THE VTMX 2000 CAMPAIGN

BY J. C. DORAN, J. D. FAST, AND J. HOREL

A field campaign during October 2000 in the Salt Lake Valley focused on vertical transport and mixing (VTMX) at night and during morning and evening transition periods.

The Vertical Transport and Mixing (VTMX) campaign took place in the Salt Lake Valley during October 2000. It was sponsored by the U.S. Department of Energy (DOE) through their Environmental Meteorology Program (EMP), which is one of the principal components of the Atmospheric Sciences Program in DOE's Office of Science.

The goals of the VTMX program (www.pnl.gov/VTMX/) are to improve the understanding of the meteorological processes responsible for the vertical transport and mixing of quantities such as heat, momentum, and air pollutants in the atmosphere; to improve the ability to measure and characterize those processes; and to incorporate that improved knowledge into conceptual and numerical models that can be used to describe and predict them. The program is currently concentrating on nocturnal stable periods and the morning and evening transition periods, and it is further focused on urban areas located in valleys, basins, or other settings affected by nearby elevated terrain.

Studies of the stable boundary layer have long been challenging, and interest in this area of research remains high. There is a vast literature describing this work and we will not attempt to survey it here. A summary of much of the current state of understanding has recently been provided in a special issue of *Boundary-Layer Meteorology* (1999, Vol. 90, No. 3) and references contained therein. A recent major field program to study the properties of stable boundary layers was CASES-99 (Poulos et al. 2002), conducted in October 1999, whose goal was "to identify the sources and quantify the physical characteristics of the mixing phenomena that populate the stable boundary layers" (www.co-ra.com/cases/CASES-99.html). It featured a heavily instrumented central site near Leon, Kansas, and several satellite sites with more limited instrumentation 15–20 km away. Results are just starting to appear in the literature but there is already evidence for and useful data on an extensive array of interesting phenomena, including waves, low-level jets, intermittent turbulence, extreme stratification, and katabatic flows.

Most observational and modeling studies of meteorology and air quality in urban areas in or near complex terrain in North America and Europe have focused on the daytime convective periods. Examples of study sites include Los Angeles (Lu and Turco 1996; McElroy and Smith 1993); the San Joaquin Valley, California (Jacobson 2001); Phoenix, Arizona (Fast et al. 2000); Mexico City, Mexico (Doran et al. 1998); Vancouver, British Columbia (McKendry et al. 1997; McKendry and Lundgren 2000); and the populated regions adjacent to the Alps (Furger et al. 2000; Kossmann et al. 1998; Lehning et al. 1998). Analogous studies in stably stratified conditions are less common. Nevertheless, some work has been undertaken in or near a number of cities, particularly in the western United States. Examples include Denver, Colorado

AFFILIATIONS: DORAN AND FAST—Pacific Northwest National Laboratory, Richland, Washington; HOREL—University of Utah, Salt Lake City, Utah
CORRESPONDING AUTHOR: J. C. Doran, Pacific Northwest National Laboratory, P.O. Box 999, MSIN K9-30, Richland, WA 99352
E-mail: christopher.doran@pnl.gov

(Neff 1997); Roanoke, Virginia (Allwine and Lamb 1992); Phoenix (Grachev et al. 1999); Las Vegas, Nevada (Bowen et al. 1998); and Vancouver (Banta et al. 1997).

The Salt Lake Valley was chosen for the site of the first VTMX experimental campaign because it had a number of features that made it attractive for the study of stable boundary layers. It is bordered by the Wasatch Mountains to the east, the Oquirrh Mountains to the west, the Traverse Range to the south, and the Great Salt Lake to the northwest. There are a number of major canyons on the east side of the valley, including Parley's Canyon and Big and Little Cottonwood Canyons. Figure 1 shows a map of the study area and its surroundings. The downtown metropolitan area is located in the northeastern part of the valley. Thermally driven mountain and lake circulations typically develop during periods with weak synoptic forcing, which facilitated some aspects of the experimental design, particularly the deployment of samplers used in some tracer studies that are described later. The higher terrain surrounding Salt Lake City contributes to the formation of stable nocturnal cold pools each night that are normally broken up the following day in October but can persist for several days or even weeks in the winter. Downslope flows, canyon flows, waves, multiple elevated stable layers, and localized shear flows are all affected or generated by the topography. In addition, thermal contrasts between the Great Salt Lake 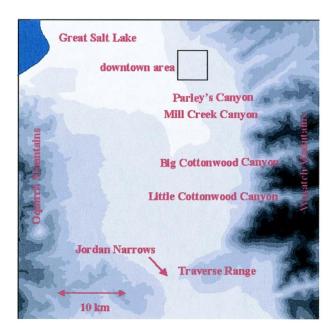and surrounding terrain drive land/lake breezes through the Salt Lake Valley. Although these factors complicate the analyses of the observations, they also provide an opportunity to study a wealth of interesting and important mechanisms affecting vertical transport and mixing. Finally, excellent local support was available in the form of an extensive network of surface meteorological stations, logistical assistance from the faculty and students at the University of Utah's Department of Meteorology in preparing for the study and in forecasting support, and the participation of a large number of the students in the field measurements themselves.

The VTMX program is currently providing funding to individual investigators from 14 different institutions, including 4 DOE national laboratories, 2 National Oceanic and Atmospheric Administration (NOAA) laboratories, 6 universities, 1 private research company, and the National Center for Atmospheric Research (NCAR). Although some of the research grants are predominantly for modeling studies, most of these institutions also had one or more participants in the field program. In addition, scientists from several collaborating organizations took part in the experimental campaign. A total of approximately 75 people, including numerous students, participated. A list of the DOE-funded organizations who took part in the experiment and the initials or abbreviated names used to refer to them later in this paper are given in Table 1.

Coincident with the VTMX campaign was a second one that focused on urban diffusion over considerably smaller spatial scales (Allwine et al. 2002). This second experiment was sponsored by DOE's Office of Nonproliferation Research and Engineering under the auspices of their Chemical and Biological National Security Program (CBNP). No formal arrangement between the two sponsoring programs was established but investigators from each collaborated closely in various logistical arrangements, instrument siting, and preliminary data interpretation during the measurement period, and extensive sharing of the data collected by both groups is anticipated. Some additional information on the CBNP measurements are provided later in this paper.

SCIENCE ISSUES. Within the framework of the general objectives that were given above, there are a number of more specific questions that have been raised by VTMX participants. The following list is not intended to be exhaustive, but it does indicate the range of interests and the variety of measurement, analytical, and modeling efforts that are features of the VTMX program.

FIG. 1. Map of the Salt Lake Valley. Contour intervals are 200 m.

