

# OVERVIEW OF URBAN 2000

## A Multiscale Field Study of Dispersion through an Urban Environment

K. J. ALLWINE, J. H. SHINN, G. E. STREIT, K. L. CLAWSON, AND M. BROWN

A unique atmospheric tracer and meteorological study shows the complicated patterns of contaminant transport around buildings, through an urban area, and into the surrounding region

**F**ield tracer experiments investigating atmospheric dispersion around buildings and in urban areas are essential for understanding and addressing urban air pollution, toxic contaminant dispersal, and indoor/outdoor contaminant exchange. Results from field studies are used to identify and understand the physical processes governing dispersion and to formulate mathematical equations describing the processes. Field data are also necessary to evaluate and validate computer models that simulate atmospheric dispersion. The primary objective of the U.S. Department of Energy's (DOE's) Chemical and Biological National Security Program (CBNP) URBAN 2000 tracer and meteorological study, described in this paper, is to provide tracer concentrations and meteorological observations throughout an urban area and beyond for evaluating a hierarchy of atmospheric models (Brown et al. 2001) being devel-

oped by CBNP scientists. CBNP is an applied research and development program that focuses emerging science and technology on countering the challenging threat of chemical and biological weapons attack against civilian populations (U.S. Department of Energy 2001). The atmospheric dispersion models being developed will be used to simulate toxic agent dispersal in urban environments and beyond. These models will allow personnel in intelligence, law enforcement, and emergency management to adequately plan against, train for, and respond to potential terrorist attacks.

Over the years, many tracer field studies have been conducted investigating dispersion in individual street canyons (e.g., Huang et al. 2000; DePaul and Sheih 1985), around individual buildings (e.g., Oikawa and Meng 1997; Jones and Griffiths 1984; Ogawa and Oikawa 1982), through multibuilding and industrial complexes (e.g., Thistle et al. 1995; Guenther et al. 1990; Sagendorf et al. 1980), and through urban areas (e.g., Cooke et al. 2000; McElroy 1997; Allwine et al. 1992; Gryning and Lyck 1984). Additionally, numerous wind tunnel and laboratory studies have been conducted investigating flows and diffusion around idealized structures, individual buildings, and industrial complexes (e.g., Zhang et al. 1996; Higson et al. 1994; Mirzai et al. 1994; Ramsdell 1990; Huber 1989; Hosker 1987; Hosker 1984; Huber and Snyder 1982; Allwine et al. 1980; Abbey 1976). These previous field and laboratory studies are certainly a rich resource of

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In final form 29 January 2002  
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data for model development and evaluation. In fact, existing field and wind tunnel data have been and are being used for testing and evaluating CBNP-developed models and model components.

The justification for URBAN 2000 given such an extensive set of existing data, is based on one overriding requirement that is not addressed by existing data—that a short duration, small release be tracked around an individual building, through multiple buildings, through an urban area, and continuing into the surrounding region tens-of-kilometers to a hundred kilometers from the release location *under the same meteorological conditions*. This release will mimic a small terrorist attack in an urban area where the release must be tracked through the urban area and into the surrounding region. The suite of CBNP models currently under development is formulated to explicitly resolve mechanically altered flows around individual buildings and through the urban area, and to explicitly resolve meteorological flows influencing the urban area and surrounding region. No single atmospheric dispersion model can yet resolve all scales of atmospheric motion simultaneously, so current models must still be formulated where the scale of motion not resolved is either treated as boundary conditions (in the case of mesoscale flows in building models) or parameterized (in the case of urban effects in mesoscale models). Having tracer and meteorological data from URBAN 2000 at various scales for the same meteorological conditions allows for urban parameterizations (simplified formulations) in mesoscale atmospheric models to be properly evaluated. Additionally, the influence of mesoscale flows on results from building-scale models can be evaluated.

The URBAN 2000 comprehensive urban dispersion field campaign was conducted in Salt Lake City, Utah, during October 2000. It is the first comprehensive field tracer study that concurrently resolved multiple interacting scales of motion. Atmospheric meteorological and tracer experiments were conducted to investigate transport and diffusion around a single downtown building, through the downtown area, and into the greater Salt Lake City (SLC) urban area. The study area was extended beyond the urban scale by embedding the URBAN 2000 study in DOE's Vertical Transport and Mixing (VTMX) tracer and meteorological study conducted simultaneously in the greater Salt Lake Valley (SLV; Doran et al. 2002). The results of the urban dispersion field experiments will also be used to better understand meteorological and fluid dynamical processes governing dispersion in urban areas. URBAN 2000 was designed to investi-

gate the urban nocturnal boundary layer (stable to neutral atmospheric conditions), whereas a second major field campaign being planned for 2003 will be designed to investigate the daytime boundary layer (neutral to unstable).

In addition to providing an extensive dataset for model evaluations, some specific scientific questions addressed by the URBAN 2000 field study include the following: 1) Are street canyons preferred pathways of tracer transport during nighttime light wind speed conditions? 2) Do short duration (5–15 min) oscillations in the approach flow wind direction and speed affect tracer dispersion near the release building, through the downtown area, and into the greater urban area? 3) Does the tracer mix rapidly in the vertical within the urban area? 4) Does the tracer remain trapped in the urban area, ventilating at a much slower rate than expected from mean advective transport? 5) Do diurnal thermally driven flows (e.g., downslope winds, valley winds, lake breezes) strongly influence winds in downtown SLC?

Planning URBAN 2000 initially required approval by applicable government agencies (city and state) and completion of environmental documentation. Design considerations involved balancing scientific objectives with constraints on budgets, site permissions, and available instrumentation. Field operations in SLC required coordination with city services (police, transportation, parking, etc.), conducting field operations during regular city activities, access to instrument sites, and last, but not least, acceptable public perception of releases of safe, inert tracer gases into the atmosphere. Considerable negotiations and compromises during the year of planning and preparation for the URBAN 2000 study resulted in successful and generally problem-free field operations during October 2000. The success of the study was due largely to the support of government agencies, private companies, and individuals in and around SLC. In spite of our detailed planning for URBAN 2000, a couple of unexpected problems arose near the end of our field operations. We made news (unwanted) around the country as “unleashing gas attacks” on SLC. And one of our tracer samplers was destroyed by a bomb squad. Needless to say, we *learned* from these two events that, when conducting future urban tracer studies, the *public should be fully informed* of our scientific studies and the *police should be provided* with detailed maps of all our sampler locations.

Urban tracer/meteorological studies are typically very costly (can be several million dollars) and logistically complicated. Many compromises are required between accomplishing desired scientific objectives

and actually deploying instruments and making successful measurements. For example, measuring the vertical distribution of tracer within the urban canopy at several locations would be very desirable for determining the effects of building-altered flows on vertical diffusion. Initially, it would seem obvious that with all the buildings in an urban area, determining the vertical distribution of tracer could easily be accomplished by locating tracer samplers at various locations on many buildings. However, for numerous reasons, ranging from liability concerns to logistical difficulties, locating tracer samplers on and around many buildings is not practical. For the URBAN 2000 study we had tracer samplers on rooftops of five buildings. Gaining permissions (from different property owners) to locate the samplers on the buildings in SLC required considerable effort before the study period. During the study, placing and retrieving the tracer samplers on the buildings for each tracer experiment required considerable time in arranging building access from security personnel and in negotiating the buildings.

This paper summarizes the URBAN 2000 study by describing the experimental design, instrument layout, experiments, meteorological conditions, and some initial findings. The URBAN 2000 study should be of general interest to all investigating urban dispersion, urban air quality, and atmospheric transport and diffusion.

**THE URBAN 2000 FIELD STUDY.** Scientists funded by CBNP, the U.S. Department of Defense (DOD) Defense Threat Reduction Agency (DTRA), the U.S. Army Research Office (ARO), and the United Kingdom's Defense Evaluation and Research Agency (DERA) participated in the URBAN 2000 field efforts. Project leadership was shared by DOE's Pacific Northwest, Lawrence Livermore, and Los Alamos National Laboratories under CBNP funding. Other CBNP-funded investigators were from the National Oceanic and Atmospheric Administration's (NOAA's) Air Resources Laboratory Field Research Division, DOE's Brookhaven National Laboratory, and Indiana University. Investigators from DOD's Dugway Proving Ground (DTRA funded), Coherent Technologies (ARO and CBNP funded), Vaisala Corporation,

and Litton Industries were key collaborators in the study.

