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Wintertime $PM_{2.5}$ concentrations during persistent, multi-day cold-air pools in a mountain valley

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ABSTRACT

In January and February 2011, $PM_{2.5}$ concentrations in residential and nonresidential areas of Salt Lake City, Utah, were elevated during days with persistent multi-day stable layers or cold-air pools (CAPs). Under most conditions the $PM_{2.5}$ concentrations and atmospheric stability increased with time during these events, so that the highest $PM_{2.5}$ concentrations were observed in long-lived CAPs. $PM_{2.5}$ concentrations were generally observed to decrease with increasing elevation and were linearly related to the pre-sunrise valley heat deficit, an instantaneous measure of atmospheric stability. Decreases of up to 30 percent were observed as elevation increased from 1300 to 1600 m. During the CAP episode of 23–30 January, concentrations of $PM_{2.5}$ increased roughly linearly with time at all elevations at the rate of about 6 μg $(m^3\ day)^{-1}$. Higher elevation sites also experienced more rapid influxes of clean air during the mix-out of a CAP on 16 January, although short-lived episodes of higher concentrations occurred at times when polluted air was carried upslope from the residual CAP that persisted at lower elevations.

1. Introduction

Winters in the Salt Lake Valley and other nearby valleys are punctuated by persistent cold-air pools (CAPs) or multi-day episodes of high ambient atmospheric stability that are accompanied by high levels of particulate matter with diameters less than 2.5 microns ($PM_{2.5}$). These polluted, high-stability episodes are referred to locally as the Salt Lake Valley 'inversion'. Concentrations of $PM_{2.5}$ can reach 100 μg m^{-3}, exceeding the 24-h average National Ambient Air Quality Standard (NAAQS) of 35 μg m^{-3} (U.S. EPA, 2011). In 2009, the U.S. EPA declared three regions in northern Utah nonattainment areas for 24-h average $PM_{2.5}$ (Utah Division of Air Quality, 2011a). A study conducted by the State of Utah and other organizations (Utah Asthma Program et al., 2010) showed that the odds of emergency department visits in Salt Lake County, with a primary diagnosis of asthma, are 42% higher during days 5–7 of prolonged inversions than for non-inversion periods.

Persistent multi-day CAPs in Salt Lake County and along the Wasatch Front are common in the winter months of November through February (Holzworth, 1962; Holzworth and Fisher, 1979; Wolyn and McKee, 1989; Reeves and Stensrud, 2009). Because vertical mixing of pollutants is suppressed in the stable atmospheric layers, $PM_{2.5}$ aerosols emitted into the CAP or produced there through chemical and photochemical processes lead to high levels of $PM_{2.5}$. The conditions that determine the frequency and duration of the CAPs and their associated $PM_{2.5}$ concentrations are high-pressure weather systems and the large solar zenith angles of winter that reduce insolation and, thus, surface heating (Savoie and McKee, 1995; Whiteman et al., 2001). Under a high-pressure weather system, the subsiding warm air traps cold air in the Wasatch Front's mountain valleys. The pool of cold air is reinforced by radiational cooling during clear nights and by snow-cover and cloudiness that reduce daytime warming of the ground by reflecting much of the incoming solar radiation back to space.

The depths of wintertime surface-based stable layers tend to increase with time during a CAP episode. These surface-based stable layers, which are sometimes associated with additional elevated stable layers, often reach 500 m above the valley floor to elevations of 1800 m above mean sea level (MSL). Residential areas in Salt Lake County extend to about 1600 m MSL and are thus often within the typical stable layers.

The effects of surface-based stable layers on $PM_{2.5}$ concentrations are well documented and are not limited to mountain valleys.

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During the winter months in Steubenville, OH, for example, one-hour average ambient $PM_{2.5}$ showed peak concentrations of 140 μg m^{-3} during nighttime, surface-based temperature inversions. The following afternoon concentrations were dramatically lower (Connell et al., 2005). Similarly, levels of $PM_{2.5}$ in Hamilton, Ontario, Canada increased by 54% during nighttime inversions (Wallace and Kanaroglou, 2009).

Dramatic effects of stable conditions have been observed in Fairbanks, Alaska (Tran and Mölders, 2011). A review of 10 years of data (1999–2009) for Nov–Feb showed that the NAAQS for $PM_{2.5}$, 35 μg m^{-3}, were exceeded under calm, low temperature, low humidity, multi-day surface inversion conditions. Low temperatures (≤ -20 °C) were a significant contributing factor because of increased emissions from domestic heating and electric power production during cold periods. During multi-day events at temperatures above −20 °C, high humidity (>75%) acted to lower $PM_{2.5}$. This occurred because of water adsorption by particles, swelling, coagulation, and increased sedimentation rates. Ice fog had no impact on $PM_{2.5}$ concentrations.

A study conducted in the Cache Valley, Utah, 145 km north of Salt Lake City, examined the meteorological, geographical, and environmental causes of high concentrations of $PM_{2.5}$ during January 2004 (Malek et al., 2006). One persistent CAP event led to a 24-h $PM_{2.5}$ concentration of 133 μg m^{-3} on 15 January 2004. The meteorological conditions responsible for these episodes included the lack of precipitation and winds, snow-covered ground that reflected incident solar radiation, and stable atmospheric conditions enhanced by prolonged high surface pressures. Similar conditions are common in the nearby Salt Lake Valley.