Cold pools

- How do cold pools form and evolve and what are the primary mechanisms contributing to their breakup?
- How do drainage flows down slopes, canyons, and a valley interact with and contribute to the buildup of cold pools or other stratified layers in that valley?
- What is the nature of the interaction of the cold pools forming in the Salt Lake Valley with synoptic forcing and cold pools that develop over the Intermountain Basin?

Flow patterns and dispersion

- How do the convergent and divergent flow patterns that develop in the Salt Lake Valley as a result of thermal and terrain forcing generate organized vertical velocities?
- What are the preferred local patterns of motion at various scales and how are they related to the intensity and location of active areas of turbulence?
- How do pollutants accumulate in the Salt Lake Valley at night and to what extent are they ventilated out of the valley during the day?

Turbulence and waves

- How does the atmospheric boundary layer turbulence in an urban valley evolve during nonstationary periods, particularly during the transition period from day to night?
- What processes are responsible for the occurrence of intermittent turbulence?
- What are the characteristics of gravity waves found over the valley and how do they affect turbulence and mixing?

Modeling

- What insights can be provided by mesoscale modeling, large eddy simulations (LES), and direct numerical simulations (DNS) in the study of the role of gravity waves and shear instability processes on the flow evolution, turbulent mixing, and fluxes within the stable basin cold pool?

Miscellaneous

- To what extent can remote sensing instruments such as radar wind profilers, sodars, and Doppler

Table 1. Funded participants in the VTMX 2000 campaign.	
Organization	**Abbreviation**
Arizona State University	ASU
Argonne National Laboratory	ANL
Brookhaven National Laboratory	BNL
Colorado Research Associates	CORA
Desert Research Institute	DRI
Los Alamos National Laboratory	LANL
National Center for Atmospheric Research	NCAR
National Oceanic and Atmospheric Administration/ Atmospheric Turbulence and Diffusion Division	NOAA/ATDD
National Oceanic and Atmospheric Administration/ Environmental Technology Laboratory	NOAA/ETL
Pacific Northwest National Laboratory	PNNL
University of Massachusetts	UMass
University of Utah	UUtah

and Raman lidars be used to characterize features of the stable nocturnal atmosphere?
- What processes affect the dynamics and evolution of elevated stable layers and how do they differ from those found over simpler terrain?
- What are the sensible heat and roughness influences of the urban areas in the basin and how do they affect dispersion?

INSTRUMENTATION. A combination of in situ and remote sensing instruments was deployed for the VTMX campaign. These instruments are briefly described below. Their locations are given by a number in the text that can be used to locate their positions by referring to the corresponding numbers in Fig. 2 (top-left panel).

Radar wind profilers. Six radar wind profilers were deployed to provide a picture of the three-dimensional wind fields in the valley and to study selected turbulence features of the atmosphere. Three 915-MHz profilers were provided by ANL (site 9), LANL (site 5), and PNNL (site 7), and a 924-MHz profiler was obtained from Dugway Proving Grounds (site 11) under a subcontract to PNNL. In addition to these more conventional radar wind profilers, a turbulent eddy profiler (TEP; Mead et al. 1998) was operated by UMass (site 2). TEP has a densely packed array of 90 boundary layer wind profilers sharing a common transmitter
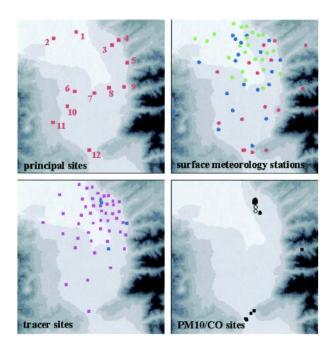
FIG. 2. Measurement locations in the Salt Lake Valley during the Oct 2000 VTMX experiment: (top left) principal instrument sites; (top right) surface meteorological network stations. The blue circles are existing long-term stations, the red circles are surface meteorological stations installed for the VTMX campaign, and the green circles are the sites of HOBO temperature loggers. (bottom left) PFT sampler locations (magenta squares) and release points (blue squares) for the valley-scale diffusion experiments; and (bottom right) PM10 monitors (filled squares) and CO monitors (open circles).

and can provide a time series of the three-dimensional atmospheric turbulence structure within a volume of the boundary layer at spatial resolutions comparable to those used in large eddy simulation (LES). Finally, NCAR (site 12) operated their multiple antenna wind profiler radar (MAPR). MAPR is also a 915-MHz system but points continuously in the vertical direction, in contrast to typical Doppler-based systems, allowing a continuous measure of the vertical motion.

Radio acoustic sounding systems (RASSs). A RASS is capable of measuring profiles of virtual temperature up to heights in excess of 1 km above the surface, although performance will vary with ambient conditions. A RASS was operated at five of the six wind profiler sites. The proximity of the profiler to local residences precluded the operation of a RASS at the site near the exit of Parley's Canyon (site 5). The RASS data, in conjunction with measurements from tethered sondes, rawinsondes, and surface instruments, will provide information needed to construct a three-

dimensional representation of the temperature structure in the Salt Lake Valley.

FMCW. UMass (site 2) deployed their S-band frequency modulated continuous wave (FMCW) radar profiler to complement their TEP by providing finer resolution profiles through the TEP volume. The FMCW's beamwidth was matched to the focused TEP resolution. For reflectivity measurements, the FMCW can provide over 10 subpixels for each TEP pixel.

Sodars. Monostatic sodars configured to measure 3D wind components were operated at four of the profiler locations (sites 2, 9, 11, 12), while at a fifth site (site 7) the sodar was limited to measuring along the vertical axis only. A vertical-only sodar was also operated at site 9. These instruments typically provide winds in the first 100–150 m above the surface, where the profilers do not collect data. Some sodars with greater ranges also provided overlapping data in the region covered by the lowest few range gates of the profilers, but with coarser vertical resolution. Several additional sodars were installed in the downtown area to support the data needs for the urban dispersion experiment.

Lidars. An infrared Doppler lidar (Post and Cupp 1990) was operated from a location near the center of the valley (site 6) by NOAA/ETL. This instrument was able to measure the radial component of the wind velocity over a substantial portion of the study domain, and was well positioned for monitoring lake breezes during the day and downvalley and downcanyon winds at night. Its range extended to the major canyons in the Wasatch Mountains on days when stagnant conditions allowed the haze levels to build up and dirtier air was carried into the canyons. At night, however, cleaner drainage winds out of the canyons reduced the level of backscatter and the detection range for the lidar became shorter. The horizontal resolution of the instrument was 300 m and its range varied between approximately 12 and 18 km.

LANL installed a high-resolution (1.5 m) Raman water vapor lidar (Cooper et al. 2000; Eichinger et al. 2000) in the southwest quadrant of the valley (site 11) to measure water vapor fluctuations in the developing slope flows on the flanks of the Oquirrh Mountains. The maximum range of this instrument was approximately 700 m.

