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Meteorological and environmental aspects of one of the worst national air pollution episodes (January, 2004) in Logan, Cache Valley, Utah, USA

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Abstract

Logan, Utah, USA, had the nation's worst air pollution on 15 January, 2004. The high concentration of $PM_{2.5}$ (particulates smaller than 2.5 μm in diameter) in the air resulted from geographical, meteorological, and environmental aspects of Cache Valley. A strong inversion (increase of temperature with height) and light precipitation and/or wind were the major causes for trapping pollutants in the air. Other meteorological factors enhancing the inversion were: the prolonged high atmospheric surface pressure, a snow-covered surface which plunged temperatures to as low as -23.6 °C on January 23rd and high reflection of solar radiation (up to about 80%), which caused less solar radiation absorption during the day throughout the most part of January 2004. Among non-meteorological factors are Cache Valley's small-basin geographical structure which traps air, with no big body of water to help the air circulation (as a result of differential heating and cooling rates for land and water), motor vehicle emissions, and existence of excess ammonia gas as a byproduct of livestock manure and urine. Concentration of $PM_{2.5}$ was monitored in downtown Logan. On January 15, 2004, the 24-h, filter-based concentration reached about 132.5 μg per cubic meter of air, an astonishingly high value compared to the values of 65 μg m^{-3} and over, indicating a health alert for everyone. These tiny particles in the air have an enormous impact on health, aggravating heart and lung disease, triggering asthma and even death. The causes of this inversion

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and some suggestions to alleviate the wintertime particle concentration in Cache Valley will be addressed in this article.

Keywords: Air pollution; Cache Valley; Inversion; Meteorology; Particulate matter

1. Introduction

It was widely reported in the media that on 15 January, 2004, the nation's worst air pollution occurred in Logan, Utah (USA), the County Seat of Cache Valley, a metropolitan area with a population of about 100,000. The populated area is characterized as a flat-bottom mountain valley, approximately 61 km long by 50 km wide (Utah History for Kids—Cache County, 2004), almost completely surrounded by steep mountains up to about 1370 m above the valley floor. Among reported comments were: "Logan air is the dirtiest in the USA," and "Logan air found worst to breathe in the USA" (The Salt Lake Tribune, 2004). Inversions and high concentrations of air pollutants have occurred in Cache Valley in the past, but the episode of January 2004 was the worst to date. Mangelson et al. (1997) studied the contribution of sulfates and nitrates to atmospheric fine particles during winter inversion fogs in Cache Valley, Utah. They reported significant conversion of SO_2 and NO_x in the presence of excess oxidants to sulfuric and nitric acids that were neutralized by excess ammonia.

Air pollution is referred to as the degradation of air quality resulting from unwanted gases and particulates occurring in the air. These substances in the atmosphere may result in adverse effects to humans, animals, vegetation and materials. The air quality index (AQI) is used for reporting severity of air pollution levels to the public (40 CFR 58 App. G., 2000a). The AQI incorporates one or a combination of five criteria pollutants: ground level ozone, particulate matter ($PM_{2.5}$ or PM_{10}, e.g., $PM_{2.5}$ is the gravitational mass of all particles #2.5 μm in diameter), carbon monoxide, sulfur dioxide, and nitrogen dioxide. AQI levels range from zero (good air quality) to 500 (hazardous air quality). The range 101–150 is categorized as unhealthy for sensitive groups for each of these five categories of air pollutants. An AQI value is calculated daily for each of these pollutants; the highest AQI for an individual pollutant is the AQI value for that day. The AQI conversion for each of the above-mentioned pollutants can be found at the U.S. Environmental Protection Agency web page (EPA, 2004).

Particulate matter is a collective term used to describe small solid particles and liquid droplets (excluding water vapor) that are present in the atmosphere over relatively brief (minutes) to extended periods of time (days to weeks). Of major concern are particles <20 μm because they can remain suspended in the atmosphere, as they settle out relatively slowly. The formation and increase of atmospheric aerosols from the combination of natural (e.g., animal) and anthropogenic sources is a major air-quality concern. The aerosols may 1) scatter light, reducing visibility, 2) pose an inhalation hazard to humans and animals, 3) affect climate on a regional and global scale, and 4) be a nuisance due to their soiling potential. Sulfates and nitrates are often species that comprise the major components of fine particles (including $PM_{2.5}$ and PM_{10}), although their abundance varies greatly depending on the relative strength of local precursor sources (Godish, 1997).