A study of the Salt Lake Valley compared one-hour average $PM_{2.5}$ concentration measurements from TEOM (Tapered Element Oscillating Microbalance) and RAMS (Real-time total Ambient Mass Sampler) analyzers (Longa et al., 2003). Data from the breakup of a January 2000 temperature inversion were particularly striking with $PM_{2.5}$ abruptly dropping from 100 to 10 μg m^{-3}. The authors attribute evening and morning peaks in $PM_{2.5}$ during temperature inversions to automobile emissions from the evening and morning commutes. The RAMS was designed to include and retain semi-volatile species such as ammonium nitrate and organic compounds. The TEOM $PM_{2.5}$ readings were about 30% lower than those from the RAMS.

While the 'inversions' are well known to residents of the Salt Lake Valley, little information is available in the scientific literature on how concentrations of $PM_{2.5}$ change with time and elevation during wintertime along the Wasatch Front. The primary objective of this study is to measure $PM_{2.5}$ in residential and non-residential areas of Salt Lake City at altitudes ranging from 1300 to 1800 m and to determine the characteristics of $PM_{2.5}$ as the wintertime atmosphere evolves and CAPs form and dissipate. Most of the results were obtained with portable samplers with a sampling period of 24 h. Supplementary results came from 5-min-average measurements made at two locations.

2. Materials and methods

Table 1 lists the sites and site characteristics for the aerosol sampling and meteorological equipment used in this paper. A map of the sites is given in Fig. 1, and further information on the four different types of aerosol samplers used in the study (TEOM, Grimm, Partisol and MiniVol) is given in Table 2. The samplers were deployed on a line that ascended monotonically from south to north through and above the Avenues residential district on the north side of the Salt Lake Valley from 1306 m (4285 ft) to 1774 m (5820 ft). The three northern-most sites were on steep hillsides above the residential area and were covered with a mixture of grass, scrub oak, and maple. The distance of the line from end-to-end is 7.7 km (4.8 mi). A description of the aerosol samplers and the meteorological instrumentation follows.

The six portable MiniVol samplers were operated over selected 24-h periods, collecting filter samples from midnight to midnight Mountain Standard Time (MST). They are designed to operate at a volumetric flow rate of 5.0 l min^{-1}. Their rotometers were calibrated outdoors in December 2010 at ambient conditions using a NIST-traceable, TetraCal Calibrator (BGI Inc). Lead-acid batteries were used to power the samplers at the three nonresidential sites. The MiniVols were checked for correct flow rates and leaks before and after each 24-h sampling period. The sample inlets were roughly 1.8 m above ground level. Sample filters were weighed using an automated filter conditioning and weighing system (Measurement Technology Laboratories, Model AH225.6) coupled with a microbalance (Mettler Toledo, Model XP2U).

The two Grimm samplers (Grimm and Eatough, 2009), with averaging periods of 5 min, measured concentrations of aerosols with diameters less than 1, 2.5, and 10 μm over the 6 January to 11 February 2011 experimental period. The Grimm samplers operate on the principle of light scattering and the results are dependent on particle optical properties. The samplers were factory calibrated with dolomite dust and the readings must be adjusted for aerosols with different optical properties. Therefore, the Grimm results for 2.5 μm were calibrated using the 24-h, 2.5 μm MiniVol filter exposures from the corresponding locations: 2nd Avenue and Hilltop. The Grimm $PM_{2.5}$ concentrations were integrated over the same midnight-to-midnight period as the MiniVols for calibration. The calibration factors ranged from 0.9 to 2.7 (ratio of MiniVol $PM_{2.5}$ concentration to Grimm concentration), and if a calibration was not available for a given day, the factor for the closest concentration value was selected. The lowest $PM_{2.5}$ concentrations were associated with the highest calibration factors, suggesting that the optical properties of particles associated with lower $PM_{2.5}$ concentrations differed more from dolomite dust than the optical properties associated with higher $PM_{2.5}$ concentrations.

The meteorological data used in the present study is a subset of data collected as part of the Persistent Cold-Air Pool Study (PCAPS) conducted in the Salt Lake Valley during the period from 1

Table 1
Sampling site names, locations, elevations, and sampler types.

Name	Symbol	Latitude	Longitude	Elevation (m)	Samplers
Salt Lake City International Airport	SLC	40.7781	−111.9694	1288	Rawinsonde
DAQ Hawthorne Air Monitoring Station	HTE	40.7343	−111.8727	1306	TEOM, Partisol, MiniVol
Integrated Sounding System	ISS	40.6007	−111.9253	1325	Rawinsonde, laser ceilometer
2nd Ave	2ND	40.7720	−111.8613	1366	MiniVol, Grimm, HOBO
9th Ave	9TH	40.7799	−111.8678	1384	MiniVol
William Browning Building	WBB	40.7662	−111.8476	1465	automatic weather station
Hilltop	HTOP	40.7862	−111.8694	1536	MiniVol, Grimm, HOBO
S1	S1	40.7955	−111.8662	1646	MiniVol, HOBO
S2	S2	40.7974	−111.8634	1731	MiniVol
S3	S3	40.7977	−111.8614	1774	MinVol, HOBO