Aerosol lidars were operated by NCAR (site 12) and by UUtah (site 4; Sassen 1994). NCAR operated their instrument in a vertically staring model while UUtah used both vertical staring and some limited sweeping modes for their measurements. These lidars

will provide information on the depth of the well-mixed layer during the day, the formation of layers at night, and the presence of waves.

Tethered balloons. Because of the air traffic in the area, tethered balloon operations were limited to the periphery of the valley. Tethered balloons were operated at four sites in the valley by ASU (site 3), ANL (site 9), PNNL (site 11), and NCAR (site 12) to obtain profiles of wind velocity, temperature, and humidity. A second tethered balloon was also deployed by ASU at site 3 to collect data on aerosol loading. PNNL deployed 4 tethered balloons along a line approximately 2 km in length to study the development of drainage flows along the slopes of the Oquirrh Mountains in the southwest corner of the valley (site 11). Three other tethered balloons were also deployed in the same area as part of a tracer study that is described below.

Rawinsondes. During intensive observing periods (IOPs) rawinsondes were released from three sites in the valley to obtain profiles of winds, temperatures, and humidity. The National Weather Service was contracted to obtain soundings at 2200 and 0200 local standard time (LST) in addition to their usual soundings at 1700 and 0500 LST (0000 and 1200 UTC, respectively) at site 1. A second site (site 8) was located at Wheeler Historic Farm approximately 11 km west of the mouth of Big Cottonwood Canyon. Students from UUtah took up to 13 soundings from this site during each IOP, with nominal release times of 1500, 1600, 1700, 1800, 2000, 2200, 0000, 0200, 0500, 0600, 0700, 0800, and 0900 LST. NCAR also took soundings at the south end of the valley (site 12). Release times at this site were 1700, 2000, 2200, 0000, 0200, and 0500 LST, and on some occasions an additional rawinsonde was released at 0800 LST.

Sonic anemometers. For turbulence measurements VTMX participants deployed 3D sonic anemometers at six sites distributed around the valley. Two ASU instruments were located at heights of 4.5 and 13.9 m at site 3 and UMass operated one at site 2 at a height of 3 m. Three sonic anemometers provided by NOAA/ATDD were placed at heights of 2, 10, and 20 m on towers at site 10. Additional sonics were installed at sites 7, 11, and 12 by PNNL; all of these latter instruments were mounted at elevations of approximately 9 m.

Surface stations. There are a number of existing surface meteorological stations distributed over the Salt Lake Valley and the surrounding area. They form part of the MesoWest network (Horel et al. 2000), and their data are routinely archived at the University of Utah. To supplement this existing network of surface meteorological stations, 13 weather stations were installed by PNNL and UUtah to measure wind velocities and temperatures and store the data at 5-min intervals. Additional weather stations were deployed at sites operated by ASU (site 3), PNNL (site 11), and NCAR (site 12). These instruments were further supplemented with 25 HOBO (Whiteman et al. 2000) sensors, which recorded temperatures continuously and stored them as 5-min averages. Figure 2 (top-right panel) shows the locations of these various stations. The data from the surface stations will be used to map the near-surface flows and temperature patterns throughout the valley.

A number of radiometers were also operated at locations throughout the valley, including two at site 3, several at the supplemental weather stations installed for the experiment, and one at site 11.

Tracers. BNL provided seven perfluorocarbon tracers (PFTs) and samplers for releases during six of the IOPs. The tracer data will be used to study convergence and divergence patterns in the valley and the interactions of slope flows with cold pools. Four PFTs were released for the former studies, two in the downtown area and two farther south. In the downtown area, one release was near street level while the other was from the top of a nearby building 30 m high. One of the southern release points was selected to provide information on the effects of winds from Parley's Canyon; the second, located at Wheeler Farm (site 8), was chosen to help characterize flow patterns closer to the center of the valley and well within the cold pools forming there. Releases at the two downtown sites began at 0000 LST and continued for 6 h. Releases at the southern sites began at 2200 LST and continued for 8 h. Fifty samplers were programmed to obtain 2-h samples beginning at 2200 LST and continuing until 1200 LST the following afternoon. Six additional samplers were programmed to obtain 4-h samples; these were operated for periods ranging from 24 to 48 h beginning at 2200 LST. Figure 2 (bottom-left panel) shows the locations of these tracer release and sampling sites.

For the slope flow studies (site 11) three additional PFTs were used. These were released at three different heights, ranging from 0.5 to 30 m, using balloon-borne release tubes. Two arcs of surface samplers were deployed approximately 1- and 3-km downslope from the release site. There were 13 samplers in the closer

arc and 15 in the arc farther downslope and the sampling times ranged from 30 minutes to several hours. In addition two sets of sampling tubes were carried by two tethered balloons deployed in the farther downslope sampling arc to obtain tracer concentrations aloft. The sampling tubes collected samples up to 125-m elevation in 5-m increments. To capture the initiation and breakup of slope flows, sampling began around sunset or sunrise and continue for several hours thereafter.

The release heights were chosen to lie in or above the slope flows forming on the lower reaches of the Oquirrh Mountains, while the sampling heights were chosen to encompass the most stable lower portion of the cold pool forming in the valley at night. Tracers released at one height and detected at another would therefore provide information on the vertical coupling and interaction of slope flows and the cold pool.

To study the accumulation of particles and carbon monoxide (CO) in the nocturnal boundary layer and the interchange of air between the Salt Lake Valley and Utah Valley to the south, DRI deployed sets of aerosol monitors and CO detectors. The latter instruments were located in the downtown Salt Lake City area while the former were located there, at the southern end of the Salt Lake Valley, and in Big Cottonwood Canyon (Fig. 2, bottom-right panel). ASU also deployed a tapered element oscillating microbalance device for continuous aerosol sampling at a height of 2.8 m on the roof of their instrument trailer at site 3.

As noted earlier, the CBNP conducted their own urban dispersion field campaign during the VTMX campaign. The primary goal of the modeling and prediction initiative within the CBNP is the accurate prediction of chemical and biological agent dispersal that might occur in an urban environment from potential terrorist activities. Sulfur hexafluoride (SF_6) tracer was released in downtown Salt Lake City at the VTMX PFT surface release site (Fig. 2, bottom-left panel) and sampled by 145 integrated samplers and six fast-response analyzers to investigate transport and diffusion around downtown buildings and through the main Salt Lake City urban area. PFT samples were also collected at 40 locations in downtown Salt Lake City to enhance the coverage of VTMX sampling of four PFTs released by VTMX. The CBNP also deployed a radar wind profiler/RASS as well as several sodars, surface meteorological stations, temperature sensors, sonic anemometers, and two lidars. The data will be used to test and refine atmospheric dispersion models being developed to respond to potential releases of toxic agents. A description of this campaign will be published separately (Allwine et al. 2002).