Preliminary numbers indicated that Logan had record-breaking pollution levels in Utah and the nation during the period of 10–17 January, 2004. The instantaneous real-time concentration of $PM_{2.5}$ was reported to be 182 μg m^{-3} at around 6 p.m. in Cache Valley on 15 January, 2004. This would be equivalent to an AQI reading of 232, well into the "very unhealthy" category. The 24-h, filter-based $PM_{2.5}$ concentration for this particular day has been reported as 132.5 μg per cubic meter of air. The USA Environmental Protection Agency (EPA) has recorded 24-h readings of 213.7 and 199.8 μg m^{-3} in Montana, associated with large-scale summertime wildfires in 2003 and 2000, respectively. The highest recorded $PM_{2.5}$ concentrations for a more "normal" event was 160 μg m^{-3}, recorded on 1 January, 2000, in Fresno, California (The Salt Lake Tribune, 2004).

The AQI range at 151–200 is categorized as "unhealthy," which is equivalent to concentration ranges of 65.5 to 150.4 μg m^{-3}. During January and February, 2004, Cache Valley was within this AQI category for 17 individual days (Utah Department of Environmental Quality, 2004). In this condition, people with heart or lung disease, older adults, and children are advised to avoid prolonged or heavy exertion. The remainder of the population is recommended to reduce prolonged or heavy exertion. Among the wintertime major sources of air pollution in Cache Valley are: motor vehicles, wood stove combustion, and ammonia produced by livestock. Due to frequent inversions and favorable chemical reactions, the resultant particulate matter may stay suspended in the air for long periods of time and has the potential to cause serious health problems.

The most significant particle-forming chemical reactions in the Logan airshed are those involving acid-based reactions between gas-phase compounds emitted from agricultural and vehicular sources. Gasoline and diesel vehicles and other combustion sources emit nitric oxide (NO), which rapidly oxidizes by ozone (O_3) to nitrogen dioxide (NO_2) in the atmosphere. The NO_2 is converted into nitric acid (HNO_3) by several different reactions, the most common being reaction with hydroxyl radicals (OH) during the daytime and the reaction with O_3 at night. Ammonia (NH_3) is converted from urea, as well as emitted directly from animal waste. In the atmosphere, NH_3 and HNO_3 are present in the gas-phase; however, they undergo a simple acid–base reaction to form a salt, ammonium nitrate (NH_4NO_3). Ammonium nitrate is a common component of $PM_{2.5}$, especially in the Western U.S., and it rapidly builds up concentration during inversion events in Logan. In most of the US, ammonia reacts primarily with sulfuric acid which comes from coal-fired combustion plants. However, because there are no major coal-fired facilities in Cache Valley, the ammonia reacts with readily available nitric acid (Martin and Koford, 2004).

How and why did this high concentration of $PM_{2.5}$ occur in Cache Valley? This article reports the responsible factors for creation of the reported worst national air pollution in Logan (the County seat) in mid-January, 2004. Additionally, some suggestions to alleviate the wintertime particle concentration in Cache Valley will be addressed.

2. Location of Cache Valley

The north–south oriented Cache Valley (about 3050 km^2) is located in northern Utah, USA. This valley is situated in a geographically tight bowl, with tall surrounding mountains. The Cache Valley location, with an average of about 1430 m above mean sea level (msl), is shown in Fig. 1. It is surrounded by the Clarkston Mountains to the northwest, the Wellsville Mountains to the southwest, Davenport Hollow ridges to the south, and the Bear River Range to the east, with an elevation of 2513 m, 2857 m, 2601 m, and 3042 m, respectively. The north part of Cache Valley extends into the state of Idaho (Franklin County) with almost the same airshed as in Cache Valley. The 3-dimensional nature of the bowl-shaped Cache Valley is depicted in Fig. 2 (with permission, Topo USA-5.0, 2004).