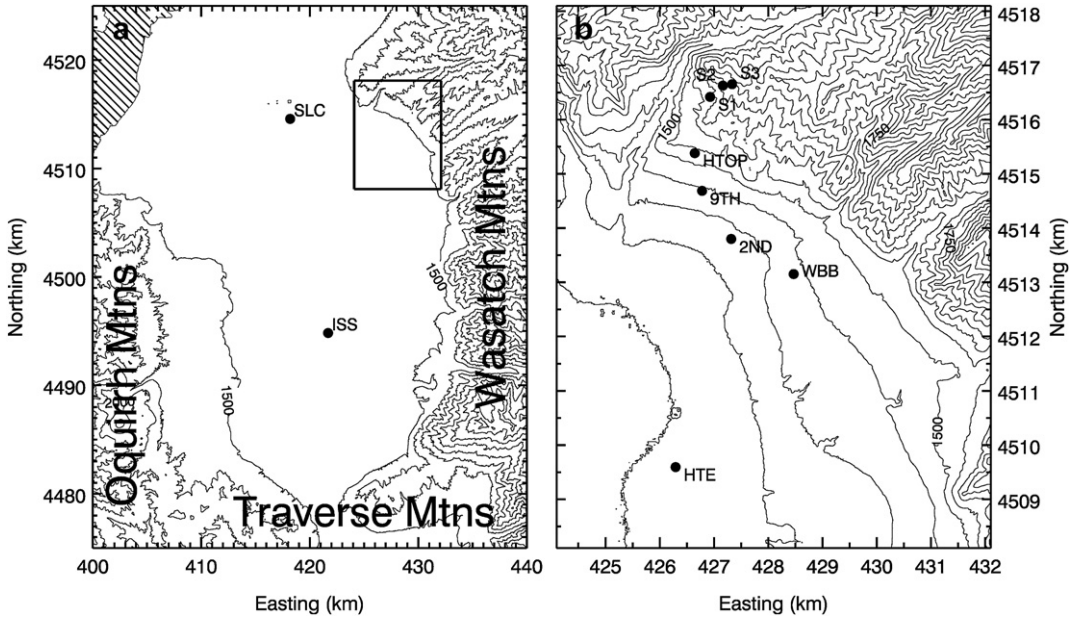

Fig. 1. Topographic map of Utah's Salt Lake Valley indicating the major terrain features and instrument locations. (a) The Salt Lake Valley with major mountain barriers, the Great Salt Lake (hatched area in upper left), and the area of expanded scale (small rectangle) that makes up b). The figures use Universal Transverse Mercator zone 12 coordinates, with a vertical contour interval of 250 m in a) and 50 m in b).

December 2010 through 8 February 2011. The subset includes data from an automatic weather station at WBB, HOBO temperature data loggers (Onset Computer Corporation, Bourne, MA) with radiation shields at 2nd Avenue, Hilltop, S1 and S3; rawinsondes launched from SLC and the Integrated Sounding System (ISS); and a laser ceilometer at ISS. The automatic weather station provided 5-min-average relative humidity data from a height of 10 m above the roof of an 8-story building. The temperature data loggers provided 10-min-average temperature data from a height of 2 m above ground. Vertical profiles of temperature and dew point temperature were obtained from standard expendable rawinsondes carried aloft by helium-filled balloons (Whiteman, 2000). A Vaisala model CL31 laser ceilometer provided continuous qualitative information on the aerosol content of the atmosphere by measuring the amount of laser light scattered back to the surface-based laser from aerosols in the vertically pointing beam (Vaisala, 2006).

3. Results and discussion

3.1. Temporal variation of $PM_{2.5}$ concentrations

$PM_{2.5}$ concentrations were quite variable in the Salt Lake Valley during the 1 January through 20 February period of data collection, as meteorological conditions changed and persistent cold-air pools came and went (Fig. 2). Fig. 2a shows how the valley atmosphere's heat deficit, a measure of CAP strength, changed with time during the experimental period. The valley heat deficit (Whiteman et al., 1999) is calculated from

$$Q = \int_0^h \rho c_p \{[T_h + \Gamma_d(h-z)] - T(z)\} dz \left[\mathrm{Jm^{-2}}\right] \quad (1)$$

where ρ is the air density, c_p is the specific heat of air at constant pressure, $\Gamma_d = 0.0098^{\circ}\mathrm{C\ m^{-1}}$ is the dry adiabatic lapse rate, $h = 1200$ m is the height above the valley floor of the Oquirrh Mountain ridgeline, T_h is the temperature at 1200 m, and $T(z)$ is air temperature. Equation (1) computes the heat required to bring the atmospheric column to a vertical temperature profile defined by a dry adiabatic lapse rate ($9.8\ ^{\circ}\mathrm{C\ km^{-1}}$) starting from the temperature at height h and extending downwards to the ground. Alternatively stated, this is the heat required to bring the atmospheric column to the potential temperature at height h. The equation is evaluated once per day using 10-m vertical resolution temperature soundings obtained from rawinsondes launched at 0415 MST from the Salt Lake City International Airport (SLC in Fig. 1). Fig. 2b shows measured $PM_{2.5}$ concentrations from the TEOM, Partisol and MiniVol samplers at Hawthorne for comparison with the heat deficit measurements in Fig. 2a. The concentrations are 24-h averages, and the MiniVol results are shown by the squares. The agreement between the three $PM_{2.5}$ measurement techniques is generally good except at the lower concentrations. For example, the sum of the squared differences between the Minivol and TEOM values is 77.4, and the two lowest readings (21 and 23 January) contribute 58.1 to that sum.