Instrumented aircraft. NOAA/ATDD flew the LongEZ (www.noaa.inel.gov/frd/Capabilities/LongEZ) instrumented aircraft on several nights of the campaign. North–south patterns covered both sides of the valley at the lowest legal altitude (300 m above ground) including frequent passes near the tower-mounted sonic anemometers at site 10. The horizontal structure of wind, temperature, and turbulence was sampled as it varied in response to the canyon flows out of the Wasatch Mountains on the east and the west side current draining toward the Great Salt Lake.

Microbarograph Array. An array of six microbarographs was operated by NOAA/ATDD at site 7 to capture perturbation surface pressure data. The data were sampled at 10 Hz from which 1-s averages were calculated and stored. Because a 0.01-K change in reference chamber temperature results in about a 3.3-Pa change in the reference chamber pressure, aluminum slugs were placed in the chamber to increase thermal inertia and the chamber was kept in an ice-filled 10-gal (38 L) cooler. To avoid saturation or damage to the sensor, the reference pressure was reset to atmospheric pressure every 90 min by opening a solenoid-controlled valve on the chamber. The microbarograph data will be used to study the incidence and characteristics of gravity waves moving over the central part of the valley.

INTENSIVE OBSERVING PERIODS. Much of the instrumentation that was deployed, such as the conventional radar wind profilers and the surface meteorological stations, operated on a continuous basis throughout the duration of the measurement campaign. Other instruments either required hands-on attention (e.g., radiosonde and tethered sonde flights, tracer releases, and sampler collection) or involved the generation of such large volumes of data (TEP) that routine data collection was impractical. Accordingly, on selected nights when the meteorological conditions were particularly favorable for the purposes of the VTMX study, an IOP was held. These typically commenced with a radiosonde release at 1500 LST and continued through the night into the following morning or early afternoon. The last radiosonde release normally took place at 0900 LST, but some other observations occasionally continued for several hours after.

In all, 10 IOPs were held. Because of instrument malfunctions, logistical and funding limitations, and other reasons, not all instruments were operational in each IOP. Table 2 gives a list of the IOPs conducted

TABLE 2. List of IOPs, their dates, and status of some of the major instruments. An "x" in a box indicates that the instrument was operating during the period indicated.

	2–3 Oct IOP 1	6–7 Oct IOP 2	7–8 Oct IOP 3	8–9 Oct IOP 4	14-15 Oct IOP 5	16–17 Oct IOP 6	17–18 Oct IOP 7	19–20 Oct IOP 8	20–21 Oct IOP 9	25–26 Oct IOP 10
Profiler site 9	x	x	x	x	x	x	x	x	x	x
MAPR site 12	x	x	x	x	x	x	x	x	x	x
Profiler site 11	x	x	x	x	x	x	x	x	x	x
TEP site 2	no	x	x	x	x	x	x	no	no	no
Profiler site 5	x	x	x	x	x	x	x	x	x	x
Profiler site 7	no	x	x	x	x	x	x	x	x	x
Doppler lidar	x	x	x	x	x	x	x	x	no	x
Tsondes site 3	x	x	x	x	x	x	x	no	no	no
Tsonde site 5	x	x	x	x	x	x	x	x	no	x
Tsonde site 12	x	x	no	x	x	no	x	x	no	x
Tsonde site 9	x	x	x	x	x	x	x	x	no	x
Tsondes site 11	P.M. only	P.M. only	P.M. only	A.M. and P.M.	A.M. and P.M.	A.M. only	no	A.M. only	no	P.M. only
Rawinsondes site 1	x	x	x	x	x	x	x	x	no	x
Rawinsondes sites 8	x	x	x	x	x	x	x	x	4 only	x
Rawinsondes site 12	x	x	x	x	x	x	x	x	no	x
PFT tracer	no	x	no	x	x	no	x	x	no	x

during the campaign as well as some information on which instruments were operating during each IOP. The first IOP ended with the release of the last radiosonde at 0800 LST. IOP 3 was terminated around 2300 LST because of windy conditions. During IOP 8, radiosonde releases were made only at 1500, 1700, 1900, and 2100 LST. The release of radiosondes on all of the other IOPs continued until 0900 LST.

SYNOPTIC CONDITIONS. *Synoptic conditions during VTMX.* Weather conditions in the Salt Lake Valley during October usually reflect a transition from the relatively dry conditions observed during September to the onset of major winter storms during November (Pope and Brough 1996). October 2000 was representative of that transition: warm and dry conditions prevailed for the first 10 days, a couple of storms interrupted field operations during the middle of the month, and operations ended after 26 October due to inclement weather. Overall, October was cooler and wetter than normal based upon long-term records at the Salt Lake City International Airport. The large-scale midtropospheric circulation during the month was characterized by split flow over the western United States.

Nocturnal stable boundary layers were found during roughly two-thirds of the month. For example, strong surface-based inversions (greater than 5 K in the lowest 100 hPa) were observed during 15 of the 31 morning (0500 LST) soundings at the Salt Lake City International Airport. Weak surface invasions with stable layers aloft below the crest of the Wasatch Mountains were evident during 5 other mornings while well-mixed conditions were present during the other 11 mornings. The winds at 700 hPa (near the crest of the Wasatch Mountains) were less than 10 m s^{-1} in 19 of the 31 morning soundings.

The operational design of the VTMX experiment assumed that sufficient mixing would occur during the afternoon to remove from the valley tracers released during the early morning or the previous evening. (Nevertheless, PFTs were never released on two successive nights to avoid possible contamination from tracers released in an earlier IOP.) Such mixing occurred nearly every afternoon as a result of the lake breeze from the Great Salt Lake and local valley–mountain circulations. The strength of the mixing from these diurnal circulations, coupled with the occasional occurrence of strong easterly downslope flows and the passage of frontal systems, helped to remove particulates and aerosols typically present in the Salt Lake Valley during October. PM-10 records provided by the the Utah Air Monitoring Center showed reduced concentrations during the month compared to those measured during previous years. In fact, October 2000 had the lowest particulate concentration of the calendar year and the particulate concentration was half that observed during October 1999. A consequence of the relatively clean air was that some remote sensors that rely upon aerosols being present had reduced ranges during much of the field program.

Synoptic and mesoscale conditions during IOPs. Prior to the field experiment, at least three categories of meteorological conditions were identified as especially interesting: 1) clear skies and light winds at the surface and aloft, 2) clear skies and light winds near the surface but moderate to strong winds aloft, and 3) light winds at the surface and aloft but with cloudy skies. The primary conditions defined to be ideal for an IOP were the development of typical nocturnal drainage flows in the Salt Lake Valley. Those drainage flows are normally accompanied by well-defined surface inversions and weak winds at the crest level of the Wasatch Mountains (i.e., 700-hPa winds less than 10 m s^{-1}). As noted above, the general conditions required to conduct an IOP were found during roughly two-thirds of October.