3. Materials and methods

Since 1996, measurements have been conducted at the Cache Logan Airport (41°47′N, 111°51′W, 1460 m above mean sea level), recording meteorological parameters such as the

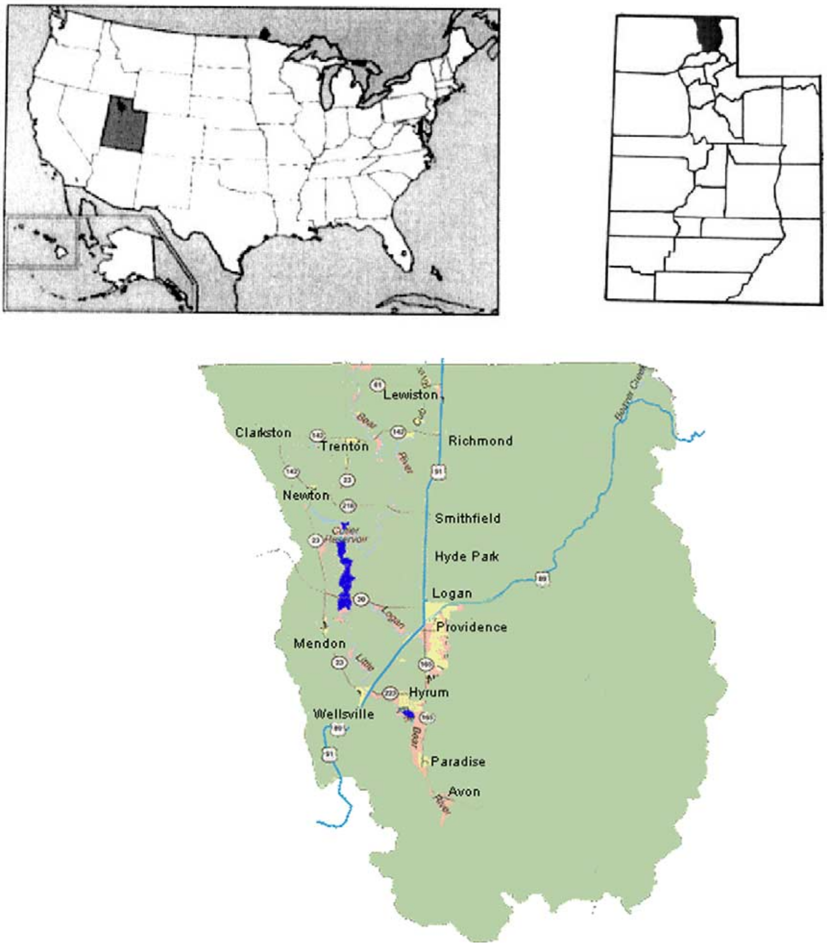

Fig. 1. Cache Valley in northern Utah, USA.

Fig. 2. The 3-dimensional nature of the bowl-shaped Cache Valley (Topo USA-5.0, 2004).

overall radiation budget components, namely: incoming (R_{si}) and outgoing (R_{so}) solar or shortwave radiation, using two Kipp and Zonen CM11 pyranometers (one inverted), as well as the incoming (R_{li} or atmospheric) and outgoing (R_{lo} or terrestrial) longwave radiation, using two Kipp and Zonen CG1 pyrgeometers (one inverted) (Malek, 1997). These sensors were ventilated with four Kipp and Zonen CVB1 blowers powered by two CVP1 units throughout the year to prevent dew and frost formation. Summation of these components yields the net or available (R_n) radiation. Supporting parameters measured were the 2-m air temperature and relative humidity (Campbell Sci., Inc., CSI), the surface temperature (Radiation and Energy Balance Systems, REBS, Inc.), the 3-m wind speed (U_3) and direction (R.M. Young wind monitor), precipitation (using a heated raingage), and the surface pressure (CSI).