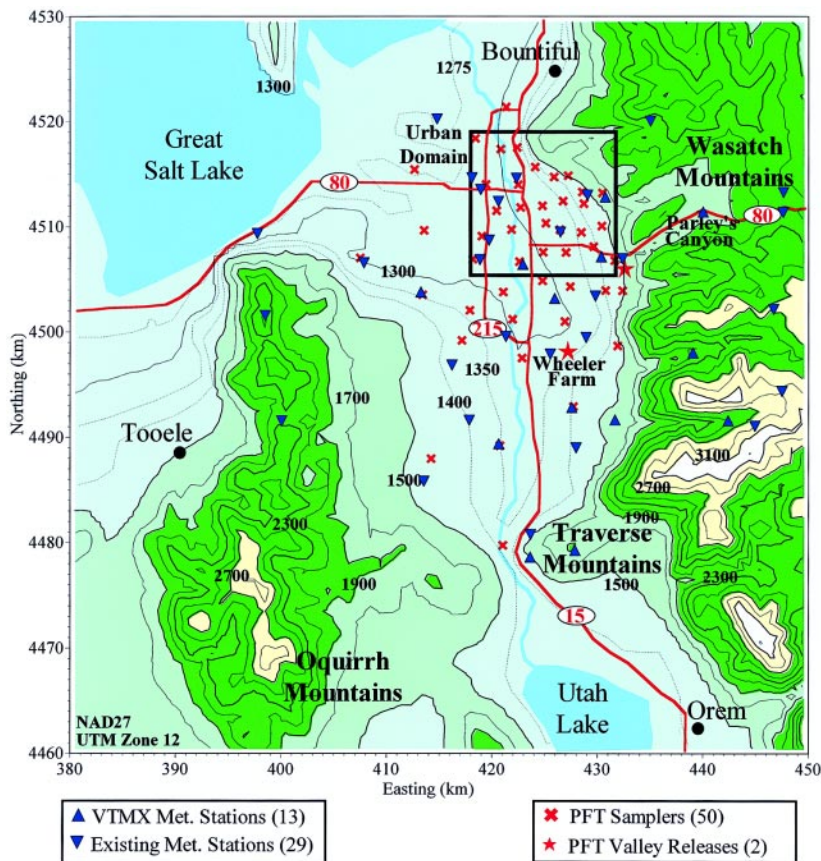
**Site description.** The VTMX program chose the SLV as the site of its first experimental campaign because of many attractive features for studying vertical transport and mixing processes in the nocturnal stable boundary layer. SLC was a natural choice for the site of the first CBNP urban dispersion experiments because of the significant benefit of combining resources with VTMX and the fact that SLC has a well-developed downtown area. A nearly 5-block-by-5-block area (~1.5 km<sup>2</sup>) has buildings ranging in height from a few stories to 40 stories, and has numerous parking lots, parking structures, and open areas that are characteristic of many U.S. cities (Fig. 1). SLC is Utah's state capital and is the central city to 1.7 million inhabitants residing within an hour's drive from downtown. The city's daytime population increases from 182,000 residents to over 370,000 as 40% of Salt Lake County's workforce and 20% of the state's total workforce commute to jobs located within the city limits.

The SLC metropolitan area is located in a large mountain valley about 50 km long and 25 km wide, with the high Wasatch Mountains on the east, Oquirrh Mountains on the west, Great Salt Lake just to the northwest, and Traverse Mountains to the south (Fig. 2). The valley is bisected nearly north to south by the Jordan River, which flows from the freshwater Utah Lake in Utah County through a gap in the Traverse Mountains and north to the Great Salt Lake. The average elevation of SLC is approximately 1320 m above sea level and the greater metropolitan area covers approximately 288 km<sup>2</sup>.

SLC has a semiarid continental climate with four well-defined seasons. Precipitation is typically low



**FIG. 1. Aerial view of downtown SLC looking toward the northeast into City Creek Canyon. (Photograph from Don Green Photography, Salt Lake City, Utah.)**



**FIG. 2. Map of Salt Lake Valley (regional domain) showing terrain elevations (m) and locations of VTMX tracer samplers, surface meteorological stations, and valley release locations.**

during October and surface winds through downtown show a pronounced diurnal cycle of winds from the southeast during nighttime and from the northwest during daytime. Synoptic disturbances can interrupt the diurnal processes, but are infrequent occurrences during October. The near-persistent southeast winds during the night allowed the tracer sampling network consolidated to the northwest of the release site for the nighttime tracer and meteorological experiments.

**Meteorological measurements.** The URBAN 2000 comprehensive meteorological and tracer field campaign was conducted during October 2000 and was highlighted by seven nightlong intensive operation periods (IOPs) in which extensive meteorological measurements were made and tracer gases were released and tracked across SLC. The instruments were deployed over three experimental domains identified as *urban*, *downtown*, and *building*. Meteorological instruments deployed by CBNP-funded investigators and other collaborators (DPG, DERA, and the Vaisala Corporation) over the 3 experimental domains con-

sisted of 29 temperature data loggers for mapping the surface temperature across the urban area; 15 two-dimensional (2D) sonic anemometers for measuring the horizontal components of winds and turbulence; 9 three-dimensional (3D) sonic anemometers for measuring the horizontal and vertical components of winds and turbulence; a Doppler lidar for mapping the winds across the urban area; a radar wind profiler giving vertical profiles of winds; a lidar ceilometer for characterizing the vertical structure of the boundary layer; 3 acoustic sodars for vertical profiling of winds; 15 surface weather stations; 1 mobile van for mapping temperature; and 1 energy budget station measuring net radiation, sensible heat flux, latent heat flux, and 3 levels of temperature to 18 m above ground level (AGL). Most instrument systems were operated continuously throughout October, with the exception of the lidars, the temperature van, and some of

the 2D and 3D sonic anemometers that only operated during IOPs.

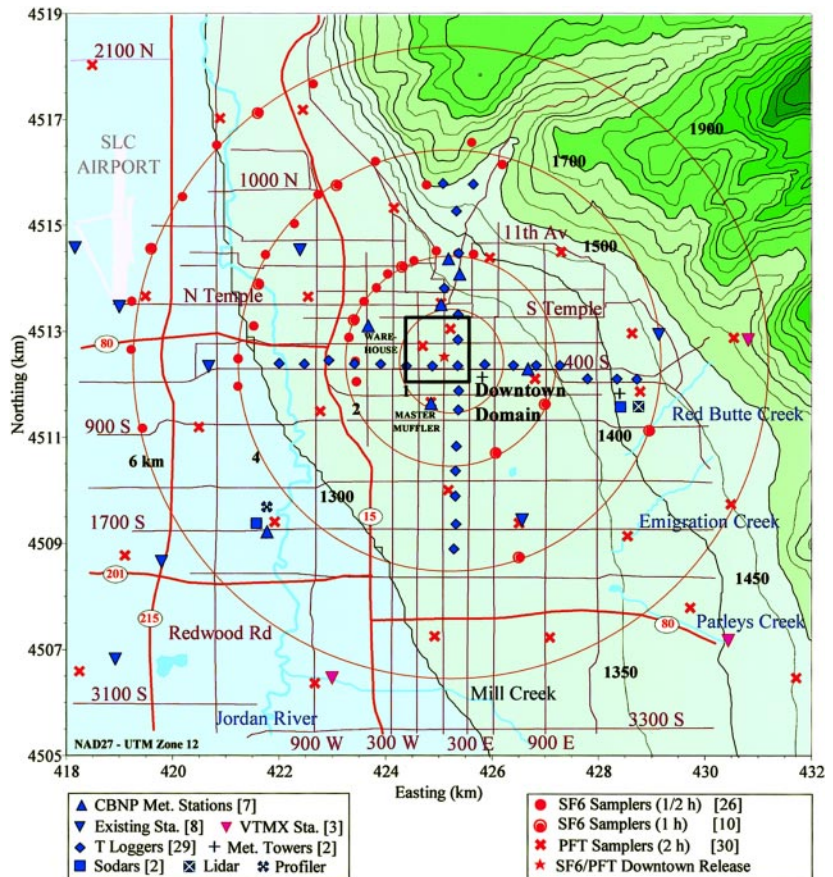
VTMX operated numerous meteorological instruments around the SLV (*regional domain*) during the month of October. These consisted of 6 radar wind profilers; 5 radio acoustic sounding system (RASS) temperature profilers; 5 sodars; an infrared Doppler lidar for mapping the radial (from instrument) component of winds; a high-resolution Raman water vapor lidar to measure water vapor fluctuations; 2 aerosol lidars for providing mixing depths and nocturnal layering information; 4 tethered balloons; 3 sites for rawinsondes; 10 three-dimensional sonic anemometers; 14 surface weather stations to supplement the network of 29 existing stations; and 25 temperature loggers. Figure 2 shows VTMX surface weather stations and existing surface weather stations in the *regional domain*. Refer to Doran et al. (2002) in this issue for a detailed description and deployment of the VTMX instrument systems.

