon that drains the basin (Whiteman et al. 1996). We found that turbulent flux divergence was the dominant cooling mechanism in the basin. The drainage flows detached from the slopes and recirculating flow patterns were predicted over the basin floor near the steepest slopes of the sidewalls, similar to observations in another closed basin described by Petkovsek (1978). The results suggested that convergence regions along the basin floor may be largely governed by characteristics of the basin topography, such as variations in the steepness of the sidewall slopes. We intend to investigate whether the concepts about convergence in basins first described by Petkovsek can be applied to urban basins of the western U.S.

In another study, RAMS was applied to simulate the evolution of the NBL along the Front Range of the Rocky Mountains during a SF_6 tracer experiment in the winter of 1991 (Fast

1995). Tracer was released from the DOE's Rocky Flats Plant, located northwest of Denver, and two sampler rings surrounded the release site at 8 and 16 km radius. During the evening, the winds exiting canyons along the Front Range had a profound impact on the advection and diffusion of the tracer. The plume that was advected to the east by near-surface drainage flows spread horizontally much more than one would expect in stably stratified conditions. Significant variations in the strength and direction of the canyon winds over a periods of 1 h indicated that the canyon winds were controlled not only by radiational cooling, but by other mechanisms, including multi-scale interactions with the flow above the ridge tops. The winds predicted by the model using a 330-m horizontal grid spacing compared quite well to Doppler lidar measurements near the elevation of the maximum canyon wind speeds a few hundred meters above the ground. The mean and turbulent wind components produced by the model using data assimilation were also used to drive a Lagrangian particle dispersion model to simulate tracer transport and diffusion. Many of the characteristics of the SF_6 tracer plume were reproduced by the particle model, demonstrating that mesoscale model captured the overall variations in the strength and direction of the downslope winds.

2.2 Ongoing Studies

As part of an ACP project, we have recently performed mesoscale model simulations of the evolution of the CBL and NBL near Phoenix that utilized measurements made during a field campaign conducted in May and June of 1998 (Doran et al. 1999). The meteorological fields produced by RAMS and the Lagrangian particle dispersion model are being used to describe transport and vertical mixing processes in the region. Chemical production and destruction mechanisms associated with the basin circulations will be investigated using a photochemical model. Preliminary analysis of the measurements and the modeling studies suggest that the spatial variations in ozone observed during the afternoon are due primarily to thermally-driven upslope circulations produced by the higher terrain to the north and east of Phoenix. The diurnal cycle of the surface winds over the basin suggest that terrain influences were strong (Shaw et al. 1999b); however, measurements from a mini-sodar and a radar wind profiler located in a valley northeast of Phoenix indicated that nocturnal drainage winds above the surface were weak. High ozone mixing ratios observed at remote mountain sites during the early evening were probably due to lower chemical destruction rates within the residual boundary layer. We are investigating whether pollutants in the residual layer contributed to surface concentrations on subsequent days.

A few preliminary mesoscale simulations of the circulations in the vicinity of Salt Lake City have already been completed. This work is being performed as part of a transition project between the ASCOT and VTMX programs to identify the types of vertical exchange processes that may be significant in urban basins. Previous field experiments at the U.S. Army's Tooele Depot, located 60 km southwest of Salt Lake City, have shown the occurrence of strong daytime up-valley winds, weak nighttime down-valley winds, and strong winds that develop over the terrain gaps between adjacent basins (Astling 1990; Stone and Hoard 1990a,b). To represent the various scales of motion that may affect the thermally-driven circulations within the basin, we have employed five nested grids in RAMS. The outer domain encompasses all of western North America with a horizontal grid spacing of 45 km and the second domain encompasses the intermountain region with Δx=15 km. These two domains are approximately the same as those employed by real-time MM5 model (Dudhia 1993) simulations made by the University of Utah (http://www.met.utah.edu/models.html). In addition to these regional domains, we have included

a third domain that encompasses northern Utah and southern Idaho with Δx=5 km, a fourth domain for the entire Salt Lake City basin with Δx=1.67 km, and a fifth domain that resolves the canyons along the Wasatch front with Δx=555 m.

Simulations have been completed using this grid configuration for a two-day period in October, 1998. We have found that the strength of the downslope flows varies significantly around the basin during the evening. For example, the model predicts moderate drainage winds over the slopes of the Oquirrh mountains, weak winds over the steep slopes of the Wasatch Front, and strong katabatic valley winds within Emigration, Parleys, Little Cottonwood, and Big Cottonwood canyons. The downslope flows decelerate as they converge over the basin floor and propagate to the north over the Great Salt Lake. Regions of convergence are predicted within the basin atmosphere with positive vertical velocities as high as 25 cm s^{-1}. Rising motions are also associated with eddies that form on either side of the Little and Big Cottonwood canyons as the katabatic flows enter the basin. An example of the drainage flows and vertical motions is shown in Fig 2. Similar to Arritt and Young (1990), elevated stable layers are produced by drainage flows that detach from the basin sidewalls. Flow reversal occurs within the modeled basin atmosphere above the NBL with relatively strong northerly winds close to the Wasatch Front. The strong vertical wind shears and converging downslope flows are likely to have a large impact on the vertical mixing of pollutants emitted from the surface.

Fig. 2 Model predictions over a subset of the fifth domain at 02 LST including (a) near-surface winds and (b) winds along a vertical cross section just north of Little Cottonwood Canyon with positive vertical velocities shaded and a contour interval of 5 cm s^{-1}.

3. Research Design and Methods

In this section we describe the specific tasks that will be performed to address the principal science questions and the two objectives 1) *determine the spatial and temporal distribution of vertical motions resulting from convergence and divergence patterns in a basin and their effect on the mixing of near-surface emissions during stably stratified conditions* and 2) *determine how multi-scale flows interact to either enhance or suppress the mixing of pollutants within a basin*. Measurements, analyses, and model simulations are used for both objectives.

The VTMX science plan states that Salt Lake City or Phoenix are likely candidates for the field campaign. We will assume for the purposes of this proposal that a field campaign will take place in Salt Lake City over a four-week period, although the instrumentation sites we discuss can be altered for another location. There are many advantages for choosing Salt Lake

City as a field campaign site. For example, an extensive network of surface stations already exists in the vicinity of Salt Lake City and there will be opportunities to collaborate with atmospheric scientists at the University of Utah, U.S. Army Dugway Proving Grounds, and the Utah Department of Environmental Quality (UDEQ). The steep slopes of the Wasatch Mountains will have a strong influence on the vertical exchange mechanisms associated with convergence and divergence and multi-scale interactions of local, regional, and synoptic flows.

Data from existing instrumentation and from the additional meteorological measurements to be made during a field campaign are described next in Section 3.1. Analyses of the field campaign measurements, such as those described in Section 3.2, will be performed to systematically find evidence of regions of convergence and divergence and vertical motions within the basin. To obtain a complete picture of the three-dimensional flow field and how it varies in time requires the use of an atmospheric mesoscale model as discussed in Section 3.3.

3.1 Measurements

3.1.1 *Existing instrumentation*

The Utah mesonet is an ongoing project carried out by the University of Utah in cooperation with several other groups (Horel et al. 1999). The mesonet brings together surface observations from many station networks in the intermountain region. Each network is maintained by the agency that installed it; therefore, the type and frequency of meteorological information varies. Access to the mesonet data is available via the internet. There are 13 stations in the Salt Lake City basin alone and there are many others located in the surrounding basins and mountains. These surface stations will be very useful in determining areas of near-surface convergence and divergence over the basin floor. The twice-daily rawinsondes at the airport and a radar wind profiler located in the southern Tooele Valley are the only upper-air observations in the vicinity of Salt Lake City. The profiler winds will be useful in providing hourly synoptic winds aloft, but the measurements within 1 to 2 km of the surface are unlikely to be representative of the winds in the Salt Lake City basin. In addition to these measurements, the NOAA Cooperative Institute for Regional Prediction (CIRP) at the University of Utah developed a real-time mesoscale analysis system, called ADAS, at high temporal and spatial resolution over northwest Utah (Lazarus et al. 1998) based on Utah mesonet data and the Oklahoma Advanced Regional Prediction System (ARPS) model (Xu et al. 1995).

Additional wind information may be available from the NEXRAD WSR-88D radar which is located on Promontory Point on the northern shore of the Great Salt Lake. NEXRAD radars not only detect the presence of hydrometeors, they also measure Doppler-shifted radial wind speeds using reflectivities from hydrometeors and small particles advected by the wind such as dust and insects. Vertical azimuth display (VAD) of the NEXRAD winds can be obtained that are spatially averaged soundings at radii on the order of 20 to 50 km with a vertical resolution of a few hundred meters (Xu and Qui 1995); however, quality assurance procedures are still being developed. Wind, temperature, and humidity measurements made by commercial aircraft flying into and out of the Salt Lake City airport may also be available via the Aircraft Communication and Reporting System (ACARS). The ACARS data (Schwartz and Benjamin 1995) will be useful in providing vertical temperature distributions that depict the evolution of multiple stable layers within the basin atmosphere, although the ascent and descent flight paths

will complicate the interpretation of the data. It is anticipated that the University of Utah will incorporate local VAD and ACARS data into the mesonet database in the near future.

3.1.2 *Field campaign instrumentation*

The existing observations will be useful, but they are not sufficient to describe many important meteorological processes within a basin. The types of instrumentation needed to address the objectives of this proposal are discussed next. The proposed instrumentation sites in the vicinity of Salt Lake City are shown in Fig. 3, although we realize that modifications will be necessary to accommodate other EMP investigators. For logistical reasons, sites were not chosen along the steep slopes of the Wasatch Mountains. Instead, characteristics of the upslope and downslope winds can be obtained at more easily assessable sites over the gradual slopes of the Oquirrh Mountains and along the base of the Wasatch Mountains.

The VTMX science plan states the the field campaign will probably take place in the fall or winter. The instrumentation described below assumes that many of the measurements will be made at night when stably stratified atmospheric conditions occur. Shallow daytime convective boundary layers are likely to develop during the fall, which is not the focus of the program.