An air monitoring station in downtown Logan (Utah Air Monitoring Center, 2004a) collected $PM_{2.5}$ aerosols according to the prescribed Federal Reference Method (FRM) for $PM_{2.5}$ (40 CFR 50 App. L, 2000b). In brief, ambient air is drawn into the system

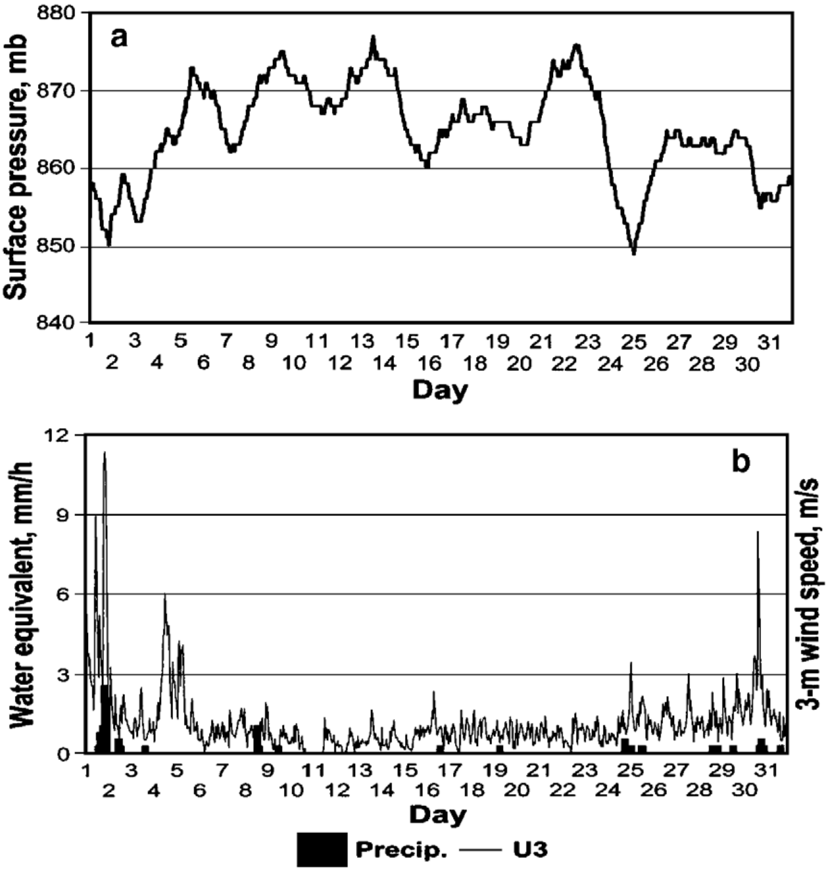

Fig. 3. a) The hourly pressure distribution, and b) precipitation and windiness in Cache Valley during the month of January, 2004.

(Rupprecht and Patashnick Partisol-Plus Model 2025 Sequential Sampler) through a specifically designed inertial size-segregating impactor to separate and discard particles greater than 2.5 μm in diameter. The air containing the $PM_{2.5}$ material is then pulled through a preweighed filter, with the total sample air volume measured and recorded over the length of the specified 24-h sampling period. After sampling, the filter is recovered and returned to an analytical laboratory for post-test conditioning and mass determination. The $PM_{2.5}$ is subsequently determined as the total collected mass divided by the 24-h measured air volume.

4. Results and discussion

Factors responsible for the creation of high $PM_{2.5}$ episodes in Cache Valley can be categorized as: (1) meteorological factors and (2) air pollutant sources/formation factors. These are discussed in detail below.

4.1. Meteorological factors

4.1.1. Surface pressure, precipitation, windiness, and $PM_{2.5}$ concentrations

During January, 2004, Cache Valley was covered with an average of about 392 mm of snow. The total snowfall in January, 2004, amounted to 259 mm, which yielded about 19 mm water (using heated raingage). This means that each 10 mm of this light snow could produce about 0.7 mm of water. The 3-m prevailing southwesterly wind speed averaged about 1.2 m s^{-1} during the month of January, 2004, in Cache Valley. Fig. 3a and b show the January, 2004, hourly pressure, precipitation, and wind distribution in Cache Valley. The 24-h concentrations of $PM_{2.5}$ for Logan during January, 2004, are shown in Fig. 4 (Utah Air Monitoring Center, 2004b). Comparison between Figs. 3 and 4 shows that low pressures in early days of January, 2004, (day 1 through 5) were associated with strong winds and precipitation, which resulted in low concentrations of $PM_{2.5}$. Then, the high