Locations of meteorological systems deployed in the *urban domain* are shown in Fig. 3. CBNP investi-

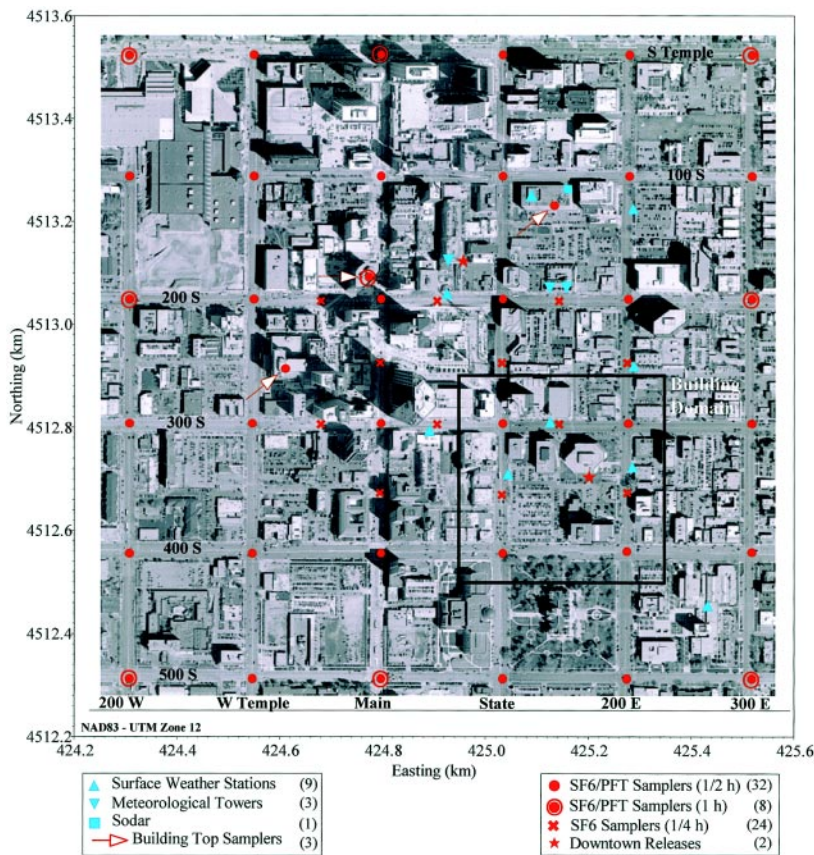
gators and collaborators deployed 7 of the 19 surface weather stations; 1 of the 2 instrumented towers; the radar wind profiler; the 2 sodars; the Doppler lidar; and the 29 temperature loggers shown in the *urban domain*. Weather stations were located primarily on building tops to measure 5-min-average winds, temperature, and relative humidity in flows at the top of the urban canopy. The network of 29 temperature loggers was located at 3 m AGL on light poles measuring 5-min-average temperature across the SLC urban area, with the primary intent of characterizing the SLC urban heat island. A radar wind profiler was operated continuously at the Raging Waters site (located at the intersection of 1700 South and the Jordan River) giving 1-h-average winds from 70 to 2160 m AGL in 55-m-interval range gates, and 1-h-average winds from 75 to 3725 m in 96-m-interval range gates. A sodar was also operated at the Raging Waters site giving 15-min-average winds from 30 to 300 m in 10-m-interval range gates. The tower near the southeast corner of the downtown study domain was actually a construction lift instrumented with two 2D sonic anemometers at 7.3 and 11 m AGL, and three temperature sensors at 7.8, 12.5, and 18 m AGL operating at 1 Hz. Net radiation, latent heat flux, and sensible heat flux were also measured at 12 m AGL on the construction lift using a net radiometer, krypton hygrometer, and 1D sonic anemometer with a fine-wire thermocouple, respectively. The Doppler lidar was operated by Coherent Technologies and was deployed during the later half (beginning 19 October) of the October study period from the higher terrain just east of downtown scanning through downtown measuring the radial component of winds.

In the *downtown domain* shown in Fig. 4, investigators operated nine surface weather stations measuring winds, temperature, and relative humidity; three instrumented towers measuring wind and turbulence profiles; and one sodar measuring wind profiles. The

sodar was operated by DPG on top of the 35-m-high Federal Building collecting 10-min-average wind data from 15 m above the building top to 200 m above the building top in 5-m-interval range gates. Seven of the surface weather stations, operated by DPG, were attached at 3 m AGL on light poles collecting 1-min-average wind and temperature data along downtown streets. The other two surface weather stations were operated on building tops acquiring wind and temperature data near the top of the urban canopy. Each of the three 10-m-high meteorological towers, operated by DERA, contained two 3D sonic anemometers at 5 and 10 m above the surface. Two towers were located ~50 m apart on the top of a 20-m-high parking structure and the other tower was located on the top of a 35-m-high parking structure. The primary intent of the three towers was to provide turbulence data for model validation points within the urban canopy. The data from the six sonic anemometers on the three towers were collected continuously at a 21-Hz sampling rate.



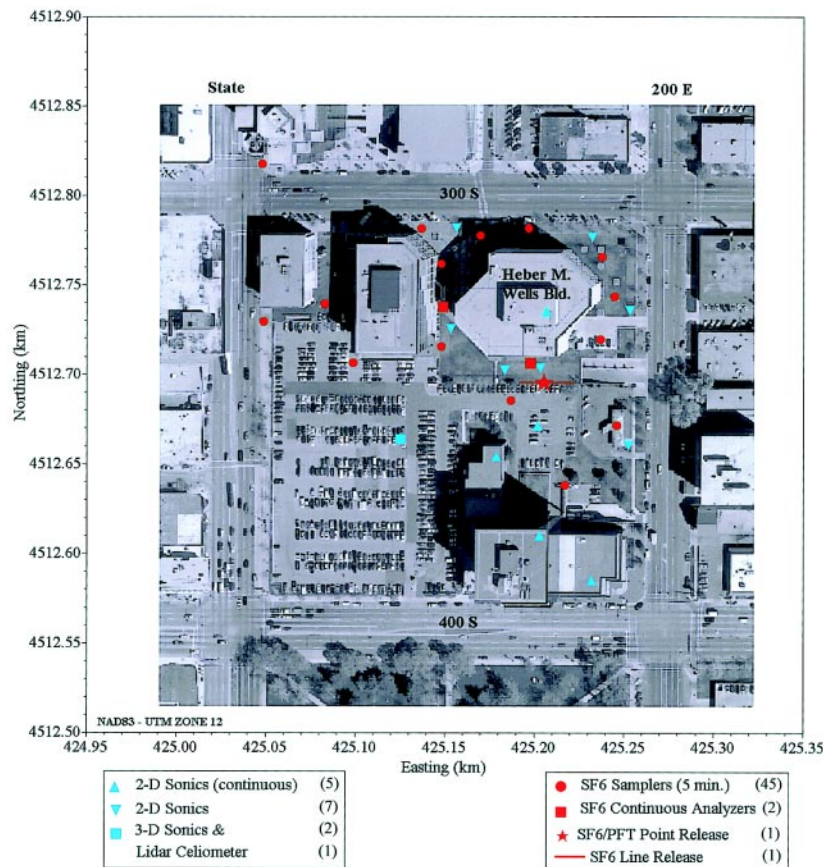
**Fig. 3. Map of greater SLC area (*urban domain*) showing terrain elevations (m) and locations of CBNP tracer samplers and meteorological measurement sites. VTMX tracer samplers and surface weather stations, and existing surface weather stations shown in Fig. 2 are also shown here.**



**FIG. 4. Map of downtown SLC area (downtown domain) showing locations of CBNP tracer samplers, meteorological measurement sites, and downtown release locations.**

Twelve 2D sonic anemometers collected wind data at 1 Hz during the IOPs within the *building domain* (Fig. 5) to characterize the winds and turbulence around and on top of the buildings in the direct vicinity of the tracer release location. At one location in a parking lot near the release location, two 3D sonic anemometers collected wind and turbulence data at 10 Hz on a tip-up tower. The sonics were located at 6.6 m and 9.3 m AGL to provide the models with another point of comparison. A lidar ceilometer (provided by Vaisala Corporation) was also operated near the tip-up tower measuring the layering structure of the boundary layer from 30 m to ~2 km above the surface at 15-m-interval range gates. The ceilometer data were collected at 15-min-averages during IOPs.