<u>Meteorological measurements</u>

We recommend that at least six 915 MHz radar wind profilers equipped with RASS be deployed near the sites shown in Fig. 3 to obtain hourly wind and virtual temperature profiles at key locations in the basin. To supplement the wind profiles near the surface within the NBL, we also propose that mini-sodars be deployed at each wind radar profiler site.

One of the six sites is needed near the airport to measure flows into and out of the north end of the basin. Contrasts in sensible heat fluxes due to the presence of the Great Salt Lake are likely to generate low-level winds that can be measured at this site. A profiler and mini-sodar near the Oquirrh Mountains will measure upslope and downslope flows that may form over the western basin slopes. Since the terrain along the Wasatch Front is likely to be more complex, at least two sites are needed to measure the upslope and downslope flows over the eastern basin. One of these eastern sites is needed near the exit of Parleys Canyon at the base of a relatively broad gap in the Wasatch Front. Near-surface measurements indicate that strong easterly winds occur in this area on a regular basis. The other eastern site is needed at the base of either Big Cottonwood or Little Cottonwood Canyons to measure drainage flows that are likely to form in these deep and long valleys. The characteristics of the flows exiting Parleys Canyon and Big Cottonwood Canyon are probably very different. Another site should be located in the southern end of the basin to measure flows into and out of the basin and dynamic accelerations of the low-level winds that may occur because of the gap in the terrain. The final site should be located near the basin center to determine the downwind effects of the drainage flows and to find evidence of wind shears within the basin atmosphere far from the basin sidewalls. The sites shown in Fig. 3 are at least 10 km from each other to ensure that the profilers do not interfere with one another. Another mini-sodar is needed near the city center to determine the near-surface wind characteristics within the major source of pollutants in the basin.

The 915 MHz radar wind profiler is typically operated both a high and a low mode. In the high mode, the vertical resolution is about 100 m and data can be obtained at heights up to 3 to 4 km above ground level (AGL), well above the height of the tallest peak in the area. In the

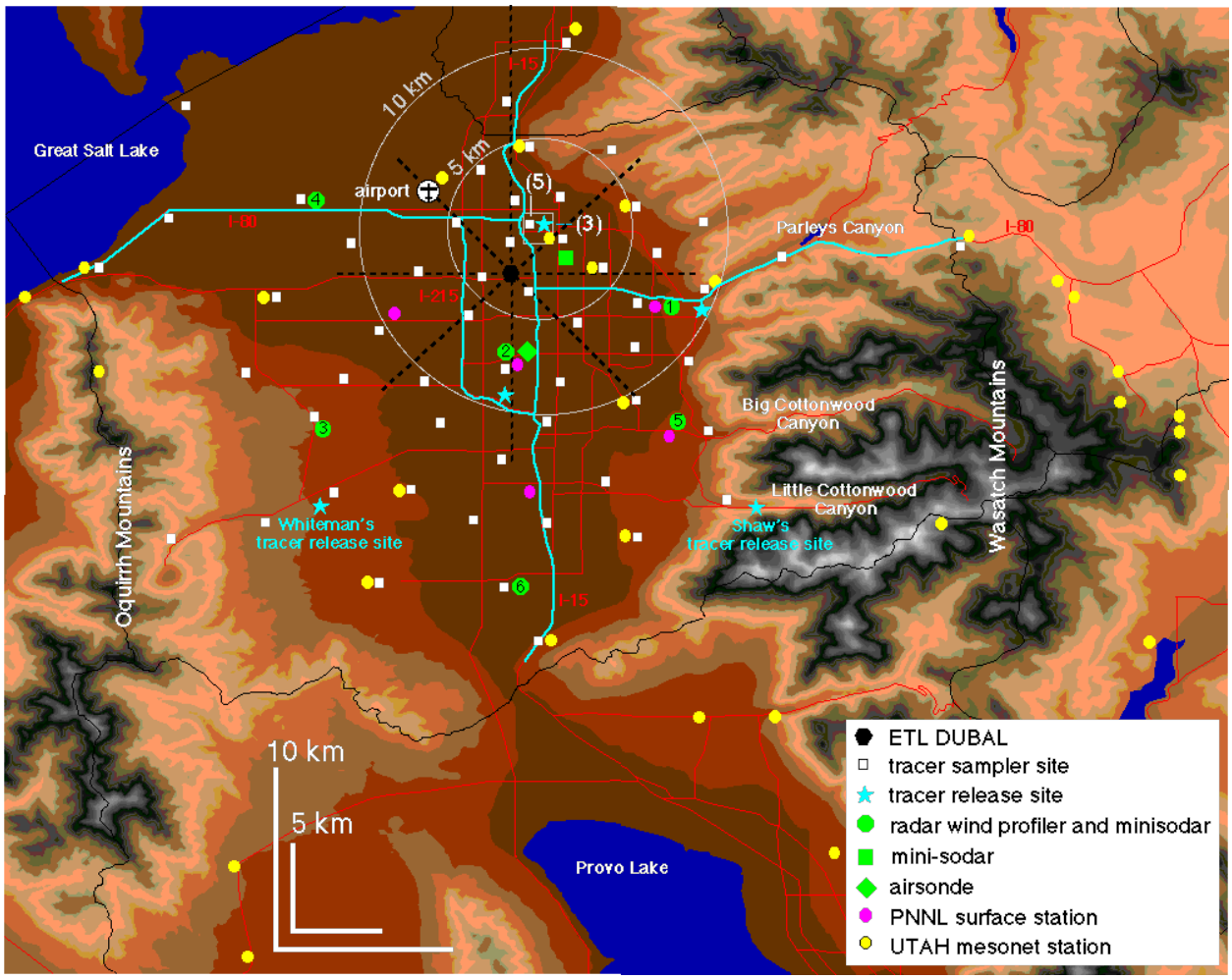

Fig. 3 Instrumentation sites proposed for the VTMX field campaign, along with the locations of the Utah mesonet surface stations.

low mode, the vertical resolution is about 60 m and data can be obtained at heights up to 1.5 to 2 km AGL. The downslope flows exiting Parleys Canyon and Big Cottonwood Canyon may become elevated above the cold pool; therefore, the two eastern profilers shown in Fig. 3 are located at lower elevations 1 or 2 km west of the canyons so that the downslope flows will be measured at higher range gates. Still, mini-sodars are needed to supplement the wind profilers near the surface. Mini-sodars have a vertical resolution of about 5 m and data can be obtained from 10 m to around 150 m AGL. Temperature profiles from the RASS can be obtained at about the same resolution as the profiler winds, but data are typically available only up to about 1 km AGL and relatively few range gates will be within the NBL that may only be 200 to 300 m deep.

While hourly virtual temperature profiles can be obtained by the RASS, strong vertical gradients near the surface will be poorly resolved and little information will likely be available above 1 km AGL. Since the rawinsondes are launched from the airport only at 00 and 12 UTC (17 and 05 LST), airsondes are needed to provide a more complete description of the thermodynamics that govern the development of circulations in the basin. In contrast to RASS, airsonde soundings can resolve sharp vertical temperature gradients associated with inversions that are likely to occur at multiple heights. Although only one airsonde site is shown in Fig. 3,

we expect that one or two additional sites will be needed to meet the objectives of the program. We propose that airsondes be launched every 2 h during the afternoon transition, evening, and morning transition periods between 15 and 09 LST for a total of 10 soundings per day. A few soundings are needed several hours before sunset and after sunrise because the daytime boundary layer during the fall or winter months will be relatively weak. The high frequency of soundings are probably only necessary on days in which there are intensive observational periods (IOPs) during the field campaign. We require six IOPs corresponding to the number of tracer experiments discussed later. On other days during the field campaign it may be sufficient to launch soundings four times a day at 17, 21, 01 and 05 LST. An advantage of the Salt Lake City location is that it may be possible to use humidity as a tracer of opportunity. Relatively high humidities measured by the airsondes may be an indication of transport from the Great Salt Lake.

As shown in Fig. 3, the Utah mesonet has a number of surface meteorological stations located throughout the basin; however, there are relatively large gaps in the network in the center of the basin. We propose to deploy five Campbell Scientific surface meteorological stations near the middle of the basin. In this way, we can better characterize convergence and divergence near the surface and determine with more accuracy how far drainage flows from the basin sidewalls penetrate into the center of the basin.

Aerosol measurements

Several weather cameras are located in Salt Lake City and real-time images can be obtained via the internet. A camera at the University of Utah has the best view of a pollutant layer that often forms over the downtown area. This layer is clearly visible in the early morning hours, suggesting the build-up of pollutants within the stable boundary layer at night. The layer gradually disperses during the day as convective mixing becomes stronger. The particulate emissions in the city are a tracer of opportunity that can be used to examine how surface flows interact to form these layers, although more precise measurements are needed for this purpose.

We intend to collaborate with NOAA's Environmental Technology Laboratory (ETL) in deploying the Depolarization and Backscatter Unattended Lidar (DABUL) as part of the field campaign to measure characteristics of the aerosol distribution (Grund and Sanberg 1996). This instrument was recently used during the SHEBA field experiment over the Arctic Ocean (Alverez et al. 1997). A horizontal slice of the particulate distribution can be obtained by an elevation scan. Information is obtained within 4 km in the vertical and horizontal directions with a 30-m range resolution, but longer distances up to 10 km are usually possible since the range depends upon the amount of particulates in the atmosphere. Clouds will occur a large fraction of the time in the vicinity of Salt Lake City during a four-week field campaign period, especially during the winter. An advantage of deploying DABUL, is that cloud base height, apparent cloud top height, phase identification for the cloud layer, mixed layer height, and extinction profiles can also be obtained. The instrument was designed as an unattended system so that elevation scans for one azimuth can be made over a long period of time. During the field campaign, the instrument will be placed on a turntable or the back of a truck so that it can be rotated to obtain multiple slices. In this way, the three-dimensional features of the particulate distribution will be revealed. DABUL will be deployed a few kilometers from the downtown area as shown in Fig. 3 where aerosol concentrations are likely to be the highest.