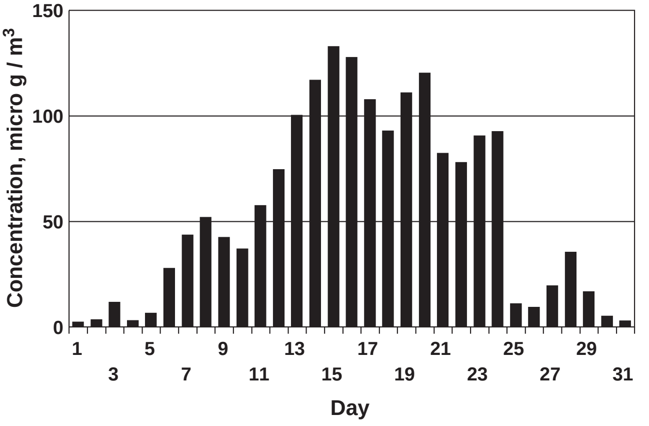

Fig. 4. The 24-h concentrations of $PH_{2.5}$ in Logan during January 2004.

pressure started to build up until January 7. Lack of precipitation paired with calm winds during this period caused a high 24-h concentration of $PM_{2.5}$ to unhealthy levels (>40 μg m^{-3}). Light precipitation in the late night and early morning of 8 and 9 January, respectively, washed out some pollutants from the air. Beginning on 11 January, 2004, high atmospheric pressure sealed down the cold, polluted air in Cache Valley under a thick layer of warm air. With no precipitation and average wind of about 0.5 m s^{-1}, $PM_{2.5}$ built up in the valley during this period (up to about a 24-h value of 132.5 μg per cubic meter of air on 15 January). Lower concentrations of $PM_{2.5}$ on 18 and 22 January, are related to light precipitation on previous days. High pressure dominated the region until 24 January, followed by a sudden decrease in $PM_{2.5}$ due to a low pressure storm system which came through the region on 25 January, 2004, and consequent cleaning of the air. During the period of 7–24 January (except on 10th), 2004, $PM_{2.5}$ levels were unhealthy (>40 μg