Another goal of URBAN 2000 was to determine sky view factors ( $\Psi_{sky}$ ) throughout the downtown area of SLC. Sky view factor is the ratio of the radiation received (or emitted) by a planar surface to the radiation emitted (or received) by the entire hemispheric environment (Watson and Johnson 1987). The  $\Psi_{sky}$  is sometimes used in radiation balance schemes to partition long- and shortwave radiation within urban and forest



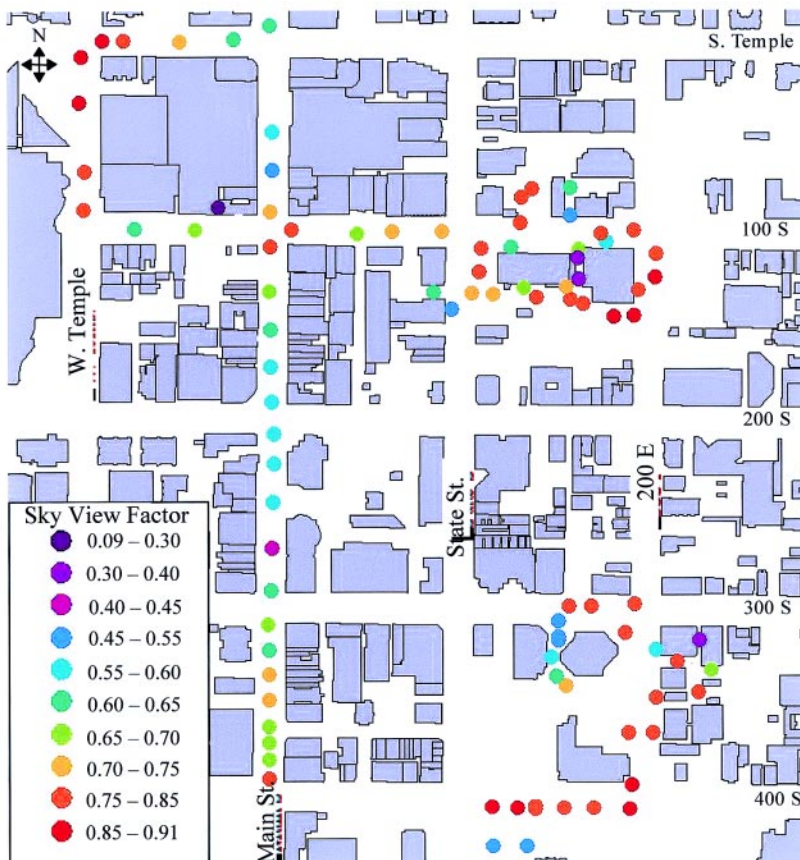
**FIG. 5. Map of release block (building domain) in SLC showing locations of CBNP tracer samplers, meteorological measurement sites, and release locations.**

**FIG. 6.** Sky view factors around downtown SLC determined from photographs using a fish-eye lens looking straight up. Red means a large sky view factor (indicating few canopy obstructions), while purple indicates a small sky view factor (canopy is dense and the sky obscured).

canopies and complex terrain. The  $\Psi_{sky}$  can be used in mesoscale meteorological models to approximate the energy exchange from the urban canopy to the atmosphere. The  $\Psi_{sky}$  measurements in SLC will help to test and improve urban parameterizations used in mesoscale models.

As described in Brown and Grimmond (2001), a digital camera (Nikon CoolPix 950) with a fish-eye hemispheric lens (Nikon FC-E8 with a 189B field of view) was used to take in situ observations in SLC. The images were converted from color to black (ground, buildings, and vegetation) and white (sky) by altering the brightness and contrast of each image. The total  $\Psi_{sky}$  at each site was then determined using the equation of Johnson and Watson (1984) and a Fortran program of Grimmond et al. (2001), which automatically detects the resolution of the image taken and allows the user to specify the field of view analyzed; that is, corrections to 180° were included at this stage.

Figure 6 depicts the sky view factor computed at each location



**FIG. 7.** Downtown SLC showing the four elevated tracer sampler locations (red arrows) and two downtown tracer release locations (blue arrows). The top picture is looking to the northwest and the bottom picture is looking to the southeast. (Photographs from Don Green Photography, Salt Lake City, Utah.)

in the downtown area of SLC. Red means that  $\Psi_{\text{sky}}$  is large, indicating few canopy obstructions; while purple indicates that  $\Psi_{\text{sky}}$  is small, meaning that the canopy is dense and the sky is obscured. Clearly  $\Psi_{\text{sky}}$  is smallest in narrow alleyways and in regions close to tall buildings. One should also note that the many trees along open streets contributed to reduced  $\Psi_{\text{sky}}$ . The  $\Psi_{\text{sky}}$  observed in downtown SLC ranged from 0.33 to 0.90, with an average of 0.70. A histogram of the computed sky view factors showed the majority in the 0.5–0.9 range.

**Tracer releases.** Eighteen 1-h-long sulfur hexafluoride tracer ( $\text{SF}_6$ ) releases occurred from one location in downtown SLC (Fig. 5); twelve 6-h-long perfluorocarbon tracer (PFT) releases occurred from two locations in downtown SLC (Figs. 4 and 7), and twelve 8-h-long PFT releases occurred from two locations around the greater SLC area (Fig. 2) during the seven IOPs. PFTs were released by VTMX investigators, but are included here because CBNP investigators fielded PFT samplers as part of their experiments.

The  $\text{SF}_6$  was released at ground level approximately 15 m south of the 35-m-high Heber M. Wells building (Figs. 5 and 7) in downtown SLC near the intersection of 400 South and 200 East. The nearest “upwind” building from the release is the 40-m-high City Center building located approximately 80 m directly south of the Heber M. Wells building. During the first 4 tracer IOPs (2, 4, 5, and 7)  $\text{SF}_6$  was released at  $1 \text{ g s}^{-1}$  from a 30-m-long line source for three 1-h periods from 0000 to 0100, 0200 to 0300, and 0400 to 0500 Mountain Standard Time (MST = UTC – 7 h). Note that the IOP numbers are a subset of the 10 VTMX

meteorological and tracer experiments when tracers were released. (VTMX IOPs 1, 3, and 6 were meteorological-only experiments, no tracers were released.) For the last IOP (10),  $\text{SF}_6$  was released for the same time periods and release rate as during the first four IOPs, except the release was from a point rather than a line source. The  $\text{SF}_6$  tracer experiment during IOP 9 was conducted earlier in the night to better coincide with the expected higher winds through downtown SLC. The tracer was released at  $2 \text{ g s}^{-1}$  from a point source for three 1-h periods from 2100 to 2200, 2300 to 0000, and 0100 to 0200 MST. The release rate of  $\text{SF}_6$  was monitored throughout each experiment and was within 5% of the desired rate. The  $\text{SF}_6$  cylinder was weighed at the beginning and ending of each experiment as a second check on the amount of tracer gas released during each experiment. The  $\text{SF}_6$  release rate was chosen to allow the tracer plume well above the approximate 3 parts per trillion (ppt) global background concentration at more than 15-km transport distance (design distance) from the release point.