DABUL measurements will be used, in conjunction with meteorological measurements, to illustrate how vertical transport and mixing processes affect the spatial and temporal variations

of the particulate concentrations within and above the basin atmosphere. We will examine the backscatter data to determine to what depth the particulates are mixed upwards in the NBL. Based on early morning camera images, we estimate that maximum particulate concentrations may occur in a layer a few hundred meters AGL. Isolated patches of high concentrations above or below the main layer may indicate the presence of intermittent turbulence. Spatial variations in the depth of the layer may reflect the influence of local convergence or gravity waves. For example, de Wekker et al. (1998c) used lidar measurements to show that spatial variations in the CBL depths northeast of Vancouver were due to thermally-driven flows over terrain slopes. As shown in Fig. 4, the lidar measurements also revealed the presence of aerosol layers above the CBL, which were probably due to pollutants that were vented into the free atmosphere by upslope flows and advected back over Vancouver (Rucker et al. 1998). Aerosol layers above the NBL and below the height of the surrounding mountains may also be observed over Salt Lake City as well. These layers provide information regarding the history of the circulations within the basin atmosphere that can be used to determine how surface emissions are exported from urban areas to the regional-scale environment. We will also use the lidar measurements to investigate the breakup of pollutant layers during morning transition periods.

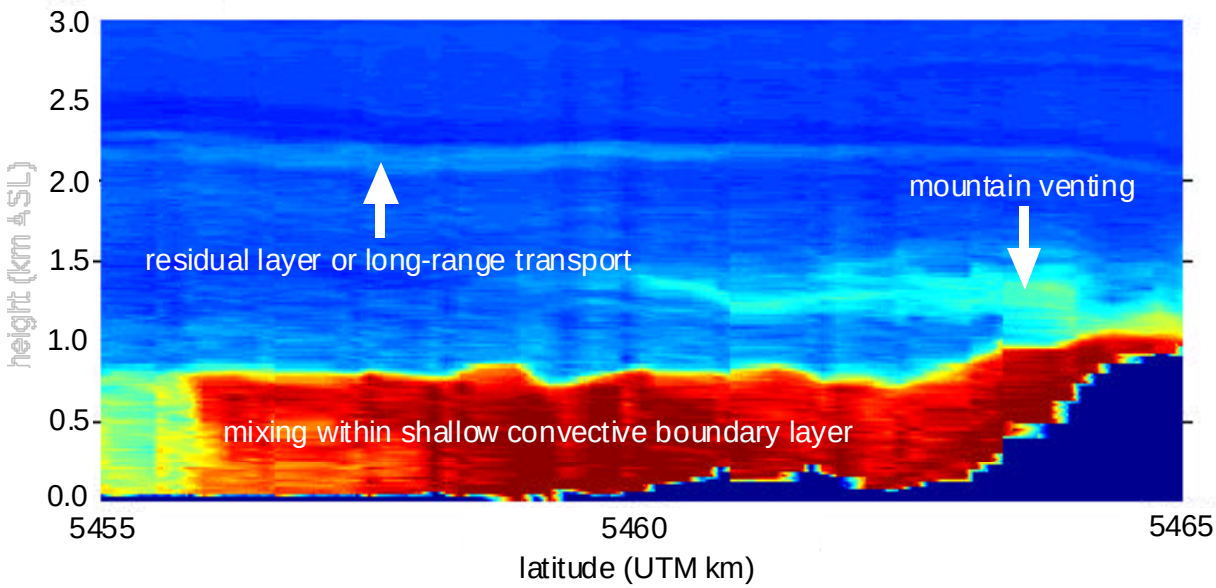

Fig. 4 Example aerosol concentrations obtained from a dial lidar between 1355 and 1406 LST on May 8, 1993 in the vicinity of Vancouver (Rucker et al. 1998).

Perfluorocarbon tracer experiments

In addition to using a backscatter lidar which qualitatively measures the effect of mixing, our proposal includes a series of perfluorocarbon tracer experiments (Dietz 1986) that will provide information concerning the history of the basin circulations that can not be obtained in any other way. By measuring tracer concentrations at surface sites throughout the basin, we will quantitatively measure how the convergence and divergence patterns affect transport and mixing during stable conditions.

Even though turbulent diffusion is normally small in stable conditions over flat terrain, tracers are likely to be spread over a large area of the Salt Lake City basin. For example, a

simple Gaussian plume model predicts that the lateral spread of a plume in a stable atmosphere (Pasquill-Gifford category F) would be 0.6 and 1 km at downwind distances of 10 and 20 km from the source, respectively. Observations from a winter SF_6 tracer experiment at the Rocky Flats Plant (Section 2.1) suggest, however, that dispersion from a point source in the vicinity of complex terrain rarely behaves like a Gaussian plume. The horizontal and vertical wind shears and the temporal variation of the near-surface drainage winds enhanced the lateral dispersion of the plume. Plume widths downwind of the release site were often 3 to 6 km and 10 to 20 km wide at downwind distances of 10 and 20 km, respectively. Other processes not included by the Gaussian plume model, such as gravity wave breaking and intermittent turbulence, will enhance dispersion. Complex flows are likely to occur within the Salt Lake City basin as well so that the chances of sampling perfluorocarbon tracer released from a point source are good, even during stable conditions. As shown by Moran and Pielke (1994), dispersion can be enhanced by vertical wind shear through the interaction of horizontal differential advection and vertical diffusion. The SF_6 tracer experiment conducted just west of Salt Lake City in the Tooele and Rush Valleys during an evening period in 1987 (Stone et al. 1989) provides evidence that tracers can be widely dispersed in a matter of a few hours.

We propose to conduct tracer experiments on six nights of the field campaign that is expected to last four weeks. Five different perfluorocarbons will be released, each at a different location. As shown in Fig. 3, three of the release sites will be located downtown, two of which will be located on the top of tall buildings. The downtown sites are chosen so that the tracers mimic pollutants emitted from the urban center. The sites at the base of Parleys Canyon and in the central basin are chosen to examine the effect of down-valley flows on transport and mixing. Tracers will be released at a constant rate for a 12-h period starting shortly after sunset at 18 LST to around sunrise. The tracer experiments will be separated by at least two days to reduce the possibility that significant concentrations are due to previous releases. Two other PNNL proposals are planning to release tracers along the lower slopes of the Oquirrh Mountain and within the Big Cottonwood Canyon. Tracers released at these locations will be used to track the path of drainage flows over the basin floor.

An array of 55 sampling stations will be deployed as depicted in Fig. 3. We will work with scientists at the University of Utah and UDEQ in selecting sites and obtaining permission to deploy the samplers; therefore, the actual configuration will change somewhat. All of the samplers will measure near-surface concentrations, except for three samplers that will be located on the top of buildings to obtain some vertical information regarding the tracer distribution. The samplers will measure 3-h averages of the perfluorocarbon concentrations for a 21-h period during the evening and morning transition period between 18 and 15 LST. While few samplers will measure significant concentrations during the first 3-h period, this sampling period is needed because the amount of vertical mixing and extent of horizontal transport shortly after the start of the release will not be known. The initial 3-h sampling period will also be used to determine if tracer material is present from prior experiments. A real-time sampler will also be used to obtain high spatial and temporal resolution of the tracer concentration at the surface. We plan to use the real-time sampler in a van and make north-south and east-west transects within the basin along the interstates as shown in Fig. 3. These transects will probably start around 21 LST and continue until a few hours after sunrise. Each transect will take between 30 min to an hour so that multiple transects can be completed during each tracer experiment.

Over a sufficient period of time, tracers will get mixed within the NBL that may be a few hundred meters deep. Since strong vertical winds shears can occur at night, the tracer will be

spread over a large area. Interpretation of the surface sampler data will require the analyses of the surface and upper-air meteorological measurements and model simulations. We expect that the measured tracer distribution patterns cannot be explained by the near-surface winds alone.

Field campaign design and support

We have described the field campaign measurements needed during a fall or winter period to address the objectives of our proposed research. Our proposal will fully support the operation of a radar wind profiler, five surface meteorological stations, the DABUL instrument, and the perfluorocarbon tracer experiments. We anticipate that the rest of the meteorological measurements discussed in this section will be supported by other EMP projects and collaborators. As mentioned earlier, at least six radar wind profilers and seven mini-sodars will be needed. The U.S. Army's Dugway Proving Ground will probably deploy one or two profilers if the field campaign is held in the Salt Lake City area. Proposals from Argonne National Laboratory (ANL), Los Alamos National Laboratory (LANL), and NOAA's Environmental Technology Laboratory (ETL) are expected to include the use of their profilers and mini-sodars. Although the airsonde soundings we have described are basic measurements that will be needed by most projects, support of this effort will be determined at a later date. Other investigators will probably propose the use of additional instrumentation that we have not anticipated that will affect what can be accomplished by our proposed research. The assistance of the EMP scientific director, J. C. Doran of PNNL, will be needed in coordinating the field campaign measurements.

3.2 Analysis

A series of analyses of the field campaign measurements will identify processes that can influence the mean vertical motions within the basin atmosphere. Our approach is not to rely on analyzing data from one particular instrument, but to combine several types of measurements to aid in the description of atmospheric processes that affect vertical mixing. We describe several analyses of the data next, but additional analyses will be developed depending on the type of instrumentation that eventually is deployed in the field. Interpretation of these analyses will be closely coupled to the mesoscale model simulations described in Section 3.3.

3.2.1 *Layering within the basin atmosphere*

Knowing how the horizontal and vertical temperature gradients evolve within the basin atmosphere is critical in determining the processes associated with vertical mixing. Much of the pollutants emitted during the evening from a basin urban area are likely to remain within a layer near the surface; therefore, temperature profiles from the airsondes and RASS and the turbulent statistics from the wind profilers (C_N^2) will be analyzed to find the depth of the NBL. In contrast to NBLs over flat terrain, relatively deep NBLs may develop in the vicinity of Salt Lake City because of drainage flows that channel cold air from the surrounding mountains into the basin. DABUL measurements will be used to determine whether the highest aerosol concentrations remain within the NBL that grows in depth during the evening.

The atmosphere above the NBL will still be stably stratified, but the potential temperature lapse rate will be less than in the NBL. Due to the complexities of the terrain, we expect that multiple inversions will be observed by the airsondes on many evenings. Multiple inversions

imply that layers of the basin atmosphere will be mechanically decoupled. On the other hand, the presence of aerosol layers in the middle and upper basin atmosphere may indicate that there were vertical motions somewhere in the basin that were large enough to advect pollutants out of the NBL. Layers of aerosols aloft may also be due to daytime emissions and recirulating flow patterns at night that prevent pollutants from being ventilated from the basin atmosphere. Cloud properties measured by DABUL will also be used to define layers in the atmosphere and determine whether cloud entrainment is an important vertical transport process in the basin.