Forecast support for the field program was provided by faculty, staff, and students of the UUtah's Department of Meteorology. In addition to output from NCEP operational models, forecasters relied upon 12-km horizontal resolution forecasts from the Pennsylvania State University–NCAR fifth-generation Mesoscale Model (MM5) (run twice daily at UUtah) and 4-km resolution forecasts from the Regional Atmospheric Modeling System (RAMS) model (provided daily by CORA) to brief team scientists on the conditions likely to be present the next day. Early in the field program, it became apparent that the conditions desired for the tracer studies on the western slope of the Salt Lake Valley (site 11) tended to be incompatible with those best suited for releases in downtown Salt Lake City, and it was quite difficult to predict which conditions would prevail. For example, tracer studies in the downtown area benefited from along-valley drainage (north–south oriented) flows but an along-valley component to the slope drainage (west–east oriented) flows from the Oquirrh Mountains was not favorable for tracer studies on the western slope. A strong radiation inversion and weak along-valley winds were best for the latter studies, but if the nocturnal radiation inversion was too strong, then the flow became too light in the downtown area to avoid nearly isotropic dispersion of the tracers there.

Suitable weather conditions for operations separated by sufficient breaks between IOPs to allow for rest led to 10 IOPs during the month. All three categories of meteorological conditions defined above to be of interest prior to the start of the field program were observed. The IOPs can be grouped into two general categories: 1) those with well-developed drainage circulations into the Salt Lake Valley during which the synoptic and mesoscale circulations were largely irrelevant (first category), and 2) those during which the drainage circulations were modulated during the IOP by synoptic and mesoscale weather systems (second and third categories.)

IOPS WITH WELL-DEVELOPED DRAINAGE CIRCULATIONS. IOPs 5 (14–15 October), 6 (16–17 October), and 8 (19–20 October) can be characterized by clear skies, weak winds aloft at crest level, strong nocturnal radiation inversions, limited moisture in the boundary layer, and pronounced drainage flow into the Salt Lake Valley from the west, south, and east. The surface-based inversions and drainage circulations developed after sunset and persisted without significant interruption until sunrise. While the synoptic and mesoscale conditions present during these periods helped to develop these stable boundary layers, the large-scale conditions were for the most part irrelevant to IOP operations.

IOPS MODULATED BY SYNOPTIC AND MESOSCALE WEATHER SYSTEMS. IOP 1 (2–3 October) was intended to test operational procedures for the field program. Operations during the evening were conducted under clear skies with drainage flows developing as the evening progressed. However, a synoptic-scale northerly pressure gradient developed overnight to such an extent that northerly winds began to penetrate into the northern end of the Salt Lake Valley before midnight and eventually reversed the downvalley (southerly) flow through the center of the valley. Drainage circulations down into the valley from the Oquirrh and Wasatch Mountains were largely unaffected, however.

IOPs 4 (8–9 October) and 7 (17–18 October) exhibited similar boundary layer structure to those in the first category until 0500 LST. Prior to that time, clear skies, weak winds aloft, and strong surface-based radiation inversions prevailed. As a result of approaching upper-level troughs from the west, however, the nocturnal inversions were then eroded in these two instances both by surface heating and by mixing due to the downward penetration of southerly winds from aloft.

During IOPs 2 (6–7 October) and 3 (7–8 October), split flow aloft was present with weak upper-level short waves to the southwest and northeast of Utah. A strong outbreak of cold air to the east of the Continental Divide progressed westward on 6 October and overnight. By 0000 LST, easterly flow developed through gaps in the Wasatch Mountains and spilled through Parley's Canyon into the Salt Lake Valley. At 0300 LST, the depth of the cold air to the east of the Wasatch Mountains built to sufficient height to spill over the lower terrain from Mill Creek Canyon to the area near the University of Utah in the northeast corner of the Salt Lake Valley and led to gusts in excess of 20 m s^{-1} that penetrated 1–2 km into the valley at the surface. These downslope wind conditions occur frequently along the Wasatch Mountains and the data collected during VTMX 2000 will provide considerable insight into their formation. The third IOP began at 1500 LST on 7 October and was terminated before midnight. Strong downslope winds persisted into the evening in the northeastern corner of the Salt Lake Valley and winds in the western part of the valley were too turbulent to permit tethersondes operations.

Conditions during the last two IOPs (IOP 9: 20–21 October and IOP 10: 25–26 October) were affected significantly by approaching upper-level troughs. Both began in the afternoon with weak short-wave ridges overhead. Skies were broken to overcast and the strength of the nocturnal surface inversion and drainage circulations were weaker than those present during the other IOPs. A cold front entered the Salt Lake Valley at 0500 LST 21 October, ending operations during IOP 9. Southerly surface winds were enhanced during IOP 10 and provided favorable conditions for the final tracer release for the downtown region.

OBSERVATIONS AND PRELIMINARY ANALYSES. In this section we provide a brief description of some of the observed wind, temperature, and turbulence features found in the Salt Lake Valley during VTMX 2000. These will serve to give an impression of the "typical" conditions found during periods with weak synoptic forcing and generally cloud-free skies. They will also provide some context for the more detailed ongoing investigations that will be the subject of later publications. More detailed analyses of the data are still in their early stages so we provide only a few examples of some of the features that individual investigators are studying.

Flow patterns. Surface observations from instruments deployed for the VTMX field program as well as the
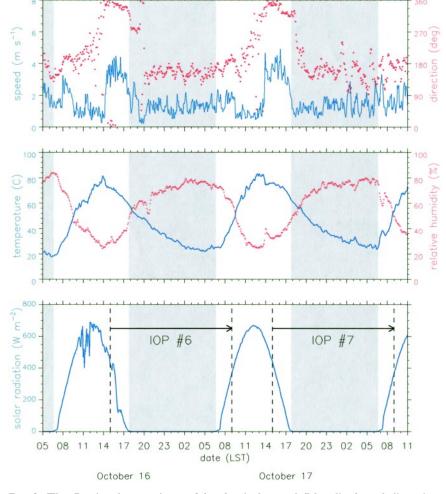
FIG. 3. The 5-min observations of (top) wind speed (blue line) and direction (red circles), (middle) temperature (blue line) and relative humidity (red circles), and (bottom) solar radiation at a site near the center of the basin during IOPs 6 and 7 near site 7.

mountains contributed to divergence out of the valley in the afternoon and convergence into the valley at night. Preliminary analyses of surface wind observations collected during VTMX indicate that the afternoon outflow/nocturnal inflow signature dominated 13 days of the field program.