Table 1 gives the PFT release rates for the six IOPs (2, 4, 5, 7, 8, and 10) during which four different PFTs were simultaneously released from four point sources—two located in downtown SLC and two south of the city in the SLV. The same PFT was always released from the same location allowing transport from different release locations to specific receptor locations to be investigated. One downtown PFT was released at ground level with the  $\text{SF}_6$  tracer (southerly release location in Figs. 4 and 7), and the other downtown PFT was released from the top of a 35-m-high parking structure (northerly release location in Figs. 4 and 7). PFTs were released at a height

**TABLE 1. PFT tracer release data for four point sources for all IOPs.**

| PFT name | Location                              | Nearby street intersection | Height (m AGL) | Time (MST) | Extent (h) | Rate ( $\text{ms s}^{-1}$ ) |
|----------|---------------------------------------|----------------------------|----------------|------------|------------|-----------------------------|
| PDCB     | Near mouth of Parley's Canyon         | 180 & 1215                 | 1.5            | 2200–0600  | 8          | 1.30                        |
| PMCP     | SE Salt Lake Valley (Wheeler Farm)    | 900 E & 6400 S             | 1.5            | 2200–0600  | 8          | 1.20                        |
| PMCH     | Downtown near Heber M. Wells Building | 200 E & 400 S              | 1.5            | 0000–0600  | 6          | 0.43                        |
| oPDCH    | Downtown on top Regents Parking       | State & 200 S              | 36.0           | 0000–0600  | 6          | 0.15                        |



of 1.5 m above the ground or building top (in the case of the parking structure release). The four PFTs used were perfluorodimethylcyclobutane (PDCB), perfluoromethylcyclopentane (PMCP), perfluoromethylcyclohexane (PMCH), and perfluoro-orthodimethylcyclohexane (oPDCH). Because of the low global background concentrations of these tracers (PDCB—1.4, PMCP—5.2, PMCH—4.8, and oPDCH—1.0 parts per quadrillion) and recent advances in sample analysis, low PFT release rates were possible. PFT concentrations were well above global background allowing detection of the PFT plumes at more than 50-km transport distance (design distance).

Each release of gaseous PFT in nitrogen was made from an aluminum cylinder equipped with a regulator and flow restrictor. The release procedure was to place the aluminum cylinder at the release location, turn on the regulator at the release start time, and set the release pressure to get the desired flow rate using a calibrated volume flow meter. Each PFT cylinder contained sufficient gas to last one experiment, so empty cylinders were retrieved at the conclusion of each experiment. The design pressure of each PFT cylinder was below the PFT saturation vapor pressure (at a design temperature of ~5°C), yet high enough to contain sufficient PFT for each release period (6 h for downtown releases and 8 h for valley releases). The design temperature of ~5°C was low enough so that

tank heaters were not necessary to maintain PFTs in the gas phase.

**Tracer measurements.** Integration times of tracer samplers ranged from 5 min for SF<sub>6</sub> samplers near the release to 4 h for some PFT samplers spread throughout the SLV (Table 2). Sampling strategy was determined based on a trade-off between the total number of sample bags/tubes available and the cost of analysis, and the time resolution of samples and experiment duration. An assortment of portable, programmable, battery-operated tracer samplers were used to collect both SF<sub>6</sub> and PFT integrated air samples. PFT samples were collected on capillary adsorption tubes and SF<sub>6</sub> samples were collected in bags. A total of 201 tracer samplers were used in the combined CBNP/VTMX tracer experiments: 56 PFT samplers, 105 SF<sub>6</sub> samplers, and 40 SF<sub>6</sub>/PFT samplers. The combined SF<sub>6</sub>/PFT samplers were SF<sub>6</sub> bag samplers modified to collect PFTs on adsorption tubes (allowing SF<sub>6</sub> to pass) at sample inlets. Nearly 9900 SF<sub>6</sub> samples and 2900 PFT samples were collected by CBNP investigators during the tracer experiments. VTMX investigators collected PFT samples at 50 locations spread throughout the SLV. Four of the PFT samplers were on building tops—three in downtown (locations 1, 3, and 4 in Fig. 7), and one on the 27-m-high WB Browning Building on the University of

**TABLE 2. PFT and SF<sub>6</sub> sampler information. Building domain and building-top samplers collected at 1 m AGL and all other samples collected at 3 m AGL.**

| Domain                | Tracer               | No. of samplers | No. of sampler locations | Avg time (h) | Duration (h) | Period (MST) |
|-----------------------|----------------------|-----------------|--------------------------|--------------|--------------|--------------|
| Valley <sup>a</sup>   | PFT                  | 50              | 50                       | 2.00         | 14           | 2200–1200    |
| Valley                | PFT                  | 6               | Collocated with above    | 4.00         | 48           | 2200–2200    |
| Urban                 | SF <sub>6</sub>      | 10              | 10                       | 1.00         | 12           | 0000–1200    |
| Urban                 | SF <sub>6</sub>      | 26              | 26                       | 0.50         | 6            | 0000–0600    |
| Downtown              | SF <sub>6</sub> /PFT | 8               | 8                        | 1.00         | 12           | 0000–1200    |
| Downtown <sup>b</sup> | SF <sub>6</sub> /PFT | 31              | 31                       | 0.50         | 6            | 0000–0600    |
| Downtown <sup>c</sup> | SF <sub>6</sub> /PFT | 1               | Collocated with above    | 0.50         | 6            | 0600–1200    |
| Downtown              | SF <sub>6</sub>      | 12              | 12                       | 0.25         | 3            | 0000–0300    |
| Downtown              | SF <sub>6</sub>      | 12              | Collocated with above    | 0.25         | 3            | 0300–0600    |
| Building              | SF <sub>6</sub>      | 15              | 15                       | 5 min        | 50 min       | 0005–0055    |
| Building              | SF <sub>6</sub>      | 15              | Collocated with above    | 5 min        | 50 min       | 0205–0255    |
| Building              | SF <sub>6</sub>      | 15              | Collocated with above    | 5 min        | 50 min       | 0405–0455    |

<sup>a</sup> Four samplers on building tops.

<sup>b</sup> Three samplers on building tops.

<sup>c</sup> One sampler on building top.

Utah campus. The heights of the buildings at locations 1, 3, and 4 in Fig. 7 are 56, 121, and 36 m, respectively. A total of nearly 2600 PFT samples were collected by VTMX investigators during six PFT experiments.

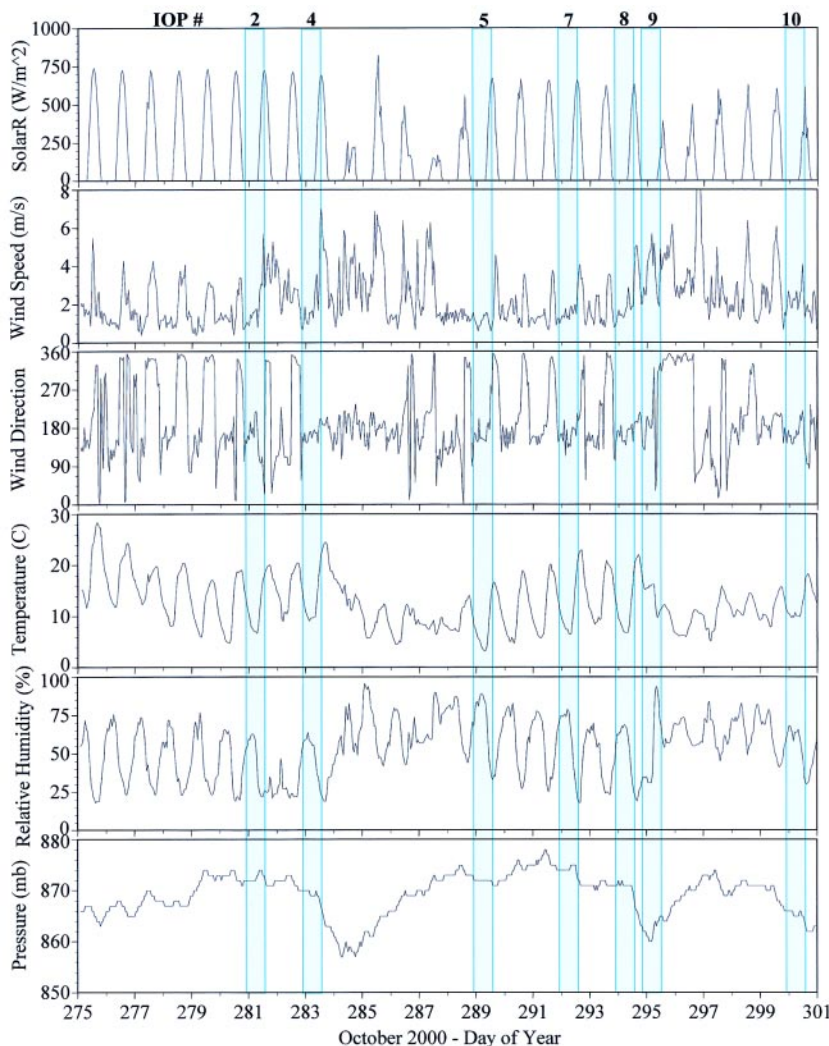
The SF<sub>6</sub> bag samples were analyzed using a gas chromatography–electron capture detector (GC–ECD) tuned for SF<sub>6</sub> analysis. The PFTs are being analyzed by Brookhaven National Laboratory using a GC–ECD system specially developed at Brookhaven to resolve up to 15 PFTs and detect at global background levels. In addition to the fixed tracer samplers, four instrumented vans with fast-response (1 Hz) SF<sub>6</sub> analyzers with electron capture detectors were driven along arcs at 1, 2, 4, and 6 km from the SF<sub>6</sub> release to

provide real-time plume tracking. Two additional fast-response analyzers operated at fixed sites in downtown. A mobile Fourier transform infrared (FTIR) spectrometer was operated during the first tracer experiment and mapped SF<sub>6</sub> concentrations in the downtown area.