In addition to temperature inversions, the presence of strong wind shears is an indication of layering of the basin atmosphere; therefore, we will also calculate the vertical wind shears from the radar wind profiler measurements. Turbulent mixing may be enhanced at heights where there are large wind shears, even in stable conditions. For example, if the wind shears are sufficiently large at the top of the shallow NBL then it may be possible for a small fraction of pollutants to be mixed upwards as a result of shear-induced turbulence. Profiles of temperature and wind speed will be used to compute vertical profiles of the gradient Richardson number, Ri. Regions with Ri less than 1.0 are likely to be turbulent and will indicate layers in which vertical mixing is enhanced. However, there is a hysteresis effect associated with Ri. The hysteresis arises because the Richardson number of nonturbulent flow must be lowered to a critical value (R_c) before turbulence will start, but once turbulent, the turbulence can continue until the Richardson number is raised above another value (R_T). Profiles of Ri and C_N^2 will be compared with the aerosol concentrations to determine whether there is significant mixing between various layers in the basin atmosphere.

3.2.2 *Convergence and divergence within the basin atmosphere*

Since mean vertical motions form as a result of horizontal wind gradients, winds obtained from the radar wind profiler array will be analyzed to find evidence of regions of convergence and divergence in the basin. A comparison of the winds from the western, central, and eastern sites will provide a rough estimate of which side of the basin convergence or divergence, and therefore rising or sinking motions, occurs. In an example shown in Fig. 5, the winds within the cold pool suggest that the strongest rising motions occur over the western side of the basin. Winds from the northern, central, and southern sites can also be compared in a similar manner. Analysis of the mesonet winds will provide a more information about convergence and divergence at the surface. A mesoscale model will be used to provide detailed estimates of regions of convergence and divergence patterns throughout the basin atmosphere.

Direct measurements of vertical velocity made by a radar wind profiler would be ideal for this project; however, measurements of mean vertical motions have proven to be among the most challenging and least reliable of wind profiler measurements (Chau and Balsley 1998). Many of the vertical measurement biases have been attributed to an off-vertical pointing direction which adds a horizontal velocity contamination to the vertical data. While it may not be possible to obtain an accurate measurement of vertical velocities with a magnitude of a few cm s^{-1} or less, larger magnitudes on the order of 10 cm s^{-1} or more may be an adequate qualitative indication of either rising or sinking motions over the profiler sites. Our preliminary simulations of the Salt Lake City basin suggest that vertical velocities on the order of 10 cm s^{-1} may often occur during the evening (e.g. Fig. 2b). Because wind direction shifts associated with the passage of convergence zones over a profiler site may produce enhanced variances in the vertical velocities, we will also determine whether there is a correlation between the vertical velocity variance and

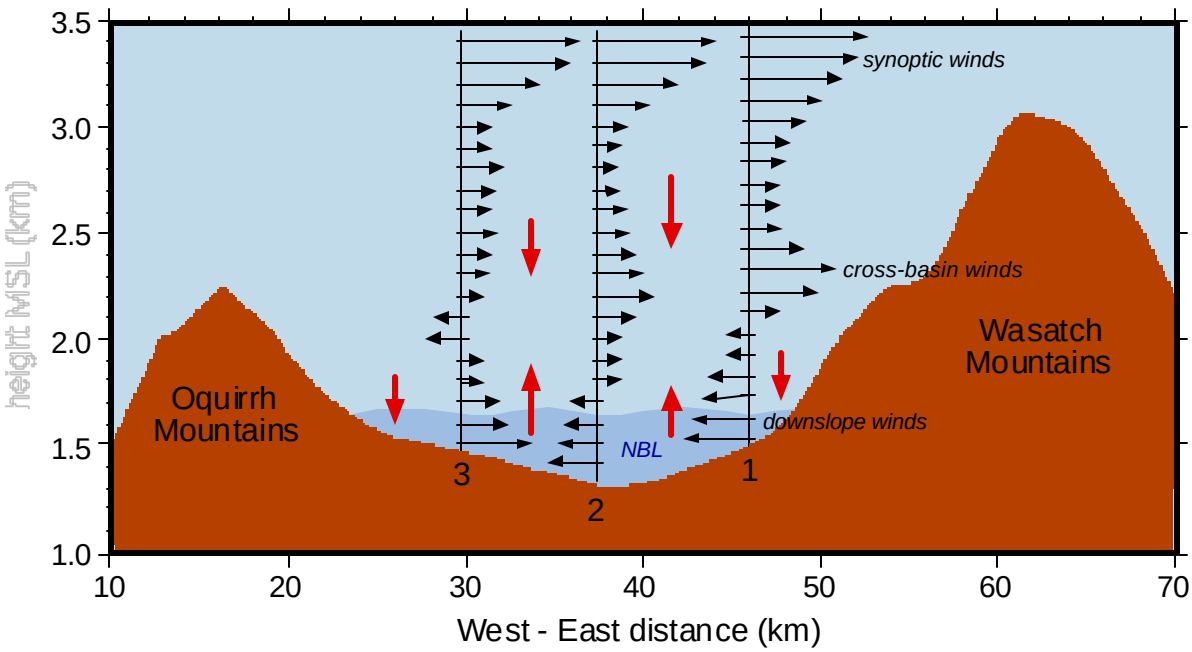

Fig. 5 Mean vertical motions due to convergence and divergence inferred from hypothetical 915 MHz radar wind profiler measurements. Sites 1, 2, and 3 are shown in Fig. 3.

the horizontal winds. Vertical velocity variances have been employed to determine gravity wave activity over flat terrain (Green et al. 1988; Nastrom et al. 1990; Nastrom and VanZandt 1994); but, other dynamic processes within basins are likely to mask the signals due to gravity waves.

The occurrence of convergence or divergence can also be inferred by examining its effects on temperatures and aerosol concentrations in the basin. For example, the location of the coldest temperatures along the basin floor may indicate where drainage flows converge. The airsondes and RASS measurements will provide evidence of horizontal variations in the depth and stability of the NBL. We will search for spatial variations in the depth of the aerosol layers to determine whether they are closely related to spatial variations in the NBL depth. Layers of aerosols that are slightly higher than surrounding areas may be due to rising motions associated with near-surface convergence. Drainage flows from the valleys along the Wasatch Mountains are expected to advect cleaner air over the urban center so that pollutants released earlier in the evening will slowly rise, producing a layer of higher aerosol concentrations aloft above the downtown area. The drainage flows could also detach from the slopes to cool the middle of the basin atmosphere that may suppress or enhance vertical mixing of aerosols at the top of this layer. Characteristics of the drainage flows that will not be available from observations alone will be provided by mesoscale model simulations. Other mechanisms that affect the mean vertical motions, such as gravity waves and intermittent turbulence, may be identified by examining the time rate of change of the aerosol concentrations from consecutive elevation scans made by the DABUL instrument.

By examining the spatial and temporal variations of the tracer concentrations from the sampler array shown in Fig. 3, we will be able to determine regions of convergence and infer vertical exchange processes associated with the nocturnal flows. While the real-time transects will provide details of the horizontal variations along the interstate highways, it will be necessary to employ analyses of the wind, temperature and aerosol fields to aid in explaining both the

horizontal and vertical transport pathways associated with the tracer data. We expect that tracers from all five sites will primarily be transported by down-valley flows to the northwest of downtown. The tracers released from the top of the buildings in the downtown area are expected to remain elevated for some distance downwind; however, any concentrations of these tracers measured at the downwind surface samplers will indicate the approximate location where vertical advection and diffusion processes bring tracer down to the ground. One of the tracer release sites will be located adjacent to the foothills to examine the effect of downslope winds through Parleys Canyon. Since this release site is about 200 m above the basin floor, it will be interesting to see whether this tracer remains near the surface or is lofted above the ground. If the tracer plume becomes lofted, it will not be detected by the samplers just downwind of the canyon. Concentrations measured at sites closer to the center of the basin will indicate that there are vertical advection and diffusion processes that can bring a portion of the tracer plume back down to the surface. Another release site will be located about 10 km south of downtown. If the downslope flows from the western and eastern basin slopes converge near the center of the basin, then tracer released from this site should be transported to the north towards the downtown area. If the downslope flows are stronger on one side of the basin, then the tracer should be transported predominately to either the eastern or western sides of the basin. A particle dispersion model will also be used to investigate these possibilities.

3.2.3 *Multi-scale interactions within the basin atmosphere*

The observed profiles of wind, temperature, humidity, and aerosol concentrations will also be examined to find evidence of synoptic and regional-scale influences on the development of the basin atmosphere. While the synoptic and regional-scale influences will complicate the interpretation of the vertical mixing processes in the basin, multi-scale interactions cannot be neglected because synoptic forcing is frequently strong during the fall and winter months in the western U.S. Our findings from Mexico City field campaign (Section 2.1) have also demonstrated that regional-scale circulations have a large impact on basin circulations and the horizontal and vertical transport of pollutants.

The observations will be used to segregate the field campaign days by weak, moderate, or strong synoptic forcing. When the larger-scale forcing is weak, only small temporal changes in the temperature profiles will occur near the height of the mountain ridges surrounding the basin and a cold pool will gradually form over the basin floor during the evening. Large temperature changes in time and strong winds near the height of the mountain ridges will indicate that advection by regional- or synoptic-scale winds may affect the development of the NBL. Temperature advection will modify the static stability in the basin atmosphere and the larger-scale flows will interact with the local thermally-driven flows to produce complex circulations.

The analyses described in the previous section for each night will be compared with one another and with synoptic and regional-scale analyses to determine whether convergence patterns within the basin are influenced by larger-scale flows. If there is such a dependence, vertical mixing may be either enhanced or suppressed by mean vertical motions associated with certain synoptic systems. It is possible that complex tracer concentrations could be produced within the basin atmosphere that will be difficult to explain from the data alone. As described in the next section, we will employ a mesoscale model to provide higher spatial and temporal resolution of wind, temperature, and turbulence fields needed to fully understand the effect of multi-scale interactions on basin convergence patterns.