Fig. 3 shows that the $PM_{2.5}$ concentrations in Fig. 2b, as measured by TEOM at HTE on the floor of the Salt Lake Valley, are well correlated ($r^2 = 0.78$) with the valley heat deficit, indicating

Table 2
Aerosol samplers used in this study, their principles of operation, and averaging periods.

Model	Manufacturer	Principle of operation	Averaging period
MiniVol Model 4.2 Portable Air Sampler	Airmetrics	Impactor and filter	24 h
Partisol Plus Model 2025 Sequential Air Sampler	Thermo Fisher Scientific, Inc	Sharp cut cyclone and filter	24 h
TEOM 1405 DF Filter Dynamics Measurement System	Thermo Fisher Scientific, Inc	Tapered element oscillating microbalance	1 h
Grimm 1.109 Portable Aerosol Spectrometer	GRIMM Technologies, Inc	Light scattering	5 min

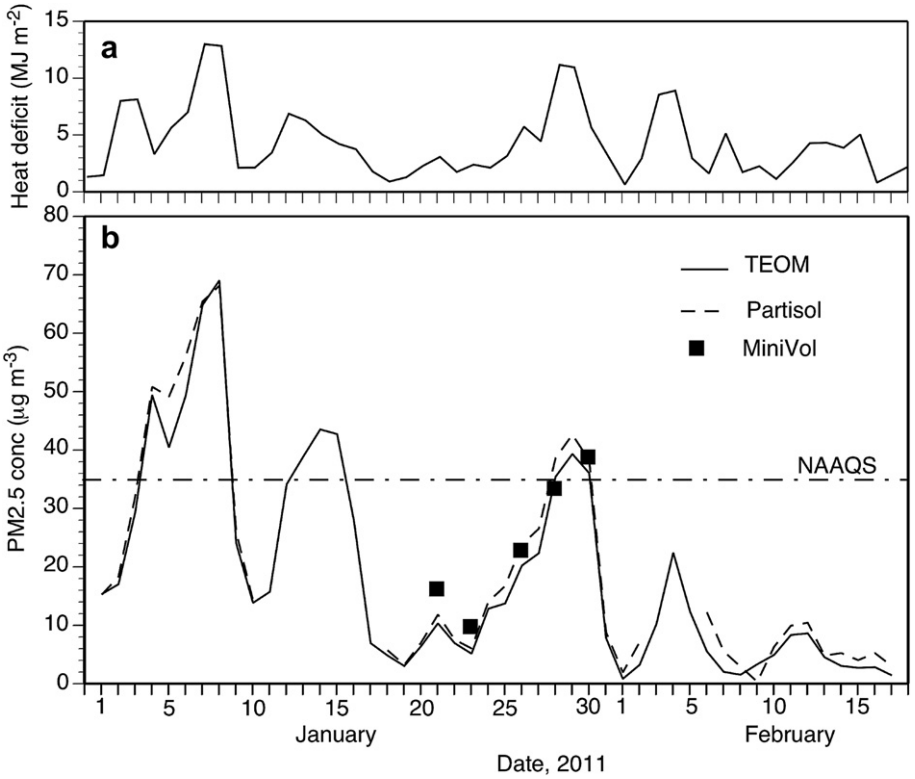

Fig. 2. a) 24-h average thermal energy deficits for 1 January – 20 February 2011. b) 24-h average $PM_{2.5}$ concentrations for 1 January – 20 February 2011 measured by three different samplers (TEOM, Partisol and MiniVol) at HTE. The horizontal line at 35 μg m^{-3} is the 24-h average NAAQS for $PM_{2.5}$.

that concentrations are a function of CAP strength. The correlation is surprisingly large considering that Eq. (1) incorporates no information on wind strength, cloud cover, snow-cover, humidity, or even $PM_{2.5}$ source strength.

$PM_{2.5}$ concentrations increase with increasing CAP duration, as the pollutants tend to accumulate in the stable atmospheric conditions associated with the CAPs. The duration of an event in Fig. 2a is given by the valley-to-valley time difference and the intensity is given by peak height. The highest $PM_{2.5}$ concentrations are associated with the longest duration CAP events and $PM_{2.5}$ concentrations increase with time as CAPs age. During January 2011, the 24-h average NAAQS $PM_{2.5}$ concentrations of 35 μg m^{-3} (U.S. EPA, 2011) were exceeded three times (Fig. 2b). In addition to the duration of the cold-air pool in modulating the overall $PM_{2.5}$ concentrations, the intensity of the CAP as shown by the heat deficit (Fig. 2a) also influences the accumulation of $PM_{2.5}$ within the valley. The duration and intensity are both important in determining $PM_{2.5}$ levels. For example, the 11–16 January event, with a peak $PM_{2.5}$ concentration of 43.5 μg m^{-3}, was characterized by a relatively low heat deficit but a long duration. The 2–5 February event, with a peak $PM_{2.5}$ concentration of 22.4 μg m^{-3}, had a higher heat deficit but a shorter duration. In a later section, we will also see that the presence or absence of a CAP influences the rate at which $PM_{2.5}$ decreases with height.