Tracer samplers were distributed to resolve the various scales-of-motion being studied. For the *building domain*, 45 SF<sub>6</sub> samplers were placed at 15 locations in the near vicinity of the tracer release (Fig. 5) and collected samples at nominally 1 m AGL. Three samplers were located at each sampling site to allow collection of 5-min-average samples during each of the 3 h that SF<sub>6</sub> was released. Additionally, one infrared spectrophotometer and one

micro gas chromatograph continuously measured SF<sub>6</sub> from four points and eight points, respectively, in the vicinity of the Heber M. Wells study building.

For the *downtown domain*, 40 SF<sub>6</sub>/PFT samplers and 24 SF<sub>6</sub> samplers were located in a 5-by-5 block downtown area (Fig. 4) and collected samples on light poles near streetside at 3 m AGL. At three locations (locations 1, 2, and 4 in Fig. 7), four of the SF<sub>6</sub>/PFT samplers (two samplers at location 2 in Fig. 7) were located on building tops, giving an indication of the vertical distribution of tracer. The heights of the buildings at locations 1, 2, and 4 in Fig. 7 are 56, 64, and 36 m, respectively. Thirty-one of the 40 SF<sub>6</sub>/PFT samplers collected 0.5-h integrated samples over the period 0000–0600 MST, and 8 of the 40 SF<sub>6</sub>/PFT samplers collected 1-h integrated samples over the period 0000–1200 MST to extend the tracer sampling through the morning transition period. Figure 4 shows 12 SF<sub>6</sub> sampling sites at midblock locations on the streets near the release location. Twelve SF<sub>6</sub> samplers collected 0.25-h integrated samples from 0000 to 0300 MST, and another 12 collected 0.25-h integrated samples from 0300 to



**FIG. 8. Hourly averaged meteorological conditions for Oct 2000 measured at 3 m above the rooftop on a 11-m-high building with unobstructed exposure to the winds. The weather station was located at the center of the Salt Lake Valley near the intersection of 900 West and 3300 South (Fig. 3). Note that the IOP numbers are a subset of the 10 within VTMX when tracers were released.**

**TABLE 3. Overview of six SF<sub>6</sub> and six PFT tracer experiments.**

| IOP no. | Start <sup>a</sup>      |      | Stop <sup>b</sup> |      | Tracers <sup>d</sup>        | Meteorology   |
|---------|-------------------------|------|-------------------|------|-----------------------------|---|
|         | Date (DOY) <sup>c</sup> | MST  | Date (DOY)        | MST  |                             |   |
| 2       | 6 Oct 2000 (280)        | 2200 | 7 Oct 2000 (281)  | 1200 | SF <sub>6</sub> line; PFTs  | Strong easterly downslope winds after 0000–0300 MST penetrating 1–2 km into valley at the surface     |
| 4       | 8 Oct 2000 (282)        | 2200 | 9 Oct 2000 (283)  | 1200 | SF <sub>6</sub> line; PFTs  | Clear skies, weak winds, well-developed drainage; approaching trough eroded inversions after 0500 MST |
| 5       | 14 Oct 2000 (288)       | 2200 | 15 Oct 2000 (289) | 1200 | SF <sub>6</sub> line; PFTs  | Clear skies, weak winds, well-developed drainage  |
| 7       | 17 Oct 2000 (291)       | 2200 | 18 Oct 2000 (292) | 1200 | SF <sub>6</sub> line; PFTs  | Clear skies, weak winds, well-developed drainage; approaching trough eroded inversions after 0500 MST |
| 8       | 19 Oct 2000 (293)       | 2200 | 20 Oct 2000 (294) | 1200 | PFTs only                   | Clear skies, weak winds, well-developed drainage  |
| 9       | 20 Oct 2000 (294)       | 2100 | 21 Oct 2000 (295) | 0900 | SF <sub>6</sub> point only  | Cloudy skies, weak to moderate winds, weak drainages; affected by approaching troughs                 |
| 10      | 25 Oct 2000 (299)       | 2200 | 26 Oct 2000 (300) | 1200 | SF <sub>6</sub> point; PFTs | Cloudy skies, moderate winds, weak drainages; affected by approaching troughs                         |

<sup>a</sup> Start of tracer sampling.

<sup>b</sup> End of tracer sampling.

<sup>c</sup> Day of year.

<sup>d</sup> SF<sub>6</sub> point and line releases, PFT point releases only.

0600 MST at these 12 sampling locations (2 samplers per location).

For the *urban domain*, 36 SF<sub>6</sub> samplers were located on 2-, 4-, and 6-km arcs (Fig. 3) from the downtown SF<sub>6</sub> release location. The samplers were located primarily in the 90° downwind sector (northwest from downtown) to track the nighttime release. Four samplers were located to the southeast of downtown to measure the SF<sub>6</sub> “plume” after wind reversal after the morning transition period. Twenty-six of the SF<sub>6</sub> samplers collected 0.5-h integrated samples from 0000 to 0600 MST, and 10 samplers collected 1-h integrated samples from 0000 to 1200 MST.

**METEOROLOGICAL CONDITIONS.** Table 3 gives the times and general meteorology of the seven IOPs during which the tracers were released. Based on daily weather forecasts given by the University of Utah meteorology faculty and students as part of their VTMX efforts, CBNP releases of SF<sub>6</sub>, and sampling

of SF<sub>6</sub> and PFTs, and VTMX releases and sampling of PFTs were accomplished at the same time. The IOPs in Table 3 are a subset of the 10 IOPs within VTMX (Doran et al. 2002) during which tracer experiments were conducted. IOP start time is the start time of the earliest tracer release, and stop time is the ending time of the last tracer sampler (excluding the six multiday PFT samplers).

The typical meteorological conditions investigated were weak synoptic influence with clear skies, weak winds aloft, and strong surface cooling leading to well-developed nocturnal drainage winds. IOPs 4, 5, 7, and 8 exhibited these desired characteristics, with conditions during IOPs 4 and 7 being altered by approaching upper-level troughs with accompanying strong southerly surface winds eroding the surface inversions after 0500 MST. A downslope wind storm occurred during IOP 2 with strong easterly winds emerging after 0000 MST into the SLV from Parley’s Canyon and other major canyons (Fig. 2) in the

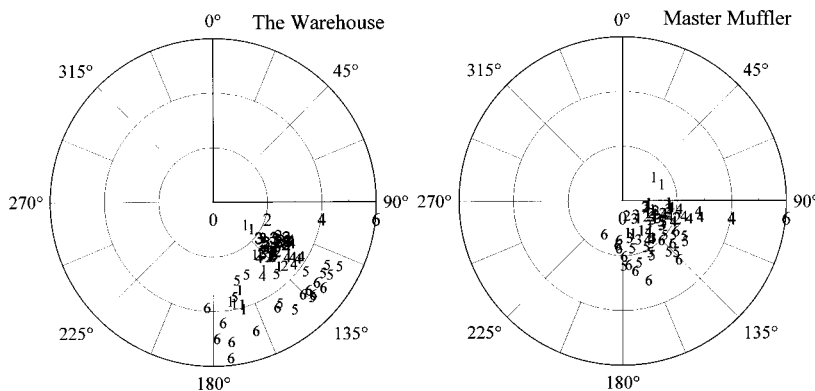
Wasatch Mountains. Cold air continued to build east of the Wasatch Mountains, eventually spilling over into the northeast portion of SLV near SLC, and leading to wind gusts in excess of  $20 \text{ m s}^{-1}$  penetrating 1–2 km into the valley at the surface. Conditions during IOPs 9 and 10 were considerably affected by approaching upper-level troughs. Skies were partly cloudy to overcast, and nocturnal surface inversions were weaker than during the other IOPs. Southerly winds were enhanced, especially during IOP 10, leading to stronger southeasterly winds through downtown SLC. Figure 8 shows the meteorology near the surface at the center of the valley for the month of October 2000, and provides a visual summary of the occurrences of well-established diurnal flows during clear conditions—the desirable experimental conditions. The meteorological conditions during each of the seven tracer IOPs are identified.