3.3 Modeling

While the field campaign measurements will provide valuable information about the basin atmosphere under stably stratified conditions, observations at individual sites may not be representative over a large area due to the complexity of the terrain. Analyses of the data are insufficient, by themselves, to fully describe the details of the three-dimensional flows within the basin that affect vertical mixing of pollutants. Prognostic mesoscale models are the only tools available that can be used to obtain realistic flow characteristics in data sparse regions. The use of models is required to meet the two objectives of the proposed research.

3.3.1 *Model description*

Mesoscale model

Although RAMS has been extremely useful in previous studies made by the ASCOT program, J. D. Fast, S. Zhong, and J. C. Doran of PNNL will also be examining and testing the ARPS and MM5 mesoscale models and the National Center for Environmental Prediction's (NCEP) nonhydrostatic Eta model during the transition between the ASCOT and VTMX programs to evaluate their strengths and weaknesses in forecasting flows in basins and valleys. One of these models will be used as part of our research; however, for the purposes of this proposal we describe here the RAMS model and how it will be used in subsequent sections of this proposal.

RAMS is based on a set of nonhydrostatic, quasi-compressible primitive equations and includes parameterizations for turbulence, radiation, clouds, soil, and vegetation (Pielke et al. 1992). The turbulence parameterization is based on a level 2.5 scheme (Mellor and Yamada 1982; Helfand and Labraga 1988) with a prognostic turbulent kinetic energy equation and a diagnostic length scale. The model simulates clouds and precipitation by employing a cumulus parameterization and/or explicit microphysics. Prognostic equations for soil temperature, soil moisture, and vegetation temperature are used to calculate the diurnal variations of temperature and moisture at the ground-atmosphere interface. Turbulent sensible heat, latent heat, and momentum fluxes in the surface layer are based on similarity equations. The model employs a terrain-following coordinate system with a stretched vertical coordinate and a two-way interactive nested grid structure. Relatively small grid spacings can be employed to resolve mesoscale and small-scale phenomena. The stretched vertical coordinate permits small grid spacings at the surface so that near-surface wind shears and nocturnal stable boundary layers can be represented.

A four-dimensional data assimilation (4DDA) scheme based on a combined analysis and observation nudging technique has been incorporated in RAMS (Fast 1995, 1996) that is similar to the 4DDA scheme employed by MM5 (Stauffer and Seaman 1994). When 4DDA is used, the resulting flow fields are a combination of the predicted and observed variables when and where the observations may occur. In data sparse regions, only the model governing equations are used to predict the flow field. If the ARPS, MM5, or Eta models are used in this project, we will either adapt our 4DDA code or employ the existing data assimilation routines in those models.

Despite considerable improvements in mesoscale models over the past two decades, predicted and observed flows in basins and valleys often fail to agree, especially under stable conditions, and it is not always apparent why this occurs (Emanuel et al. 1995; Nappo and

Johansson 1998). By using 4DDA, the magnitude of the forecast errors will be reduced so that we can examine the vertical motions in the basin atmosphere. Improving mesoscale model forecasts by incorporating subgrid-scale terrain parameterizations and modifying turbulence parameterizations will be evaluated by another PNNL proposal *"Towards an Improved Prediction of Vertical Exchange Processes in Complex Terrain."*

Lagrangian particle dispersion model

A Lagrangian particle dispersion model (Fast and Berkowitz 1996), will be used to illustrate advection and diffusion processes encountered by passive particles that are emitted from various locations within the basin. Atmospheric dispersion is simulated by tracking a large number of particle positions determined from the mean velocity component produced by RAMS and a sub-grid scale turbulent velocity component. The turbulent velocities are computed by solving the Langevin equation by a Markov-chain formulation (Legg and Raupach 1982) and includes the Thomson formulation of the equation for the turbulent vertical velocity component (Hurley and Physick 1991). A Lagrangian model has certain advantages over the Eulerian approach including a better representation of point sources and no errors associated with the numerical treatment of advection. We have found this model to be very useful in explaining the role of atmospheric processes associated with pollutant transport (Berkowitz et al. 1998; de Wekker et al. 1998b; Doran et al. 1996; Fast 1995; Fast and Berkowitz 1996, 1997)

In our research, the particle model will be used in conjunction with the perfluorocarbon tracer experiments to illustrate and quantify the effect of vertical exchange processes within the basin atmosphere. Each particle is tagged by its release location and release time, so that the history of a particle plume can be derived that describes the meteorological processes associated with pollutant transport and diffusion. The meteorological processes can be determined by examining individual particle trajectories or groups of trajectories and identifying atmospheric quantities, such as the wind components, temperature, and turbulence kinetic energy vary along trajectory paths.

3.3.2 *Model experiments*

Field experiment design simulations

During the first project year, one or two of the mesoscale models described in the previous section will be employed to 1) examine basin circulations and vertical exchange processes associated with fall and winter pollution episodes for Salt Lake City and 2) identify recommended instrumentation sites for the VTMX field campaign. Routine air-quality measurements will be used to identify the fall and winter pollution episodes consisting of high concentrations of trace gases or particulates and low visibility, and existing meteorological measurements (Section 3.1.1) will be obtained to evaluate the models. The mesoscale model forecasts will be analyzed to find evidence of processes such as recirculation, ventilation, mountain venting, re-entrainment, and slope flow detrainment and determine how they affect vertical advection and diffusion during stable conditions. Based on the forecasts and the observations, we will identify regions in the basin where these processes are likely to occur, which will be helpful in choosing instrumentation sites for the VTMX field campaign. In this way, the likelihood of measuring the meteorological processes associated with vertical mixing

processes is increased. For example, a radar wind profiler located directly west of the base of Big Cottonwood Canyon (Fig. 3) may not be the best site to measure down-valley flows along the Wasatch Mountains. The model forecasts and observations may suggest that drainage flows exiting the canyon flow predominately to the northwest instead of directly into the basin. Using a mesoscale model as a tool prior to a field campaign proved to be very useful for DOE's field campaigns in Mexico City (Doran et al. 1998) and Phoenix (Doran et al. 1999). The instrument sites, as shown in Fig. 3, will be altered based on the findings of this study, as well as the needs of other investigators.

4DDA simulations

A series of simulations that employ continuous 4DDA will be performed after the VTMX field campaign to produce high spatial and temporal resolution analyses within the basin and in the regions surrounding the basin. The u and v component of the wind, potential temperature, and humidity measurements from the radar wind profilers, mini-sodars, airsondes, rawinsondes, and the mesonet will be incorporated by the mesoscale model. The 4DDA simulations will reconstruct the mesoscale features of the basin atmosphere with a high degree of confidence so that the predicted vertical motions associated with regions of convergence and divergence can be used to interpret how they affect the vertical transport of pollutants within the basin atmosphere.

Some work after the field campaign will involve organizing the data from several sources into a format that can be easily used by the model. This is valuable in itself, because files with a common data format will be created that can be used by a variety of analysis programs and three-dimensional graphics and animation programs to interpret and quality-check the data.

Our initial 4DDA simulations will focus on the six IOP periods of the perfluorocarbon tracer experiments. The frequency of the analysis fields that we will generate will be the same as the shortest averaging interval of the wind and temperature observations, which is usually 15 min for the surface data. If the simulation results show rapid changes in the winds over terrain slopes, then the fields will be saved at 5 min intervals. For example, our simulations for the Rocky Flats Plant and Mexico City field campaigns indicated that terrain-induced flows can change significantly during an hour-long period. Dispersion models that incorporate hourly-averaged meteorological fields will perform poorly in predicting the horizontal and vertical transport in these situations. On the other hand, we expect only small changes in the meteorological fields over a 5 min period because the smallest grid spacing will be between 200 and 500 m and higher frequency subgrid-scale turbulent motions are not explicitly resolved.

After the 4DDA simulations are completed, the Lagrangian particle dispersion model will be used with two release scenarios. For the first scenario, particles will be released from point sources to mimic the emission of perfluorocarbon tracers from the surface and the tops of tall buildings. A close correspondence between the predicted particle concentrations and the observed tracer concentration fields will provide evidence that the mesoscale analyses produced by 4DDA represent the major atmospheric motions responsible for the vertical and horizontal transport and diffusion in the basin. The transport history of the particles can then be used to deduce the vertical exchange mechanisms associated with the tracer transport. Mean and turbulent atmospheric quantities along the particle trajectories will reveal how surface emissions are transported upwards and how emissions from the height of the buildings are transported back down to the surface in stably stratified conditions. The ensemble history of the particle plume will be used to determine the mechanisms associated with preferred transport pathways and

regions of convergence indicated by the tracer data. Simulations will be run with meteorological fields specified at different time intervals ranging from 5 min to 1 h to determine the significance of rapidly changing drainage flows on vertical mixing.

The second scenario is similar to the first, except that particles will be released from a surface area encompassing the urban and suburban areas so that particles are likely to be mixed horizontally and vertically throughout the basin. The predicted particle concentration fields will be compared to the aerosol measurements made by DABUL. We will look for evidence of layering in the basin atmosphere and use the particle trajectory characteristics to determine the role of mean vertical motions in producing those layers.

Of course, there may not always be a close correspondence between the predicted particle concentrations and the observed tracer concentrations and aerosol distributions. The differences between the particle and tracer concentrations will be due to uncertainties associated with the mesoscale analyses. Because the 4DDA technique only nudges the model results towards the observations, relatively large errors in the simulated wind, temperature, humidity, and turbulence fields can occur if the model does not adequately represent the physical processes in the region. A number of factors may contribute to these errors. Sensitivity simulations without 4DDA will be performed to improve the model predictions as discussed in the following section. More sophisticated 4DDA techniques, such as variational methods (Daley 1991; Errico et al. 1993), may also be tested to determine whether they produce more accurate mesoscale analyses.

After the IOP simulations have been completed, more 4DDA simulations will be performed for non-IOP periods since we expect that most of the meteorological measurements will be made continuously throughout the four-week field campaign. Particle model simulations will also be performed using the two release scenarios to increase the number of cases we study, even though no perfluorocarbon tracer data will be available for the non-IOP periods. DABUL will run continuously during the field campaign, so measurements from this instrument will be available to compare with the particle model simulations. In this way, preferential convergence regions can be determined for additional synoptic conditions.