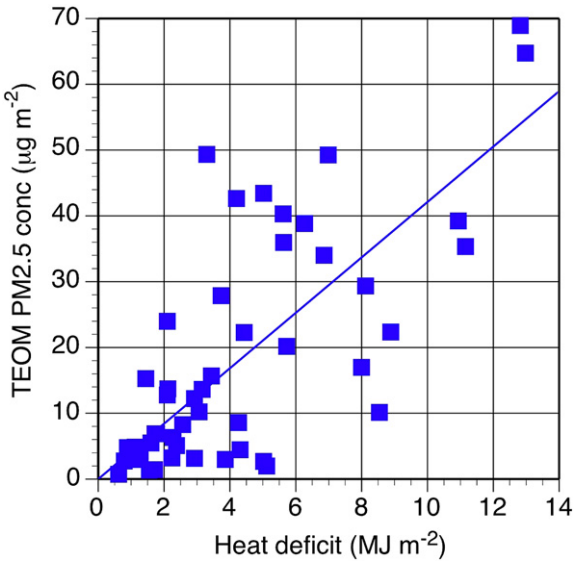

Fig. 3. Correlation of 24 h TEOM $PM_{2.5}$ concentrations in Fig. 2b with 24-h heat deficit values in Fig. 2a; $r^2 = 0.78$.

The increase in $PM_{2.5}$ concentrations during the buildup of a multi-day CAP during the period 23–30 January is shown in Fig. 4. During this period, 24-h average $PM_{2.5}$ concentrations were measured on 23, 26, 28, 30 January 2011 at sites ranging in altitude from 1306 to 1646 m. Concentrations increased from day to day as the CAP persisted. The rate of increase of concentration was 6 μg $(m^3\ day)^{-1}$ and this rate was seen at all sites, insensitive to elevation.

3.2. Altitudinal variation of $PM_{2.5}$ concentrations

Long-lived, strongly stable cold-air pool episodes accumulate $PM_{2.5}$ in the lower elevations of the Salt Lake Valley and the higher stability prevents the $PM_{2.5}$ from mixing as readily to higher elevations as on the lower stability days. Fig. 5 shows the altitudinal

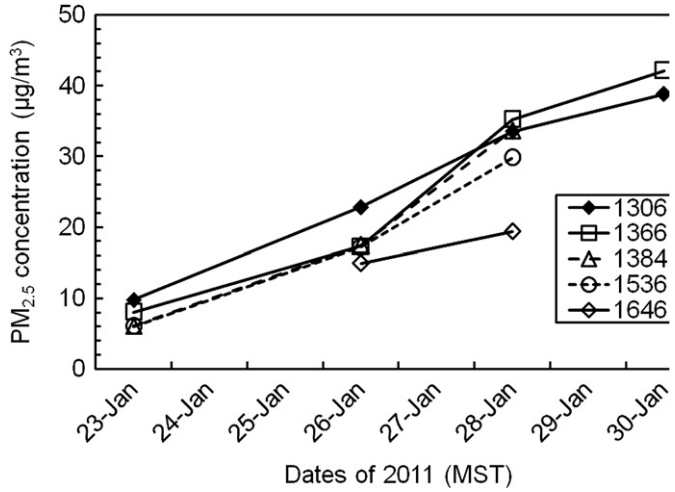

Fig. 4. MiniVol $PM_{2.5}$ concentrations for 23, 26, 28, and 30 January 2011 showing how concentration increases with time during a multi-day CAP episode. Elevations (m) of the sampling sites are given in the legend.

dependence of $PM_{2.5}$ concentrations for the days in which MiniVol samplers were deployed on the north-south line that extended to high altitudes above the Avenues residential area. Note that two MiniVols were collocated at the Hilltop site. The replicated concentration pairs are listed in Table 3; the average of the two values is plotted in Fig. 5. The replicated data enable calculation of the sample variance and standard deviation of the MiniVol filter results: $s^2 = 1.4\ \mu g^2\ m^{-6}$ and $s = 1.2\ \mu g\ m^{-3}$. Vertically averaged $PM_{2.5}$ concentrations increase as the duration of the CAP increases, with lowest $PM_{2.5}$ concentrations on days when CAPs had not been present for several days. There is often an increase of $PM_{2.5}$ with altitude in the narrow range of elevations between the valley floor and 1400 m during strong CAP events, possibly related to advection of precursors and their chemical transformations to form secondary $PM_{2.5}$ at higher elevations.