On such days, by late morning or early afternoon, the prevailing flows over much of the valley are generally from the north and northwest, driven by the lake breeze and enhanced by upslope flows toward the higher terrain, particularly the Wasatch Mountains on the east side of the valley. Within a few hours past sunset, the flows reverse and are primarily from the south. Katabatic downvalley, downslope, and downcanyon flows all contribute to the general south to north or northwest flows. The winds from Parley's Canyon are normally among the strongest observed entering the val-

large number of observations available routinely as part of MesoWest (Horel et al. 2000) provided an unprecedented picture of the near-surface wind field in the Salt Lake Valley during stable conditions. In the absence of strong synoptic disturbances and under clear skies, the characteristic flow patterns observed in the valley in October are dominated by topographic features and the thermal contrast between the land surfaces and the Great Salt Lake. Based upon a lake temperature sensor at Hat Island installed by UUtah, the lake surface temperature was 294 K at the beginning of the month and dropped to 283 K by the end of the month. The diurnal air temperature range in the Salt Lake Valley was commonly 10–15 K during the month, leading to positive land–lake temperature differences during the afternoon and negative land–lake differences at night. Thermal contrasts between the Salt Lake Valley and the surrounding

ley, with speeds in excess of 8 m s⁻¹ common. Flow through the Jordan Narrows, the gap in the Traverse Range on the northern end of the Salt Lake Valley, is of equal or larger magnitude and reverses diurnally, probably in response to the combined effects of the lake–land temperature contrasts and possible temperature contrasts between the Salt Lake Valley to the north and Utah Valley to the south. In the downtown metropolitan area of Salt Lake City located in the north-central and northeastern sections of the valley shown in Fig. 1, the winds tend to be significantly lighter.

Figure 3 gives an example of this behavior at a site near site 7 (Fig. 2) around the center of the valley during the period encompassing IOPs 6 and 7 (Fig. 6 shows observed wind and temperature patterns over the whole valley). The gray areas in Fig. 3 indicate times when the sun was below the horizon, as can be
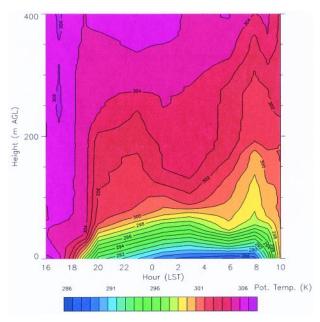
FIG. 4. Time–height cross section of potential temperature obtained from rawinsondes released from Wheeler Historic Farm (site 8) during IOP 4.
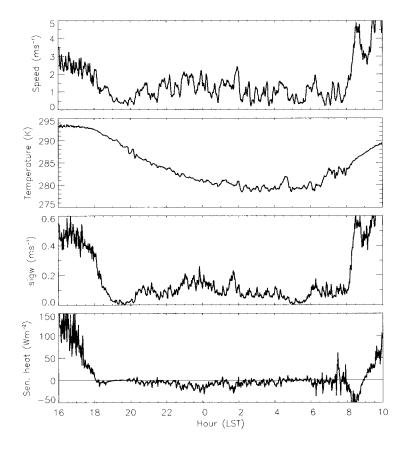
seen in the bottom panel, which shows the time variation of the solar radiation. The Wasatch Mountains shade the basin in the early morning, as indicated in the sharp increase in solar radiation after sunrise, and affect the development of the boundary layer in the morning transition period. The top panel shows how the wind speeds increase in mid- to late afternoon as the lake breeze arrives and the winds shift to northwesterly. After sunset the winds drop and the wind directions change to become generally downvalley. The middle panel shows the evolution of the temperature and relative humidity. A drop in temperature and an increase in relative humidity with the onset of the lake breeze around 1400 LST on 17 October is evident.

Cold pools and turbulence near the surface. We begin this discussion with an example of the development and evolution of a cold pool that forms near the

center of the valley. Figure 4 shows a time–height cross section of potential temperature in the lowest 400 m of the valley derived from a series of 13 rawinsonde ascents from site 8 on the night of 8–9 October, IOP4. The cooling on this night was especially strong and the cold pool reached its maximum strength around 0300 LST. The potential temperature gradient in the lowest 100 m of the atmosphere at this time was approximately 130 K km^{-1}. The radar wind profiler at site 7 showed moderate winds developing during the course of the night, reaching values in excess of 10 m s^{-1} at the lowest range gate (140 m AGL) before sunrise around 0640 LST (not shown). The strong static stability in the surface layer shown in Fig. 4 effectively decoupled this region from the flows aloft, however. This can be seen in Fig. 5, which shows a time series of wind speed; virtual temperature, σ_w; and sensible heat flux as measured by a sonic anemometer also located at site 7; the height of the sonic was approximately 9 m. The winds indicated by the sonic are very light, the strong cooling near the surface can be seen in the virtual temperature trace, and the low values of σ_w are indicative of the suppressed turbulence in this cold pool. The sensible heat fluxes are quite small and the fluxes are also intermittent; that is, much of the net flux of heat toward the sur-

FIG. 5. (top) Time series during IOP4 of wind speed, (second) virtual temperature, (third) σ_w, and (bottom) sensible heat flux as measured by a sonic anemometer at site 7.
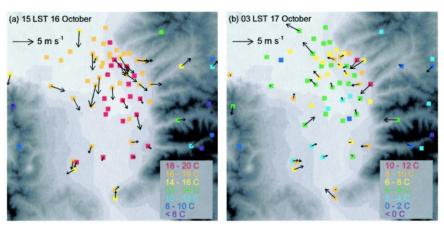
FIG. 6. Observed winds (arrows) and temperatures (squares) from the mesonet, special surface meteorological stations, and the HOBOs at 1500 LST 16 Oct (left) and 0300 LST 17 Oct (right) during IOP 6.

face during the period between 1900 and 0700 LST occurs over relatively short time intervals, while the flux between these intervals is nearly zero.

Flow convergence and divergence. Figure 6 shows an example of the wind and temperature values measured at the sites of the various surface meteorological networks at 1500 LST on 16 October and 0300 LST on 17 October. The reversal of the flow patterns, from upvalley and upslope during the day to downvalley and downslope during night can be readily seen, as can the nocturnal urban heat island and the changes in the temperature gradients from midafternoon to early morning. The nighttime surface wind field shown in Fig. 6 (right panel) indicates that the downslope flows decelerate over the lower slopes of the basin sidewalls while the downvalley flows accelerate at the northern end of the basin. This complex flow pattern should produce regions of convergence and divergence over the basin floor that vary in time and space.