The calculation of a recirculation parameter, R, will be one of the approaches we employ to understand ventilation of the basin atmosphere. As described by Allwine and Whiteman (1994), R is based on air parcel trajectory characteristics that includes wind speed and direction variations. In our research, R will be calculated using the three-dimensional mesoscale analyses produced by the case-study simulations to examine the ventilation rate of the basin atmosphere. A value of R close to 0 indicates straight-line transport has occurred over a specified time period. When no net transport has occurred, there has been complete recirculation so that R is close to 1. An estimate of how well the basin atmosphere is ventilated can be obtained by determining how R varies in time and space. For example, in a previous study we found that particles emitted from the southwestern portion of the Mexico City basin had a higher probability of remaining within the basin during the evening (Fast and Zhong 1998a) than particles emitted from other regions. Particle trajectories revealed that recirculations associated with converging downslope drainage flows were responsible for this tendency. In this study, DABUL measurements will be used to qualitatively evaluate whether the elevation of the particle layers predicted by the model occur at about the same height as observed aerosol layers. If so, then values of R from the mesoscale analyses will be useful in determining the ventilation rate of the basin atmosphere and identifying certain regions of the basin that may be more prone to stagnation conditions. Since the synoptic conditions will affect the development of the cold pool and the ventilation of the basin atmosphere, we will also determine how R varies from day to day.

Additional 4DDA simulations will also be performed using only select data from the VTMX field campaign to assess how much data is needed to adequately represent the wind and temperature fields in the basin. These simulations will be identical to those described previously, except that one or more of the meteorological sites shown in Fig. 3 will be omitted. The data not assimilated by the model can then be used as an independent data set to evaluate the mesoscale fields. In this way, we can determine whether the model adequately predicts the characteristics of flows in certain areas of the basin without 4DDA and whether assimilating winds at one site indirectly improves the forecasts in another region.

Forecast simulations

An additional series of mesoscale model and Lagrangian particle model simulations will be performed similar to those described in the previous section, except that 4DDA will not be used. The purpose of these simulations is to determine 1) mesoscale model forecast errors and their effect on simulated vertical transport, 2) whether the urban canopy influences the basin-scale circulations and convergence and divergence patterns, and 3) how synoptic, regional, and local flows interact to either enhance or suppress the mixing of pollutants in the basin.

Although 4DDA is very useful in producing high-resolution analyses that can be used to describe the mean and turbulent motions associated with pollutant transport, the extra term in the governing equations masks the forecast errors that can occur and complicates the interpretation of some meteorological processes. Mesoscale model and particle model forecasts will be made for the same periods described in the previous section. The predicted winds, temperatures, and humidities will be compared with field campaign observations and analyses based on 4DDA to evaluate the performance of the model in simulating flows that affect basin circulations under stably stratified conditions. The predicted particle concentration fields will be compared to those obtained from the 4DDA simulations and the tracer data to determine the impact of forecast errors on horizontal and vertical transport. Statistical techniques will be used to quantify model performance and identify when and where large errors occur. We will focus on the prediction of convergence and divergence and the resulting vertical motions over the basin floor; however, smaller-scale processes that affect the basin circulations, such as the drainage flows originating along the Wasatch Front and the Oquirrh Mountains, will also be investigated.

When the predicted mean wind and temperature fields in the basin are significantly different from observations from the radar wind profilers, mini-sodars, airsondes, and surface stations, the vertical advection and diffusion processes are likely to be incorrect. A number of factors may contribute to the errors, including inadequate grid resolution, erroneous specification of the surface characteristics, uncertainties associated with model parameterizations, and poorly specified initial conditions. Although the operational NCEP models use dynamic initialization techniques, most mesoscale model research applications still employ static initial conditions. The VTMX field campaign provides a unique opportunity to determine the improvement in short-range forecasts in basins and valleys due to dynamic initialization. The model performance will be evaluated using static initial conditions based on NCEP's operational Eta model and dynamic initial conditions based on analyses produced by our 4DDA simulations that incorporate the field campaign data or ADAS. We will need to explore these and other possible explanations of why the mesoscale model predictions and analyses differ from observations.

A process not accounted for by most mesoscale models is the urban heat island effect. Near surface temperatures in many large metropolitan areas are often several degrees warmer

than the surrounding areas at night or during the winter. The impact of the urban heat island on local circulations has been difficult to assess because of an insufficient number of wind measurements and the uncertainties associated with the surface wind measurements in the urban canopy. It is possible that the dynamics and thermodynamics of the urban canopy may be large enough to affect the convergence and divergence patterns that affect the vertical transport of pollutants in the basin (Fig. 1). Although RAMS does not currently incorporate an urban canopy, there are several relatively simple parameterizations reported in the literature and we will incorporate one of them in the model. For example, Brown and Williams (1998) describe an urban canopy parameterization based on three landuse categories that accounts for momentum loss, turbulence production, and radiation attenuation in the governing equations of the model. Sensitivity simulations with and without an urban canopy will be performed for select periods of the VTMX field campaign to determine whether the inclusion of an urban canopy improves the model forecasts when compared with observations. We will examine how the urban canopy affects the simulated mean vertical motions, turbulence, and atmospheric stability and determine whether those effects have a significant impact on the vertical advection and diffusion by using the particle model.

Sensitivity simulations will also be performed that eliminate synoptic forcing, so that multi-scale flow interactions can be isolated. By removing the synoptic forcing, only the local and regional thermally-driven circulations will develop. If the predicted near surface processes are similar to the observations, then synoptic interactions probably do not have a significant influence on vertical advection and diffusion processes in the NBL. There may be a number of evenings during the field campaign in which strong cold pools develop near the surface that are nearly decoupled from the flows aloft. The middle and upper basin atmosphere, however, is likely to be affected to some extent by external forcing on a more regular basis.

Forecast and 4DDA simulations for individual periods during the field campaign will be made at the same time. If the forecast simulations indicate ways of improving the model performance, then the 4DDA simulations described in the previous section will be repeated. We intend to minimize the impact of 4DDA so that the model's dynamic and thermodynamic relationships are the primary drivers that determine the circulations that affect vertical transport and diffusion processes in the basin atmosphere.

3.4 Project Personnel

This project will build on expertise developed under previous DOE ASCOT and ACP support. Dr. Jerome D. Fast will be the principal investigator for the proposed work, participate in the field campaign, perform the model simulations, coordinate the data analyses, and interpret the data analyses and modeling results. He has extensive experience in using RAMS and the Lagrangian particle dispersion model for synoptic, mesoscale, and boundary layer applications.

Dr. Robert M. Banta will be responsible for deploying the DABUL instrument during the field campaign and analyzing the measurements. He has extensive experience with several types of lidar used during field campaigns associated with the DOE, NOAA, EPA, and other agencies. Dr. Russell N. Dietz will coordinate the perfluorocarbon tracer experiment during the field campaign and will be responsible for analyzing the tracer samplers. He has been involved in the planning, execution, and analysis of tracer data from numerous field campaigns. The assistance of John M. Hubbe, a field measurements expert, will be needed during the second project year to deploy the surface meteorological stations and the radar wind profiler during the field campaign.

The assistance of Xindi Bian after the first project year will be needed to perform analyses of the field campaign data. He has extensive experience in analyzing meteorological and chemical data associated with the ASCOT, Atmospheric Radiation Measurement (ARM), and ACP programs.

Biographical sketches for these scientists are attached at the end of the proposal.

3.5 Project Schedule

In the first year of this project, the field study design simulations discussed in Section 3.3.2 will be performed. The principal investigator will travel to Salt Lake City to select tracer sampler sites and obtain permission to deploy the samplers. The VTMX field campaign will probably take place at the beginning of the second year of the project, so that measurements discussed in Section 3.1.2 will be made at that time. Data reduction will be completed during the second project year and analyses of the meteorological, aerosol, and tracer data will be initiated. While the analyses described in Section 3.2 are being made, initial modeling studies of the IOP periods will be conducted. Modeling studies for IOP and non-IOP periods, based on the findings of the data analyses, will be performed primarily during the third and fourth project year.

During the fourth project year, we will synthesize the field campaign observations, data analyses, and modeling studies to develop a conceptual model of the formation of pollutant layers within a basin atmosphere during stable atmospheric conditions. Conceptual models of the heating and cooling of the atmosphere and the flows that develop within narrow valleys have been made (e.g. Whiteman 1990) based on observations, such as those collected during the ASCOT program in the Brush Creek Valley (Clements et al. 1989). The VTMX field campaign provides a unique opportunity to obtain a sufficient amount of information needed to develop a conceptual model that could be applied to other urban basins. We expect that that our conceptual model will describe how vertical mixing in the basin atmosphere is affected by strong, moderate, and weak synoptic conditions and by the surrounding terrain. As suggested by Petkovek (1978), convergence in the basin may be dictated largely by the geometry of the basin itself. Under weak synoptic forcing, stagnant conditions may exist in the basin atmosphere. Under strong synoptic forcing the basin atmosphere is likely to become more ventilated; however, this will depend on the upper-level wind direction. It is possible that synoptic flows would induce secondary motions that can recirculate pollutants within the basin atmosphere.

3.6 Relation to Other Proposals

Our work is a part of a closely related package of research proposals developed at PNNL. For example, two other investigators are proposing to use wind profiler measurements and tracer experiments in the vicinity of Salt Lake City. William J. Shaw's proposal *Processes Due to Drainage Winds into an Urban Basin"* describes measurements in the vicinity of Big Cottonwood Canyon and C. David Whiteman's proposal *"Vertical Transport Mechanisms in Evolving Urban Cold Pools"* describes measurements over the eastern slopes of the Oquirrh Mountains. A wind profiler and tracers at either of the locations proposed by these investigators are consistent with the needs of this proposal. Our proposal would utilize measurements of the local drainage flows over the eastern and western side of the basin that can affect the basin-scale circulations, while Shaw's and Whiteman's research will benefit from the meteorological information provided by our research. The findings of another modeling proposal by Jerome D. Fast *"Towards an Improved Predictions of Vertical Exchange Processes in Urban Basins and*

Valleys" that focuses on understanding and reducing forecast errors of mesoscale models will directly benefit the modeling component of this proposal. Vertical mixing processes in other basins, such as the Los Angeles basin, will be examined by Shiyuan Zhong under her proposal *"Vertical Exchange Mechanisms in Urban Basins: A Comprehensive Study using Existing Data* Our findings in the Salt Lake City basin will be compared to Zhong's findings to find common vertical exchange mechanisms among various basins. Small-scale turbulence processes in the stable boundary layer using Direct Numerical Simulation (DNS) techniques is the subject of Jim C. Barnard's proposal *"Vertical Mixing in Basins and Valleys: A Numerical Study using Direct Numerical Simulations of Turbulence."* Our simulation results may be able to provide that project with larger-scale parameters, such as profiles of wind and Ri, required for the initial and lateral boundary conditions of the DNS simulations.