Based on the data in Fig. 5, there is a statistically significant (using the t-distribution and a 95% confidence level) trend toward lower $PM_{2.5}$ with increasing elevation, and the three highest sites (S1, S2 and S3) at 1646, 1731, and 1774 m MSL, are located so close to

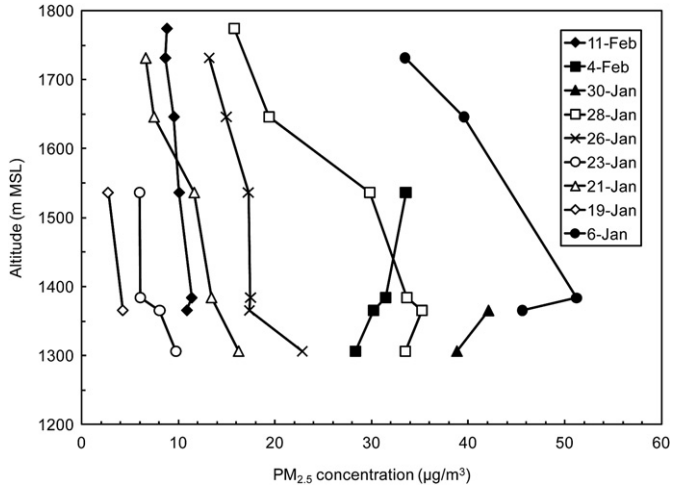

Fig. 5. 24-h average MiniVol $PM_{2.5}$ data as a function of elevation for the dates indicated in the legend. Data points are at elevations corresponding to the MiniVol sampling sites listed in Table 1.

Table 3
$PM_{2.5}$ concentrations (24-h averages) obtained from collocated MiniVols at the Hilltop site, elevation 1536 m.

Date (MST)	$PM_{2.5}$ ($\mu g\ m^{-3}$)
19 Jan 2011	3.3, 2.2
21 Jan 2011	11, 12
23 Jan 2011	5.2, 6.8
26 Jan 2011	16, 19
11 Feb 2011	10, 10

each other that it is difficult to attribute the decline in concentration to horizontal distance from sources in the valley. Data showing the degree to which horizontal position in the valley affects $PM_{2.5}$ is given in Fig. 6 using 24-h filter samples from the State's four Salt Lake Valley, $PM_{2.5}$ monitoring stations. The data were collected on 6 and 28 January 2011 at the Hawthorne, Cottonwood, Magna, and Rose Park stations (Utah Division of Air Quality, 2011b). The commas separating the pairs of concentrations in Fig. 6 mark their approximate coordinates. Their elevations are 1306, 1335, 1317, and 1295 m MSL. The data show a high degree of homogeneity for the three eastern-most stations, even though they are separated by as much as 15 km. The Magna location is on the western edge of the valley in a fairly rural area, close to the Great Salt Lake, which may explain the lower $PM_{2.5}$ level there.

The homogeneity of $PM_{2.5}$ in CAPs may be due, in part, to the high level of secondary particulate. Emissions of precursors are believed to cause more than 75% of the $PM_{2.5}$ in CAP events (Utah Division of Air Quality, 2011a). The delays associated with dispersion, mixing, and reactions of precursors may contribute to the homogeneity of $PM_{2.5}$ concentrations across the Salt Lake Valley.

The vertical concentration gradients shown in Fig. 5 are most likely a result of poor vertical mixing caused by the CAP. Higher concentrations are observed at lower elevations because the sources of primary and secondary aerosols are mainly on the valley

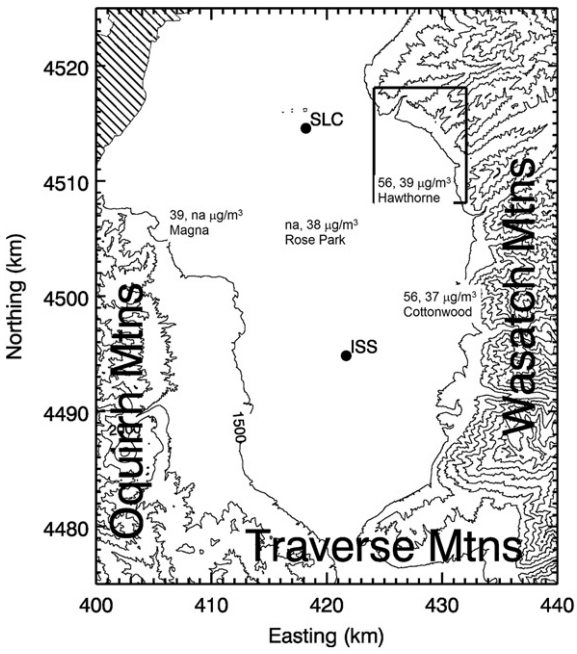

Fig. 6. 24-h average $PM_{2.5}$ data for the Salt Lake Valley for four monitoring stations (Hawthorne, Cottonwood, Magna, and Rose Park) operated by the Utah Division of Air Quality (Utah Division of Air Quality, 2011b). Data pairs represent the 24-h average $PM_{2.5}$ data for 6 and 28 January 2011, respectively. The comas separating the two values mark the locations of the stations.

floor. The unusual results on 4 February were collected during a relatively weak CAP that may have allowed for higher rates of vertical mixing compared to 6 January and 28 January. The relative weakness of the 4 February event is shown by the smaller heat deficit in Fig. 2a compared to those on 6 and 28 January.