An example of converging flows above the surface during IOP 8 is given in Fig. 7. Figure 7a shows results from the Doppler lidar (site 6 in Fig. 2) at 0630 LST just before sunrise on 20 October. In this figure, red and orange denote air flowing toward the lidar and green and blue denote air flowing away from the lidar. The black arrows are used to help illustrate features of the wind fields. The strong southerly winds observed in the center of the basin are consistent with observations from the rawinsonde released from Wheeler Farm (site 8) about 13 km east of the lidar site at 0700 LST. The wind speeds over the center of the basin are approximately 10 m s^{-1} but decrease significantly toward the east. A low-level jet maximum

at 400 m AGL with southeasterly winds at 5.5 m s^{-1} was observed at Wheeler Farm. The lidar also measured relatively strong flows exiting Parley's Canyon and Big Cottonwood Canyon. The lidar measurements suggest that a region of convergence was produced 5 to 10 km east of the lidar site.

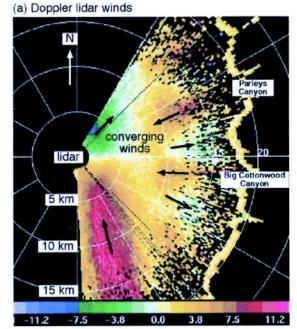To study the mean vertical motions that arise from the interaction of the downvalley and downslope flows, a mesoscale model (Pielke et al. 1992) was run, with a 550-m horizontal grid spacing, to simulate the mean vertical motions in the basin. The simulated winds at 100 m AGL produced many but not all of the features seen in the lidar observations, as shown in Fig. 7b. The black arrows again illustrate features of the local flows for comparison with the lidar results in the top panel. Maximum simulated downvalley wind speeds approached 10 m s^{-1} while the flows exiting Parley's Canyon were around 7 m s^{-1}. The modeled downslope winds near Big Cottonwood Canyon were confined to the canyon, however, and did not propagate out over the basin floor at this elevation. Over the center of the basin where the downvalley and Parley's Canyon flows converge, a narrow band of rising motions greater than 5 cm s^{-1} was simulated (Fig. 7c). Strong sinking motions were produced as the flow from Parley's Canyon descended into the basin. The complex topography of the Salt Lake Valley thus produces vertical motions much stronger than those generally associated with typical synoptic systems. While a 5 cm s^{-1} vertical velocity may still seem small, it is enough to transport an air parcel vertically by 180 m over the course of an hour. The converging flows persist for several hours so that the mean vertical motions, combined with differential horizontal advection, can contribute significantly to both horizontal and vertical pollutant transport over the area. This contribution is particularly important if turbulent mixing is otherwise suppressed by the stable stratification. Over the downtown metropolitan area the motions are generally sinking, which would tend to trap pollutants in that region during the nighttime hours. Thus, pollutants may either be vented out of the nocturnal boundary layer by the flows converging in the basin or trapped in the layer

by divergent flows in other locations. This will be a subject for future research.
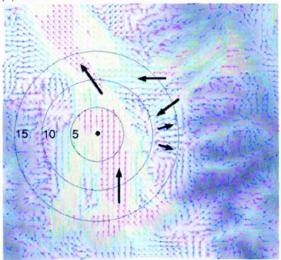
Stratified layers and waves. Understanding the formation of stratified layers aloft and their evolution during the night is an important component in the development of a more complete picture of VTMX processes. These layers often exhibit wavelike features, may ascend or descend with time, and are typically transient with lifetimes of a few minutes to few tens of minutes. They can be detected from backscattered sound or light using sodars and lidars, respectively, or as pressure fluctuations recorded by microbarographs. Such features were found frequently during the VTMX 2000 campaign and examples are given in Fig. 8. Figure 8a shows sodar data collected at site 9, along the east edge of the valley, on the morning of 10 October. The data reveal a combination of ascending (e.g., elevated red trace between 0616 and 0630 LST), fixed (e.g., green layer near 450 m between 0800 and 0830 LST), and descending layers (e.g., the elevated green trace between 0915 and 0930 LST), as well as evidence for waves. Such behavior was regularly seen at this site during the course of the measurement campaign. Relatively fixed elevated layers are shown in Fig. 8b for the south end of the valley at site 12 on 5 October (e.g., elevated green layers between 0205 and 0230 LST), and in Fig. 8c for site 4 on the eastern sidewall on 16 October (e.g., between 2340 and 0130 LST) by vertically pointing lidars. The regular oscillations in surface pressure measured by the microbarograph deployed at site 7 (Fig. 8d) may be the result of gravity waves. A search will be made for wavelike features obtained from other instrumentation deployed elsewhere in the valley.

SUMMARY. A meteorological field campaign to study vertical transport and mixing processes was carried out in the Salt Lake Valley during October 2000. The focus of the campaign was on nocturnal
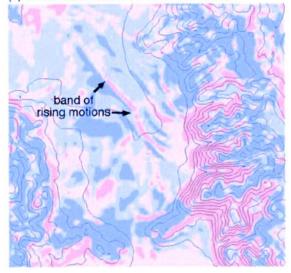

Fɪɢ. 7. (a) Doppler lidar flow field on a 0.5 degree elevation surface at 0630 LST 20 Oct. (b) Topography (shading) and simulated winds at 100 m AGL; circles denote 5-, 10-, and 15-km distances from the lidar site, (c) topography contours (black lines) and simulated vertical velocities at 100 m AGL, where blue indicates sinking motions, red indicates rising motions, and darker shading denotes speeds > 5 cm s⁻¹. The black arrows in (a) and (b) denote significant flow features seen in the observations or simulated by the model; the label in (c) identifies the band of strong rising motions discussed in the text.
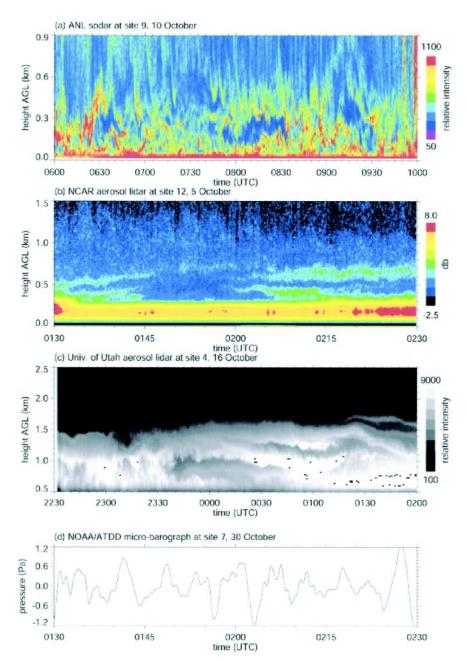
FIG. 8. Time–height cross section of backscatter intensity from (a) the ANL sodar located at site 9 on 10 Oct 2000, (b) the NCAR aerosol lidar located at site 12 on 5 Oct 2000, and (c) the University of Utah aerosol lidar located at site 4 on 16 Oct 2000. (d) Time series of NOAA/ATDD microbarograph measurements from site 7 on 30 Oct.

systems. Perfluorocarbon tracers were used to investigate interaction between slope flows and cold pools and to study convergence and divergence patterns in the valley. Observations show a complicated pattern of local flows influenced by lake effects, heating and cooling of the valley and the nearby mountains, and interactions with synoptic systems. Stably stratified layers, waves, cold pools, intermittent turbulence, and complex convergence and divergence patterns are some of the features revealed in early analyses of the data.