We expect that other proposals from other laboratories and universities will be submitted that include deploying radar wind profilers, airsondes, mini-sodars, and lidars. Our research objectives depend on additional meteorological instrumentation to be deployed during the field campaign. The measurements and analyses made by this project will be made available to other VTMX investigators.

4. Subcontract or Consortium Arrangements

Our proposed research requires the assistance of scientists at NOAA's Environmental Technology Laboratory (ETL) and at DOE's Brookhaven National Laboratory (BNL) to obtain measurements during the VTMX field campaign. As described in Section 3.1.2, ETL will be responsible for deploying the DABUL instrument and analyzing the results and BNL will be responsible for performing the perfluorocarbon tracer experiments. The costs associated with ETL and BNL subcontracts are included in the budget.

5. Summary

Relatively little is known about the mean circulations and vertical exchange processes that develop within basins during stably stratified conditions. We have described a proposal that examines our hypothesis that *the mean vertical motions within a basin can be large enough to significantly affect the vertical transport and mixing of pollutants in stable conditions and to produce layers of pollutants within the basin atmosphere*. An accurate representation of the four-dimensional dynamic and thermodynamic fields in areas of complex terrain is required to examine this issue. We present an integrated measurements, analysis, and modeling program that will enable us to describe the characteristics of the convergence and divergence fields and the meteorological processes by which near-surface emissions along the basin floor are transported upwards and downwards within the basin atmosphere during stable conditions. During the VTMX field campaign, we will deploy five surface meteorological stations, a radar wind profiler, and a backscatter lidar. Several perfluorocarbon tracer experiments will also be conducted to help quantify how convergence and divergence patterns in the basin affect vertical transport. A series of modeling studies, with and without four-dimensional data assimilation, will be performed using a coupled mesoscale meteorological and Lagrangian particle dispersion model to elucidate the interactions of synoptic, mesoscale, and boundary layer processes responsible for the vertical advection and diffusion of pollutants. Multi-scale flow interactions are expected to form that will either enhance or suppress the mixing of pollutants.

LITERATURE CITED

Allwine, K. J., and C. D. Whiteman, 1994: Single-station integral measures of atmospheric stagnation, recirculation, and ventilation. *Atmos. Environ.*, 28, 713-721.

Alvarez II, R. J., W. L. Eberhard, J. M. Intrieri, C. J. Grund, and S. P. Sanberg, 1997: A depolarization and backscatter lidar for unattended operation in varied meteorological conditions. Preprints, *Tenth Symposium on Meteorological Observations and Instruments*, Phoenix, AZ, Amer. Meteor. Soc., 140-144.

Arritt, R. W., and G. S. Young, 1990: Elevated stable layers generated by mesoscale boundary-layer dynamics over complex terrain. Preprints, *Fifth Conference on Mountain Meteorology*, Boulder, CO, Amer. Meteor. Soc., 114-117

Astling, E. G., 1990: Numerical modeling of mesoscale circulation in the Great Salt Lake desert region. Preprints, *Fifth Conference on Mountain Meteorology*, Boulder, CO, Amer. Meteor. Soc., 98-103.

Banta, R. M., P. B. Shepson, J. W. Bottenheim, K. G. Anlauf, H. A. Wiebe, A. Gallant, T. Biesenthal, L. A. Olivier, C.-J. Zhu, I. G. McKendry, and D. G. Steyn, 1997: Nocturnal cleaning flows in a tributary valley. *Atmos. Environ.*, 31, 2147-2162.

Barickman, P. and S. Swart, 1997: Status report on the Wasatch Front ozone study. Utah Department of Air Quality, DAQT-078-97.

Berkowitz, C. M, J. D. Fast, S. Springston, R. Larson, C. Spicer, and P. Doskey, 1998: Formation mechanisms and chemical characteristics of elevation photochemical layers over the northeast United States. *J. Geophys. Res.*, 103, 10631-10647.

Blumental, D., and J. G. Watson, 1991: SJVAQS/AUSPEX collaborative field study plan. Preprints, *84th Annual Meeting and Exhibition of the AWMA*, Vancover, BC, Air and Waste Manage. Assoc., 1-20.

Bossert, J. E., 1997: An investigation of flow regimes affecting the Mexico City region. *J. Appl. Meteor.*, 36, 119-140.

Bossert, J. E., and W. R. Cotton, 1994: Regional-scale flows in mountainous terrain. Part II: Simplified numerical experiments. *Mon. Wea. Rev.*, 122, 1449-1471.

Brown, M. J., and M. D. Williams, 1998: An urban canopy parameterization for mesoscale meteorological models. Preprints, *Second Urban Environment Symposium*, Albuquerque, NM, Amer. Meteor. Soc., 144-147.

Chau, J. L. and B. B. Balsley, 1998: A statistical comparison of the VHF technique to study clear-air vertical velocities in the lower atmosphere using the Jicamarca radar. Preprints, *Fourth International Symposium on Tropospheric Profiling*, Snowmass, CO, 49-51.

Clements, W. E., J. A. Archuleta, and P. H. Gudiksen, 1989: Experimental design of the 1984 ASCOT field study. *J. Appl. Meteor.*, 28, 405-413.

Daley, R., 1991: *Atmospheric Data Analysis*. Cambridge University Press, 457 pp.

Davies, R. E., and D. A. Gay, 1993: A synoptic climatological analysis of air quality in the Grand Canyon National Park, *Atmos. Environ.*, 27A, 713-727.

de Wekker, S. F. J., S. Zhong, J. D. Fast, and C. D. Whiteman, 1998a: A numerical study of the thermally driven plain-to-basin wind over idealized basin topographies. *J. Appl. Meteor.*, 37, 606-622.

de Wekker, S. F. J., J. D. Fast, C. D. Whiteman, and S. Zhong, 1998b: Development and characteristics of the plain-to-basin wind. Preprints, *Eighth Conference on Mountain Meteorology*, Flagstaff, AZ, Amer. Meteor. Soc., 460-465.

de Wekker, S. F. J., M. Rucker, and D. G. Steyn, 1998c: Depressed mixed layer depths near a mountain base. Preprints, *Eighth Conference on Mountain Meteorology*, Flagstaff, AZ, Amer. Meteor. Soc., 373-379.

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

Doran, J. C., and S. Zhong, 1994: Regional drainage flows in the Pacific Northwest, *Mon. Wea. Rev.*, 122, 1158-1167.

Doran, J. C., S. Zhong, and C. M. Berkowitz, 1996: Meteorological factors affecting ozone profiles over the western North Atlantic. *J. Geophys. Res*., 28701-28710.

Doran, J. C., S. Abbott, J. Archuleta, X. Bian, J. Chow, R. L. Coulter, S. F. J. de Wekker, S. Edgerton, S. Elliot, A. Fernandez, J. D. Fast, J. M. Hubbe, C. King, D. Langley, J. Leach, J. T. Lee, T. J. Martin, S. Martinez, D. Apam, J. L. Martinez, G. Mercado, V. Mora, M. Mulhearn, J. L. Pena, R. Petty, W. Porch, C. Russel, R. Salas, J. D. Shannon, W. J. Shaw, G. Sosa, L. Tellier, B. Templeman, J. G. Watson, R. White, C. D. Whiteman, and D. Wolfe, 1998: The IMADA-AVER boundary-layer experiment in the Mexico City area. *Bull. Amer. Meteor. Soc*., 79, 2497-2508.

Doran, J. C., J. D. Fast, J. M. Hubbe, W. J. Shaw, R. L,. Coulter, T. J. Martin, M. Pekour, and J. D. Shannon, 1999: A boundary-layer field study in Phoenix. To appear in preprints, *Thirteenth Symposium on Boundary Layers and Turbulence*, Dallas, TX, Amer. Meteor. Soc.

Dudhia, J., 1993: A non-hydrostatic version of the Penn State-NCAR Mesoscale Model: Validation tests and simulation of an Atlantic cyclone and cold front. *Mon. Wea. Rev*., 121, 1493-1513.

Emanuel, K., D. Raymond, A. Betts, L. Bosart, C. Bretherton, K. Droegemeier, B. Farrell, J. M. Fritsch, R. Houze, M. Le Mone, D. Lilly, R. Rotunno, M. Shapiro, R. Smith, and A. Thorpe, 1995: Report of the first prospectus development team of the U.S. Weather Research Program to NOAA and the NSF. *Bull. Amer. Meteor. Soc*., 76, 1194-1208.

Errico, R. M., T. Vukicevic, P. Courtier, J. Derber, and J.-F. Louis, 1993: Workshop on adjoint applications in dynamic meteorology 23 – 28 August 1992, Pacific Grove, California. *Bull. Amer. Meteor. Soc.*, 74, 845-847.

Fast, J. D., 1995: Mesoscale modeling in areas of highly complex terrain employing a four-dimensional data assimilation technique. *J. Appl. Meteor.*, 34, 2762-2782.

Fast, J. D., 1996: Mesoscale modeling of pollutant dispersion using four-dimensional data assimilation. *Monthly Update, Atmospheric Chemistry Program*. Volume 7, Number 11.

Fast, J. D., and C. M. Berkowitz, 1996: A modeling study of boundary layer processes associated with ozone layers observed during the 1993 North Atlantic Regional Experiment. *J. Geophys. Res.*, 101, 28683-28699.