3.3. Temporal and spatial variations of $PM_{2.5}$ concentrations during CAP breakup

A CAP having high values of $PM_{2.5}$ was present in the Salt Lake Valley during the 11–16 January period (Fig. 2). The breakup of the CAP on 16 January (Fig. 7) resulted in a dramatic improvement in air quality and a decrease in $PM_{2.5}$ concentrations from 40–60 to 5–15 μg m^{-3} (Fig. 7a) at the measurement sites. The rate of improvement was a strong function of elevation, with $PM_{2.5}$ decreasing more rapidly at the higher elevation Hilltop site. The high levels of $PM_{2.5}$ at the lower elevation Hawthorne and 2nd Avenue sites decreased more slowly during the course of the day, was similar at both sites, and remained consistently higher than at the Hilltop site except for periods when mix-out or advection events occurred. Major mix-out events occurred at 0300–0545 and at 0700–0800 MST. These were followed by four short-lived events centered at 0920, 1400, 1700, and 1935 MST when concentrations at Hilltop suddenly increased to attain values similar to those at the lower sites. Fig. 7b shows the temperatures recorded during 16 January at the 2nd Avenue and Hilltop sites and Fig. 7c shows the relative humidity recorded at the nearby WBB site. In Fig. 7d, the orange and red colors in the laser ceilometer plots indicate the presence of clouds and precipitation; saturation of the ceilometer beam prevents it from seeing all the way through optically thick cloud layers. The shallow, ground-based green- and light blue-colored layer indicates the presence of aerosols within the