The SLC area experiences pronounced diurnal circulations, with winds from the southeast during the nighttime established between 1800 and 2000 MST. The tracer releases and sampling were started between 2200 and 0000 MST, during well-established nocturnal flows. All tracer releases were stopped at 0600 MST and nearly all  $\text{SF}_6$  and half the PFT sampling was stopped at 0600 MST. The winds began switching to upvalley (from the northwest) at about 0800 MST, allowing for the tracer plume advected to the northwest during the nighttime to be carried back to the southeast across the sampling grid. Sampling on a subset of  $\text{SF}_6$  samplers was extended to 1200 MST to allow for the investigation of the effects of the wind reversal during the morning transition period. Sampling on all VTMX PFT samplers was through noon to investigate the effects of wind reversal on transport and diffusion throughout the entire valley.

PFT sampling at six sites within the valley was extended up to 48 h from the release start to investigate the possibility for multiday tracer residence in the SLV.

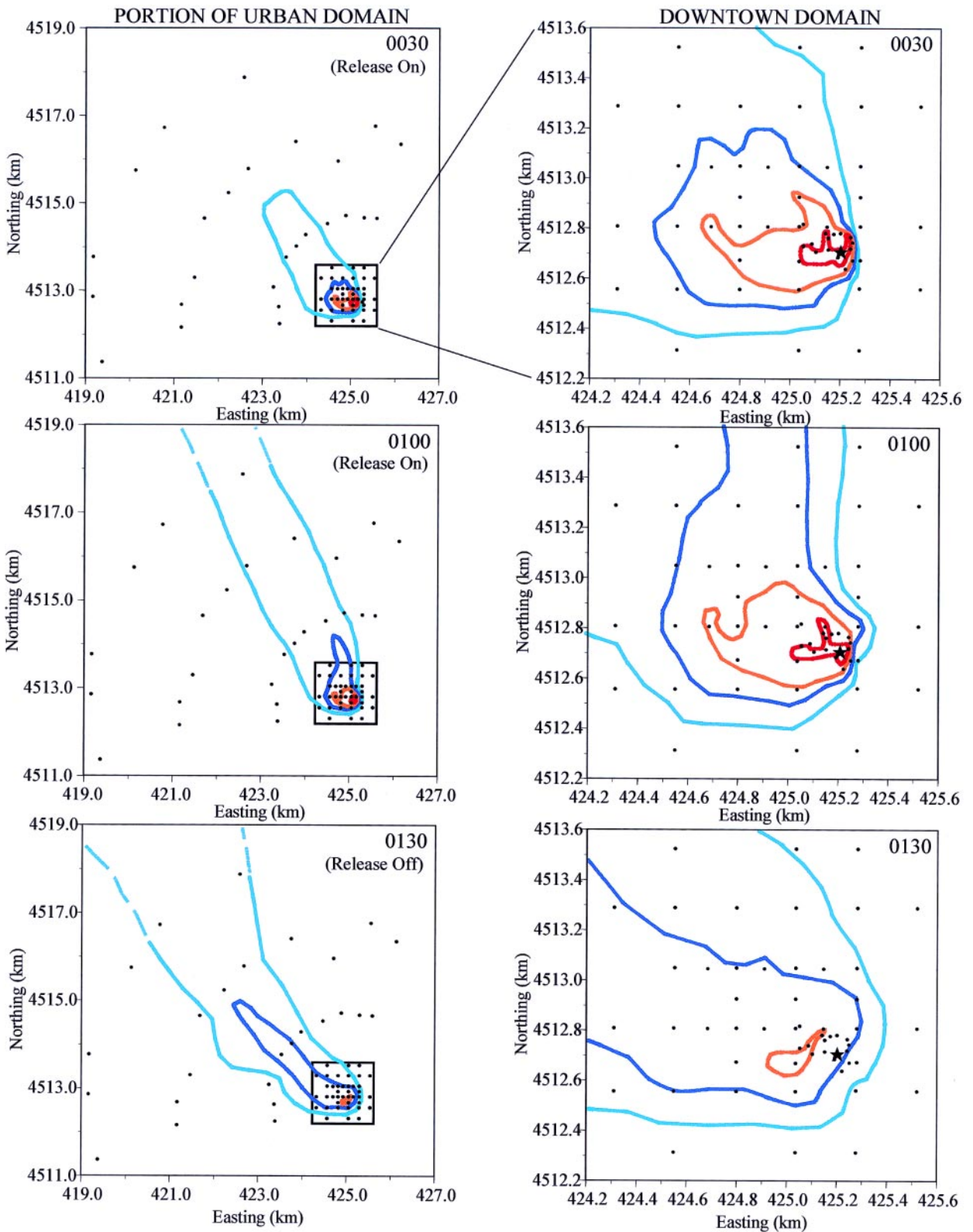
Figure 8 shows surface winds during IOP 10 of approximately  $2\text{--}4 \text{ m s}^{-1}$  from the south-southeast in the center of the SLV during the  $\text{SF}_6$  release and primary sampling period (0000–0600 MST). The 5-min-averaged winds at two locations (“Master Muffler” and “Warehouse” in Fig. 3) near downtown SLC varied from the east-northeast through south during the 0000–0600 MST period (Fig. 9). Both surface weather stations were located on building tops (Master Muffler building—4 m high, Warehouse building—20 m high) with unobstructed exposure to the winds. The 7-m AGL winds at the Master Muffler surface weather station south of downtown were less than  $2 \text{ m s}^{-1}$  from the east-northeast through the south-east during the early portion of the sampling period, increasing to  $3 \text{ m s}^{-1}$  from the east-southeast through the south during the later half of the period (0300–0600 MST). The Warehouse surface weather station northwest of downtown showed stronger winds than the Master Muffler station and more from the southerly direction. Winds were generally  $2\text{--}4 \text{ m s}^{-1}$  from the east-southeast through the south-southeast during the first half of the sampling period and  $4\text{--}6 \text{ m s}^{-1}$  from the east-southeast through the south during the later half.

Nighttime wind speeds around downtown SLC during the majority of the tracer IOPs were generally light ( $< 2\text{--}3 \text{ m s}^{-1}$ ) and the wind direction varied primarily through a  $90^\circ$  sector centered on winds from the southeast. Even higher wind speed IOPs, such as IOP 10, had considerable variation in the speed and direction of winds approaching downtown SLC.



**Fig. 9. Five-min-average wind speed ( $\text{m s}^{-1}$ ) and wind direction on building tops west (Warehouse) and south of downtown (Master Muffler). Numbers denote the ending hour (0100–0600 MST) in which measurement occurred.**

**PRELIMINARY TRACER RESULTS.** A brief discussion of results from one of the 18-h-long  $\text{SF}_6$  releases is given next as an example of the tracer results available from URBAN 2000. Data from the 145  $\text{SF}_6$  bag samplers for IOP 10 (26 October 2000) are discussed. A complete dataset for any tracer release will include, not only all the bag sampler data, but also tracer data from the eight real-time analyzers and the extensive coverage of meteorological and turbulence data.