Fast, J. D. and C. M. Berkowitz, 1997: Evaluation of back trajectories associated with ozone transport during the 1993 North Atlantic Regional Experiment. *Atmos. Environ.*, 31, 825-837.

Fast, J. D. and S. Zhong, 1998a: Meteorological factors associated with inhomogeneous ozone concentrations within the Mexico City basin. *J. Geophys. Res.*, 103, 18927-18946.

Fast, J. D., and S. Zhong, 1998b: Recirculation patterns within the Mexico City basin. Preprints, *Eighth Conference on Mountain Meteorology*, Flagstaff, AZ, Amer. Meteor. Soc., 410-416.

Fast, J. D., S. Zhong, and C. D. Whiteman, 1996: Boundary layer evolution within a canyonland basin: Part II. Numerical simulations of nocturnal flows and heat budgets. *J. of Appl. Meteor*., 35, 2162-2178.

Fujita, E. M., et al., 1997: 1997 southern California ozone study (SCOS) operational program plan. Prepared by Desert Research Institute for the California Air Resources Board, Sacramento, CA.

Gaynor, J. E., and Y. J. Ping, 1992: Flow in a narrow sloping valley and implications to power plant transport. Preprints, *Sixth Conference on Mountain Meteorology*, Portland, OR, Amer. Meteor. Soc., 175-182.

Green, J. L., L. S. Gage, T. E. VanZandt, W. L. Clark, J. M. Warnock, and G. D. Nastrom, 1988: Observations of vertical velocity over Illinois by the Flatland radar. *Geophys. Res. Lett*., 15, 269-272.

Grund, C. J., and S. P. Sandberg, 1996: Depolarization and backscatter lidar for unattended operation. Advances in Atmospheric Remote Sensing with Lidar, Eighteenth International Laser Radar Conference, Berlin, Germany, Springer, 3-6.

Hayden, K. L., K. G. Anlaur, R. M. Hoff, J. W. Strapp, J. W. Bottenheim, H. A. Wiebe, F. A. Frouder, and J. B. Martin, 1997: *Atmos. Environ*., 31, 2089-2105.

Helfand, H. M., and J. C. Labraga, 1988: Design of a nonsingular level 2.5 second-order closure model for the prediction of atmospheric turbulence. *J. Atmos. Sci.*, 45, 113-132.

Hurley, P., and W. Physick, 1991: A Lagrangian particle model of fumigation by breakdown of the nocturnal inversion. *Atmos. Environ.*, 25A, 1313-1325.

Horel, J. D., L. Dunn, J. Stiff, J. W. Slemmer, B. G. White, M. E. Splitt, D. Zaff, S. M. Lazarus, C. M. Ciliberti, and D. Judd, 1999: The Utah mesonet. Submitted *to Bull. Amer. Meteor. Soc*.

Jauregui, E., 1988: Local wind and air pollution interaction in the Mexico basin. *Atmósfera*, 1, 131-140.

Lawson, D. R., 1990: The southern California air quality study, *J. Air Waste Manage. Assoc*., 50, 156-165

Lazarus, S., C. Ciliberti, and J. Horel, 1998: Application of a local analysis system in highly variable terrain. Preprints, *Sixteenth Weather and Forecasting Conference*, Phoenix, AZ, Amer. Meteor. Soc.

Legg, B. J., and M. R. Raupach, 1982: Markov-chain simulation of particle dispersion in inhomogeneous flows: The mean drift velocity induced by a gradient in Eulerian velocity variance. *Bound.-Layer Meteor.*, 24, 3-13.

Lu, R., and R. P. Turco, 1994: Air pollution transport in a coastal environment. Part I: Two-dimensional simulations of sea-breeze and mountain effects. *J. Atmos. Sci.*, 51, 2285-2308.

Lu., R., R. P. Turco, and M. Z. Jacobson, 1997: An integrated air pollution modeling system for urban and regional scales: 2. Simulation for SCAQS 1987. *J. Geophys. Res.*, 102, 6081-6098.

McKendry, I. G., D. G. Steyn, J. Lundgren, R. M. Hoff, W. Strapp, K. Anlauf, F. Froude, J. B. Martin, R. M. Banta, and L. D. Olivier, 1997: Elevated ozone layers and vertical down-mixing over the lower Fraser valley, BC, *Atmos. Environ*., 31, 2135-2146.

Mellor, G. L., and T. Yamada, 1982: Development of a turbulent closure model for geophysical fluid problems. *Rev. Geophys. Space Phys*., 20 (10), 851-875.

Moran, M. D., and R. A. Pielke, 1994, Delayed shear enhancement in mesoscale atmospheric dispersion. Preprints, *Eighth Joint Conference on Applications of Air Pollution Meteorology with the AWMA*, Nashville, TN, Amer. Meteor. Soc., 96-101.

Nappo, C. J., and P.-E. Johansson, 1998: Summary report of the Lovanger International workshop of turbulence and diffusion in the stable planetary boundary layer. *Bull. Amer. Meteor. Soc.*, 79, 1401-1405.

Nastrom, G. D., and T. E. VanZandt, 1994: Mean vertical velocities seen by radar wind profilers. *J. Atmos. Sci*., 33, 984-995.

Nastrom, G. D., M. R. Peterson, J. L. Green, K. S. Gage, and T. E. VanZandt, 1990: Sources of gravity wave activity seen in the vertical velocities observed by the Flatland VHF radar. *J. Atmos. Sci.*, 29, 783-792.

Neff, W. D., 1994: Mesoscale air quality studies with meteorological remote sensing systems. *Int. J. Remote Sensing*, 15, 393-426.

Neff, W. D., 1997a: The relation of vertical mixing, horizontal transport, and complex terrain to wintertime air pollution episodes along the northern Colorado Front Range. *Twelfth Symposium on Boundary Layers and Turbulence*, Vancouver, BC, Amer. Meteor. Soc., 532-533.

Neff, W. D., 1997b: The Denver brown cloud studies from the perspective of model assessment needs and the role of meteorology. *J. Air Waste Manag*., 47, 269-285.

Rucker, M., S. F. J. de Wekker, and D. G. Steyn, 1998: Analysis of mountain venting charcteristics from airborne lidar data. Preprints, *Eighth Conference on Mountain Meteorology*, Flagstaff, AZ, Amer. Meteor. Soc., 404-409.

Petkovsek, Z., 1978: Zones of convergence in local air flow in valleys and basins. Preprints, 15 Internationale Tagung Fuer Alpine Meteorologie, Grindelwald, Switzerland, 92-96.

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.

Schwartz, B. E., and S. C. Benjamin, 1995: A comparison of temperature and wind measurements from ACARS-equipped aircraft and rawinsondes. *Wea. Forecasting*, 10, 528-544.

Seaman, N. L., D. R. Stauffer, and A. M. Lario-Gibbs, 1995: A multi-scale four-dimensional data assimilation system applied in the San Joaquin Valley during SARMAP. Part I: Modeling design and basic performance characteristics. *J. Appl. Meteor*., 34, 1739-1761.

Shaw, W. J., J. M. Hubbe, and J. D. Fast, 1999a: Gravity currents in the northern Mexico City plateau. To appear in preprints, *Thirteenth Symposium on Boundary Layers and Turbulence*, Dallas, TX, Amer. Meteor. Soc.

Shaw, W. J., J. C. Doran, J. P. Krug, M. J. Fitch, M. D. Hubble, and R. Redman, 1999b: Heat fluxes and the evolution of boundary layer structure in Phoenix in the late spring. To appear in preprints, *Thirteenth Symposium on Boundary Layers and Turbulence*, Dallas, TX, Amer. Meteor. Soc.

Stauffer, D. R., and N. L. Seaman, 1994: Multiscale four-dimensional data assimilation. *J. Appl. Meteor.*, 33, 416-434.

Steyn, D. G., J. W. Bottenheim, and R. B. Thomson, 1997: Overview of tropospheric ozone in the lower Fraser Valley, and the Pacific ’93 field study. *Atmos. Environ*., 31, 2025-2035.

Stone, G. L., and D. E. Hoard, 1990a: Daytime wind in valleys adjacent to the Great Salt Lake. Preprints, *Fifth Conference on Mountain Meteorology*, Boulder, CO, Amer. Meteor. Soc., 216-223.

Stone, G. L., and D. E. Hoard, 1990b: An anomalous wind between valleys – Its characteristics and a proposed explanation. Preprints, *Fifth Conference on Mountain Meteorology*, Boulder, CO, Amer. Meteor. Soc., 209-215.

Stone, G. L., D. E. Hoard, G. E. Start, J. F. Sagendorf, G. R. Ackermann, N. F. Hukari, K. L. Clawson, and C. R. Dickson, 1989: 1987 Meteorological and tracer experiments at the Tooele Army Depot. LA-UR-89-1157.

Uliasz, M., and R. A. Pielke, 1998: Validation of regional transport simulations using a tracer of opportunity and controlled tracers. *Tenth Joint Conference on Applications of Air Pollution Meteorology with the AWMA*, Phoenix, AZ, Amer. Meteor. Soc., 112-116.

Whiteman, C. D., 1990: Observations of thermally developed winds systems in mountainous terrain. *Meteorological Monograph, Atmospheric Processes over Complex Terrain*, Volume 23, Amer. Meteor. Soc., 5-42.

Whiteman, C. D., T. B. McKee, and J. C. Doran, 1996: Boundary layer evolution within an canyonland basin. Part I: Mass, heat, and moisture budgets from observations. *J. Appl Meteor*., 35, 2145-2161.

Xu, M., K. K. Droegermeier, and V. Wong, 1995: The advanced regional prediction system and real-time storm weather prediction. *Proceedings of the International Workshop on Limited Area and Variable Resolution Models*, Beijing, China, World Meteor. Org.

Xu. Q., and C. J. Qui, 1995: Adjoint-method retrievals of low-altitude wind fields from single-doppler reflectivity and radial –wind data. *J. Atmos. Oceanic Technol.*, 12, 1111-1119.

Zhong, S., and J. C. Doran, 1998: Thermally-driven winds into the Mexico City basin through a mountain gap. Preprints, *Eighth Conference on Mountain Meteorology*, Flagstaff, AZ, Amer. Meteor. Soc., 426-431.