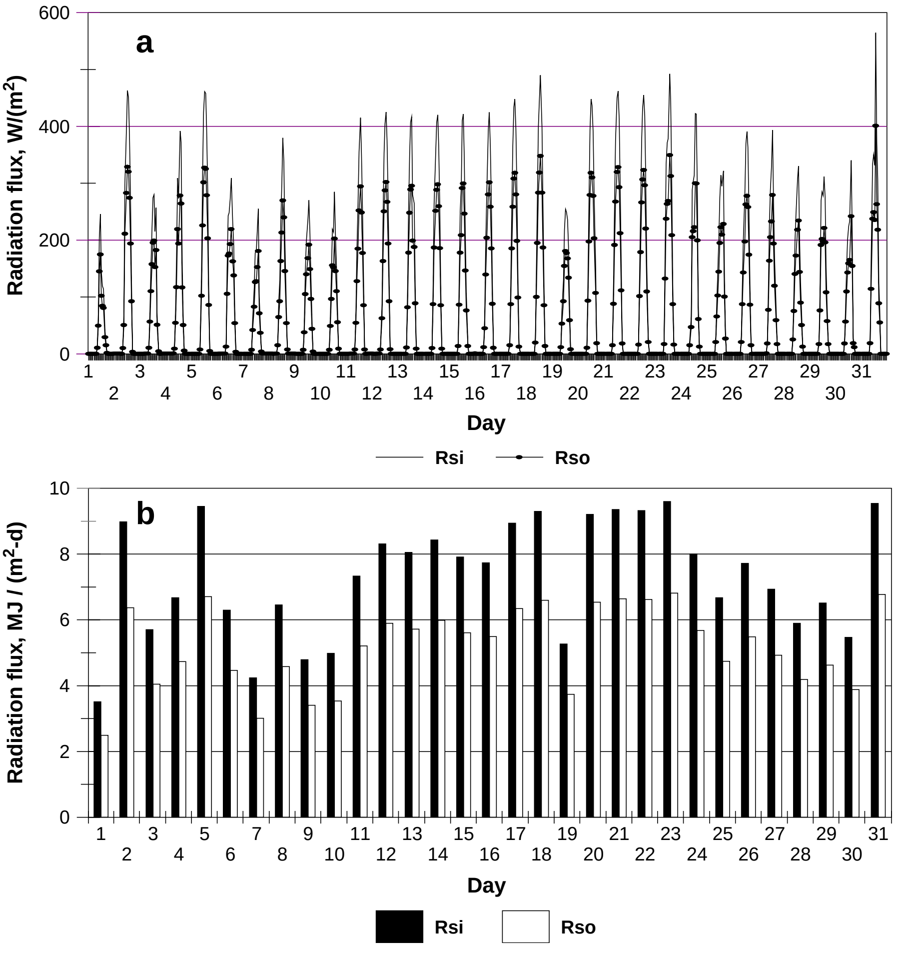

Fig. 5. a) The hourly and b) 24-h values of incoming (solar, R_{si}), outgoing (reflected solar, R_{so}) radiation in Cache Valley during the month of January, 2004.

m^{-3}). Maximum 24-h $PM_{2.5}$ concentrations were 39 μg m^{-3} during the month of December, 2003 (on 20th). The $PM_{2.5}$ concentrations on 3, 7, 13–18, and 22–25 of February, 2004, were reported as unhealthy, with a maximum of 102 μg m^{-3} on the 16th (Utah Air Monitoring Center, 2004b).

4.1.2. Radiation budget components

During the month of January, 2004, the valley floor was covered with snow. This blanket of snow was responsible for reflecting up to about 80% of the incoming solar radiation during this month. The hourly and 24-h values of incoming or solar radiation (R_{si}) and the outgoing or reflected radiation (R_{so}) in Cache Valley during the month of January, 2004, are depicted in Fig. 5. Fig. 6 shows the hourly and 24-h incoming longwave