Data obtained during the VTMX 2000 campaign are being collected on a data hub that can be accessed via the Web site for the program online (www.pnl.gov/VTMX/). These data will be made available to the general public around June 2002.

stable periods and morning and evening transition periods. A wide variety of remote sensing and in situ instruments were deployed to characterize the structure and evolution of the wind and temperature fields and to study features of waves and turbulence in the valley. Ten IOPs were conducted during which additional measurements were taken with tethered balloons, rawinsondes, a Doppler lidar, and other instrument

REFERENCES

Allwine, K. J., and B. K. Lamb, 1992: Wintertime dispersion in a mountainous basin at Roanoke, Virginia: Tracer study. *J. Appl. Meteor.,* **31,** 1295–1311.

——, J. S. Shinn, G. E. Streit, K. L. Clawson, and M. Brown, 2000: Overview of URBAN 2002: A multiscale field study of dispersion through an urban environment. *Bull. Amer. Meteor. Soc.,* in press.

Banta, R. M., and Coauthors, 1997: Nocturnal cleaning flows in a tributary valley. *Atmos. Environ.,* **31,** 2147–2162.

Bowen, J., R. Egami, C. Emery, D. Souten, F. Lurmann, P. Roberts, N. Kumar, and C. Kus, 1998: Winter 1996–97 carbon monoxide study in Las Vegas, NV. Part 1: Carbon monoxide and meteorological data collection. Preprints, *10th Joint Conf. on the Applications of Air Pollution Meteorology with the A&WMA,* Phoenix, AZ, Amer. Meteor. Soc., J51–J55.

Cooper, D. I., W. E. Eichinger, L. Hipps, J. Kao, J. Reisner, S. Smith, S. M. Schaeffer, and D. G. Williams, 2000: Spatial and temporal properties of water vapor and flux over a riparian canopy. *Agric. For. Meteor.,* **105,** 161–183.

Doran, J. C., and Coauthors, 1998: The IMADA-AVER boundary layer experiment in the Mexico City area. *Bull. Amer. Meteor. Soc.,* **79,** 2497–2508.

Eichinger, W. E., D. I. Cooper, L. C. Chen, L. Hipps, and C.-Y. J. Kao, 2000: Estimation of spatially distributed latent heat flux over complex terrain from a Raman lidar. *Agric. For. Meteor.,* **105,** 145–159.

Fast, J. D., J. C. Doran, W. J. Shaw, R. L. Coulter, and T. J. Martin, 2000: The evolution of the boundary layer and its effect on air chemistry in the Phoenix area. *J. Geophys. Res.,* **105,** 22 833–22 848.

Furger, M., and Coauthors, 2000: The VOTALP Mesocina valley campaign 1996—Concept, background and some highlights. *Atmos. Environ.* **34,** 1395–1412.

Grachev, A. A., H. J. S. Fernando, J. C. R. Hunt, E. P. Pardyjak, I. Oroud, N. Berman, F. Yu, and G. Wang, 1999: The structure of the atmospheric boundary layer over the complex terrain of Phoenix valley. Preprints, *13th Symp. on Boundary Layers and Turbulence,* Dallas, TX, Amer. Meteor. Soc., 331–334.

Horel, J., M. Splitt, B. White, and L. Dunn, 2000: MesoWest: Cooperative Mesonets in the western United States. Preprints, *Ninth Conf. on Mountain Meteorology,* Aspen, CO, Amer. Meteor. Soc., 265–268.

Jacobson, M. Z., 2001: GATOR-GCMM. 2: A study of daytime and nighttime ozone layers aloft, ozone in national parks, and weather during the SARMAP field campaign. *J. Geophys. Res.,* **106,** 5403–5420.

Kossman, M., R. Vogtlin, U. Corsmeier, B. Vogel, F. Fiedler, H.-J. Binder, N. Kaltoff, and F. Beyrich, 1998: Aspects of the convective boundary layer structure over complex terrain. *Atmos. Environ.,* **32,** 1323–1348.

Lehning, M., H. Richner, G. L. Kok, and B. Neininger, 1998: Vertical exchange and regional budgets of air pollutants over densely populated areas. *Atmos. Environ.,* **32,** 1353–1363.

Lu, R., and R. P. Turco, 1996: Ozone distributions over the Los Angeles basin: Three-dimensional simulations with the SMOG model. *Atmos. Environ.,* **30,** 4155–4176.

McElroy, J. L., and T. B. Smith, 1993: Creation and fate of ozone layers aloft in southern California. *Atmos. Environ.,* **27A,** 1917–1929.

McKendry, I. G., and J. Lundgren, 2000: Tropospheric layering of ozone in regions of urbanized complex and/or coastal terrain: A review. *Prog. Phys. Geogr.,* **24,** 329–354.

——, and Coauthors, 1997: Elevated ozone layers and vertical down-mixing over the lower Frasier Valley, BC. *Atmos. Environ.,* **31,** 2135–2146.

Mead, J. B., G. Hopcraft, S. J. Frasier, B. D. Pollard, C. D. Cherry, D. H. Schaubert, and R. E. McIntosh, 1998: A volume-imaging radar wind profiler for atmospheric boundary layer turbulence studies. *J. Atmos. Oceanic Technol.,* **15,** 849–859.

Neff, W. D., 1997: The Denver Brown Cloud Studies from the perspective of model assessment needs and the role of meteorology. *J. Air Waste Manage. Assoc.,* **47,** 269–285.

Pielke, R. A., and Coauthors, 1992: A comprehensive meteorological modeling system—RAMS. *Meteor. Atmos. Phys.,* **49,** 69–91.

Pope, D., and C. Brough, 1996: *Utah's Weather and Climate.* Publishers Press, 245 pp.

Post, M. J., and R. E. Cupp, 1990: Optimizing a pulsed Doppler lidar. *Appl. Opt.,* **29,** 4145–4158.

Poulos, G. S., and Coauthors, 2002: CASES-99: A Comprehensive Investigation of the Stable Nocturnal Boundary Layer. *Bull. Amer. Meteor.,* **83,** 555–581.

Sassen, K., 1994: Advances in polarization diversity lidar for cloud remote sensing. *Proc. IEEE,* **82,** 1907–1914.

Whiteman, C. D., J. M. Hubbe, and W. J. Shaw, 2000: Evaluation of an inexpensive temperature data logger for meteorological applications. *J. Atmos. Oceanic Technol.,* **17,** 77–81.