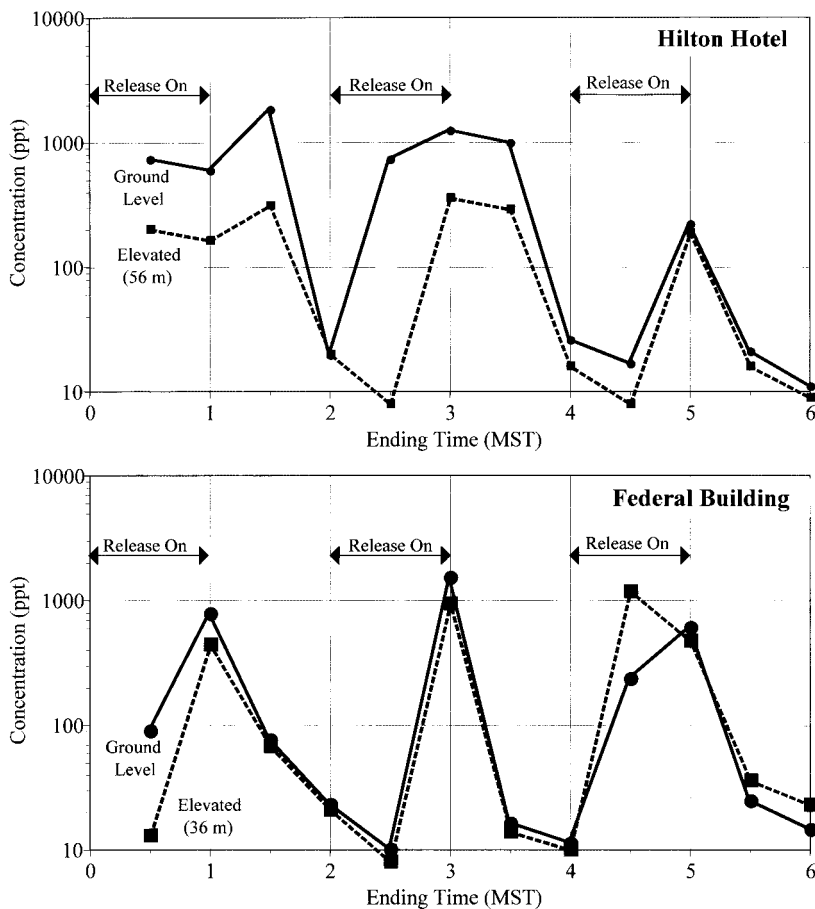
**FIG. 10.** Half-hourly average  $\text{SF}_6$  concentration isopleths (ppt) for the 0000–0100 MST release on 26 Oct 2000 (IOP 10). Ending times are shown in each panel. Black star is release point and black dots sampler locations. The isopleths include the following: cyan—30, blue—300, orange—3000, and red—30 000. (left panels) A portion of the *urban domain* and (right panels) the *downtown domain*.

The SF<sub>6</sub> concentrations isopleths for the first 1-h tracer release (0000–0100 MST) during IOP 10 are shown in Fig. 10. The isopleths are intended to identify the general coverage of the tracer plume at ground level. Tracer distributions are not resolved around individual buildings other than around the Heber M. Wells building near the release location. Half-hour-averaged concentration isopleths are displayed for three periods with ending times of 0030, 0100, and 0130 MST. The last half-hour period shows the rate of diminishing concentrations after the tracer release was stopped. Figure 10 has two panels for each of the three time periods showing the ground-level concentration isopleths for a portion of the *urban domain* out to 6 km from the release, and the ground-level concentration isopleths for the *downtown domain*. The lowest isopleth is 30 ppt, which is roughly a factor of 10 above background, giving a clear indication of the extent of the tracer plume. Additional isopleths plotted are 300, 3000, and 30,000 ppt.

The mean transport speed of the tracer plume in the *urban domain* is roughly 2 m s<sup>-1</sup> (based on its leading edge; Fig. 10), commensurate with the speed of winds approaching the downtown area. The plume transport direction in the *urban domain* is to the northwest, also commensurate with the winds west of downtown. The tracer plume in the *downtown domain* moves generally to the west near the source, pushing more to the northwest after two to three city blocks (~0.5 km) from the release location. This plume behavior is consistent with winds more from an easterly direction to the east of downtown, switching more southerly west of downtown. This behavior in the winds near downtown SLC is thought to be the interaction of the easterly downslope winds from the Wasatch Mountains to the east of downtown and from the southeasterly downvalley winds through the SLV. The land-lake breeze effect from the Great Salt Lake to the northwest of the SLV is also favorable to southeasterly winds in the SLV.

A revealing character of the tracer plume in Fig. 10 is the considerable horizontal spread of the half-hourly averaged plume in the *downtown domain*. Throughout the 1-h release period the tracer took different pathways around buildings and along roadways in the first two to three blocks from the release location. Analysis of data from the 5-min-averaged tracer samplers and the fast-response analyzers in the vicinity of the release will help identify the importance of the various mechanisms (e.g., flow channeling, vortices, wake turbulence) governing initial plume spread.

The vertical spread of the SF<sub>6</sub> plume is indicated by tracer samplers placed on building tops (Fig. 7) on an arc at roughly 0.6 km downwind of the release site. Time series plots of SF<sub>6</sub> concentrations for two elevated samplers at locations #1 (Hilton Hotel) and #4 (Federal Building) and for ground-level samplers at the two locations are shown in Fig. 11. The rise and fall of tracer concentrations from the three “1-h-on and 1-h-



**FIG. 11.** Half-hourly average SF<sub>6</sub> concentrations vs time for two building-top sampling locations in downtown SLC. Shown are concentrations for samplers at ground level and on the top of the building at locations #1 (Hilton Hotel) and #4 (Federal Building) in Fig. 7.

off" SF<sub>6</sub> releases for IOP 10 are clearly shown. Also evident is the nearly complete vertical mixing of the tracer plume through the urban canopy, especially at the Federal Building site approximately 550 m to the north-northwest of the release location. The elevated sampler (Hilton Hotel) approximately 600 m to the east-northeast of the release site showed near-complete mixing through ~60 m above ground level for the third tracer release during IOP 10.

**SUMMARY AND FUTURE DIRECTIONS.** A major urban tracer and meteorological field campaign (URBAN 2000) was conducted in SLC, Utah during October 2000 as part of the DOE's Chemical and Biological National Security Program (CBNP). CBNP is an applied research and development program that focuses emerging science and technology on countering the challenging threat of chemical and biological weapons attacks against civilian populations. To adequately plan against, train for, and respond to potential attacks, atmospheric models are being developed, tested, and evaluated within the CBNP Modeling and Prediction Initiative to provide users in intelligence, law enforcement, and emergency management with an integrated set of computer-based modeling tools by 2004. Results from the URBAN 2000 study will be used to evaluate and improve the hierarchy of atmospheric models being developed for simulating toxic agent dispersal from potential terrorist activities in urban environments. In addition, the results will be used to identify and further understand the meteorological and fluid dynamic processes governing dispersion in urban environments. The strength of the URBAN 2000 study is that it provides a dataset that resolves interacting scales of motion from the individual building up through the regional scale under the same meteorological conditions.

The hierarchy of atmospheric dispersion models under development by CBNP investigators covers transport distances ranging from dispersion around individual buildings (tens of meters), to dispersion through the urban area (hundreds of meters to a few kilometers) and dispersion beyond the urban area to the regional-scale (tens of kilometers to 100 km). To adequately evaluate the hierarchy of models, URBAN 2000 was conducted to resolve transport scales concurrently, so that various models can be evaluated using the same meteorological conditions. URBAN 2000 was designed to investigate the urban nocturnal boundary layer (stable to neutral atmospheric conditions), whereas the second major field campaign planned for 2003 will be designed to investigate the urban daytime boundary layer (neutral to unstable). Planning for the

URBAN 2003 field campaign is currently under way with DTRA. The combination of data from the already completed URBAN 2000 (nighttime) field campaign and the planned URBAN 2003 field campaign will allow the suite of CBNP dispersion models to be evaluated over a broad range of atmospheric conditions.

Work will continue during 2002 on the reduction, verification, analysis, archiving, and publication of results from the URBAN 2000 field campaign. Model evaluation workshops will be held to allow CBNP model developers and experimentalists to interact on all aspects of the data interpretation and model evaluation. It is anticipated that complete meteorological and tracer datasets for some of the seven tracer IOPs will be made available to the general scientific community for model evaluation during 2002. The URBAN 2000 study should be of general interest to all investigating urban dispersion, urban air quality, and atmospheric transport and diffusion.

**ACKNOWLEDGMENTS.** Many individuals, businesses, and scientists contributed to the successful outcome of the URBAN 2000 study. The collaboration of the CBNP-funded scientists was essential for the success of the experiments. And no less important to the success of the study was the collaboration of the VTMX scientists, especially their scientific director, Dr. Chris Doran and the principal investigator for the PFT experiments, Dr. Jerome Fast. Numerous businesses and government agencies generously allowed instruments placed and field operations conducted on their property or premises. We would especially like to thank Mr. Ben Gustafson of Gustafson Construction, Inc., whose work and connections provided us with certain key equipment and facilities. The support of the DOE CBNP staff is much appreciated, especially Drs. Page Stoutland and Richard Wheeler who were continually supportive of the work. This work was supported by the U.S. Department of Energy, under Contract DE-AC06-76RLO 1830 at the Pacific Northwest National Laboratory. Pacific Northwest National Laboratory is operated for the U.S. Department of Energy by Battelle Memorial Institute.

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