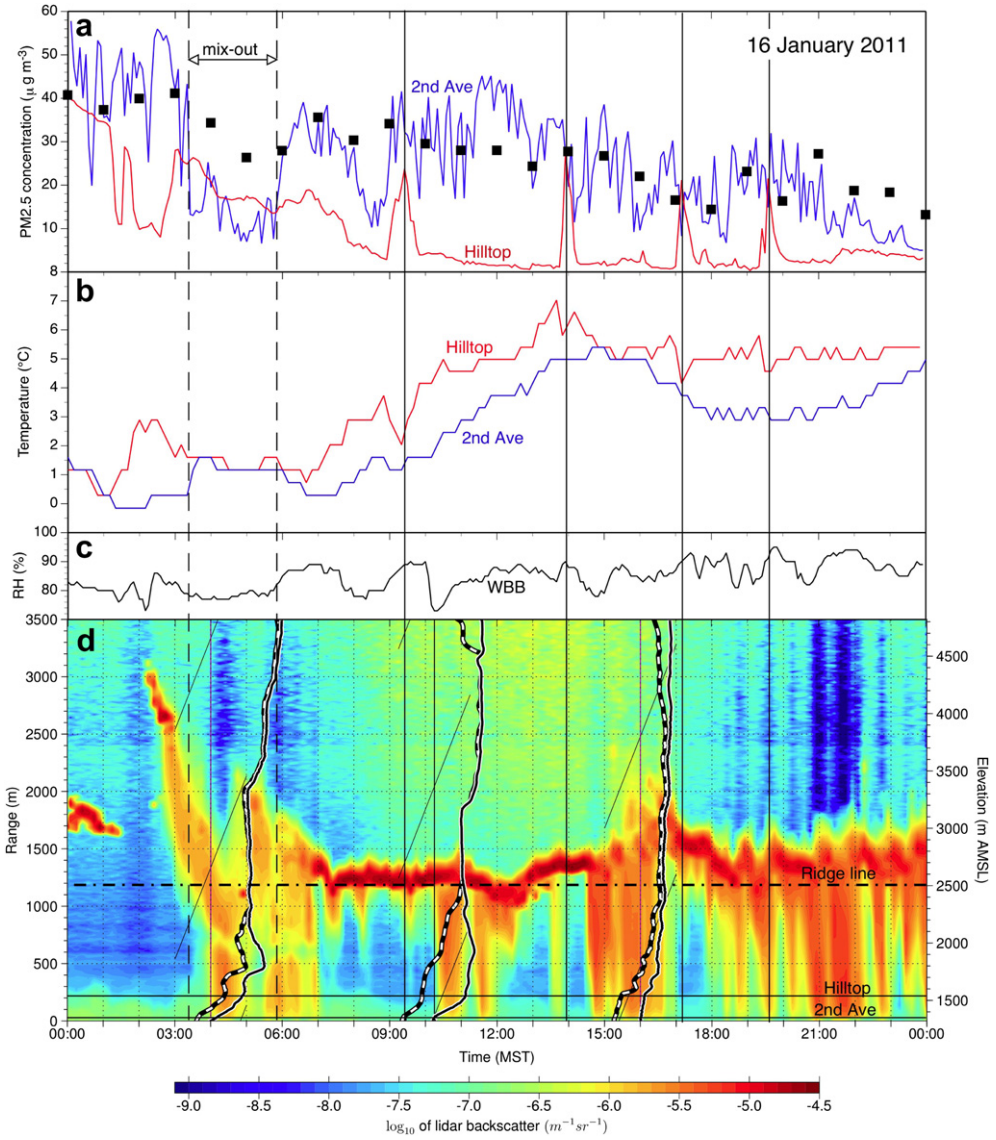

Fig. 7. a) Five minute-average $PM_{2.5}$ concentrations at Hilltop (red line, Grimm) and 2nd Avenue (blue line, Grimm), and 1-h average concentrations at Hawthorne (black squares, TEOM), b) 1-m air temperature from temperature data loggers at Hilltop (red line) and 2nd Avenue (blue line), c) relative humidity at WBB, and d) laser ceilometer backscatter coefficient (color scale), with rawinsonde temperature (black line) and dew point temperature (black-white line) soundings superimposed from ISS. The temperature soundings are plotted in a skewed temperature-height coordinate system for which isotherms are indicated by the sloping thin black lines. Rawinsonde launch times are indicated by thin black vertical lines in d). The mean height of the Oquirrh Mountain ridgeline to the west of the Salt Lake Valley (horizontal dash-dot line) and the elevations of the Hilltop and 2nd Avenue sites (horizontal black lines) are also indicated. Dashed vertical black lines indicate the "mix-out" period, while the thick vertical black lines are centered on the times of four distinct spikes in $PM_{2.5}$ concentrations at Hilltop.

surface-based CAP. The incursions of polluted air at Hilltop were meteorologically driven and are discussed in the remainder of this section.

The breakup of the CAP occurred under the influence of weak synoptic disturbances in west-northwest flow aloft, but with winds in the valley flowing down-valley from south to north. One such weather disturbance was associated with a period (0300–0545 MST) of fog and cloud with light precipitation within the Salt Lake Valley (Fig. 7d) when vertical mixing equilibrated the $PM_{2.5}$ concentrations at the 2nd Avenue and Hilltop sites (Fig. 7a). A weaker event occurred at 0700–0800 MST. Following these mix-out events, a persistent layer of altostratus appeared over the valley at about ridge-top level, with occasional shafts of rain and virga falling into the valley from the cloud base. These rain shafts, which produced only traces of precipitation at the valley floor, are evident in the laser ceilometer backscatter data (Fig. 7d) as reddish streaks descending from cloud base near mountaintop level to the near-surface level. After 0900 MST, the CAP air settled lower into the valley leaving the Hilltop site above the polluted air while the 2nd Avenue site was within it. Despite the overall weakening of the CAP seen in the rawinsonde profiles (Fig. 7d), the near-surface temperature at 2nd Avenue was generally 1–2 K cooler than at Hilltop (Fig. 7b), indicating that the temperature profile between these two locations remained inverted for much of 16 January. However, the temperature decreased with height at two locations (S1 and S3) above Hilltop (not shown), indicating that Hilltop was near the upper boundary of the CAP on this day.

Oscillations in the surface-based CAP depth were observed in the laser ceilometer backscatter signal over the valley center (Fig. 7d). Similar oscillations in depth could be expected over the Avenues, as rain shafts modulated the height of the top of the CAP or as variations occurred in the strength of the flows aloft and the channeled flows within the valley, causing oscillations in $PM_{2.5}$ concentrations at Hilltop. The distinct, short-lived maxima in $PM_{2.5}$ concentrations there at 0920, 1400, 1700, and 1935 MST were associated with temporary upslope advection of the colder, moister, and more polluted air from lower altitudes. Each of the four maxima at Hilltop matched the concentrations in the cold-air pool remnant at the lower sites and was associated with temperature decreases of about 1 K and relative humidity increases (at the nearby WBB site) of 5–10%, indicating the presence of CAP air.

4. Conclusions

Analysis of $PM_{2.5}$ concentration data from several types of near-surface samplers during a 1 January through 20 February 2011 period in which a sequence of persistent cold-air pools formed in the Salt Lake Valley led to the following conclusions:

- $PM_{2.5}$ concentrations increase with valley heat deficit, a measure of CAP strength.
- The valley heat deficit and $PM_{2.5}$ concentrations increase with time during multi-day CAPs. Higher concentrations are thus generally found in the longest lasting CAPs.
- Based on a line of ground-based $PM_{2.5}$ samplers running up a mountainside on the north edge of the valley, highest concentrations are generally found on or within the lowest 150 m above the valley floor, with concentrations then decreasing with further altitude.
- During a 23–30 January CAP episode, the day-to-day rate of increase in $PM_{2.5}$ concentration was linear at the rate of 6 μg $(m^3\ day)^{-1}$ and varied little with altitude.
- The breakup of a CAP on 16 January 2011 occurred first at the higher elevations, causing $PM_{2.5}$ concentrations to fall earlier at the higher elevations than at the lower elevations of the valley. During the subsequent breakup of the remaining CAP at the lower elevations, there were four short-lived episodes in which higher concentrations from the residual CAP were advected up the sidewall to a higher elevation site.

The availability of special $PM_{2.5}$ and meteorological observations from the winter 2011 experimental period has allowed us to draw conclusions concerning the characteristics of $PM_{2.5}$ distribution and evolution in the Salt Lake Valley. Additional observations and analyses will result in the reduction of uncertainties and the development of a better understanding of $PM_{2.5}$ behavior in this and other valleys. Model simulations are planned to further understanding of $PM_{2.5}$ behavior. We plan, in future, to conduct additional field studies and to examine the role of local meteorology in CAP events.

The meteorological conditions that give rise to persistent CAPs in Salt Lake City and surrounding areas cannot be controlled to any extent by man. To improve air quality, the State of Utah is planning to implement stricter emission controls of area, point, and mobile sources of primary aerosols and precursors that form secondary aerosols in the atmosphere.

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