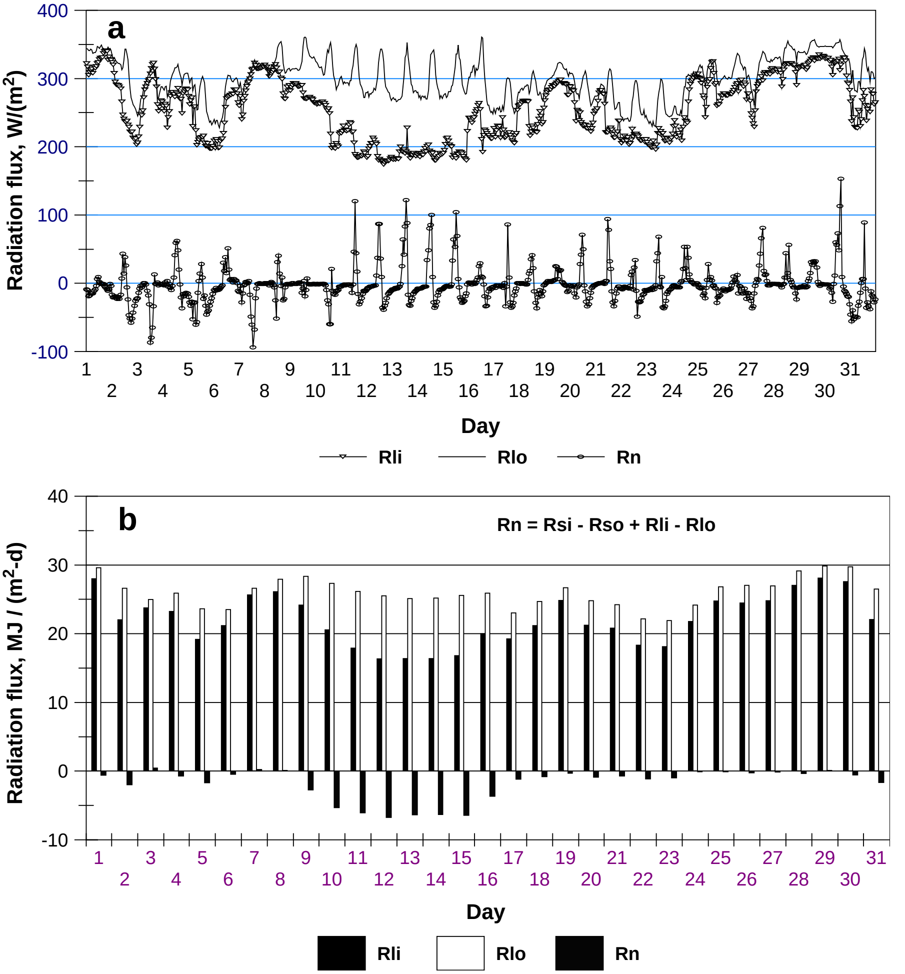

Fig. 6. a) The hourly and b) 24-h values of incoming longwave (atmospheric, R_{li}) and outgoing (terrestrial, R_{lo}) along with the net (R_n) radiation in Cache Valley during the month of January, 2004.

or atmospheric radiation (R_{li}) and outgoing longwave or terrestrial radiation (R_{lo}) along with the net (R_n) radiation for Cache Valley during January, 2004. R_n is expressed as:

$$R_n = R_{si} - R_{so} + R_{li} - R_{lo} \tag{1}$$

These radiation budget components have been shown to be useful for parameterization of clouds (Malek, 1997, 2004). The hourly cloudiness in Cache Valley during the month of January, 2004, is presented in Fig. 7. As shown, the valley was mostly overcast during this month, except for partly cloudy skies from the 12th to 16th. As depicted in Fig. 6a, the 24-h R_n was negative in the valley throughout the month of January, 2004. Snow-covered surfaces are major contributors for negative Rn in the valley during winter. As a result, inversion forms which causes high concentrations of air pollutant in the air. Solar radiation photochemically impacts on pollution by production of near surface ozone, and oxidized hydrocarbons (Silva et al., 2004).

4.1.3. The near surface weather conditions

Fig. 8 shows the hourly values of surface and 2-m air temperatures, and the 2-m relative humidity in Cache Valley during the month of January, 2004. The average 2-m air and surface temperatures were −10.1 and −10.6 °C, respectively, and the average 2-m relative humidity amounted to 84% during the month of January, 2004. The National Climatic Data Center (NCDC, 2004) archived foggy and snowy conditions at the Logan airport Automated Surface Observation System (ASOS) throughout most of the month January of 2004. This high humidity increases the probability of aqueous-phase fog chemistry. Unique nitrogen and sulfur chemistry can occur in aqueous-phase droplets that does not occur in the gas-phase (Silva et al., 2004).

We evaluated the near-surface lapse or inversion conditions (decrease or increase of temperature with height, respectively) in the valley. This was done by computing $\Delta T/\Delta z$, where $\Delta T = T_{surf} - T_{a2}$ in $°C^{-1}$ and $\Delta z = -2m$. Positive and negative outcomes were related to inversion or lapse conditions, respectively. Fig. 9 shows this ratio in Cache

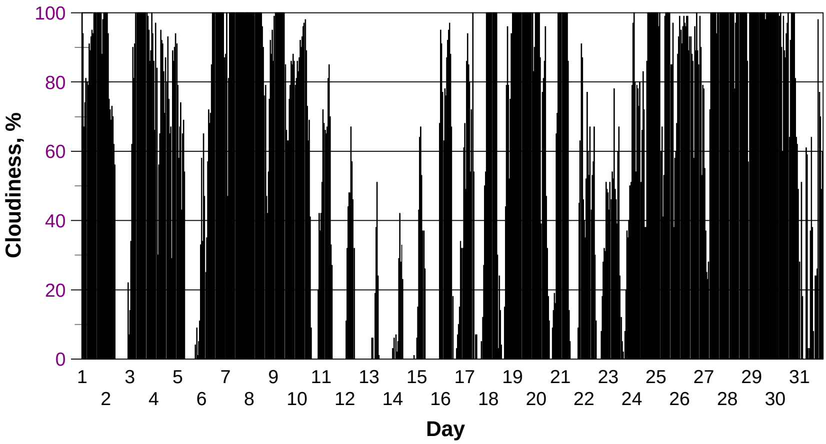

Fig. 7. The hourly cloudiness in Cache Valley during the month of January, 2004.

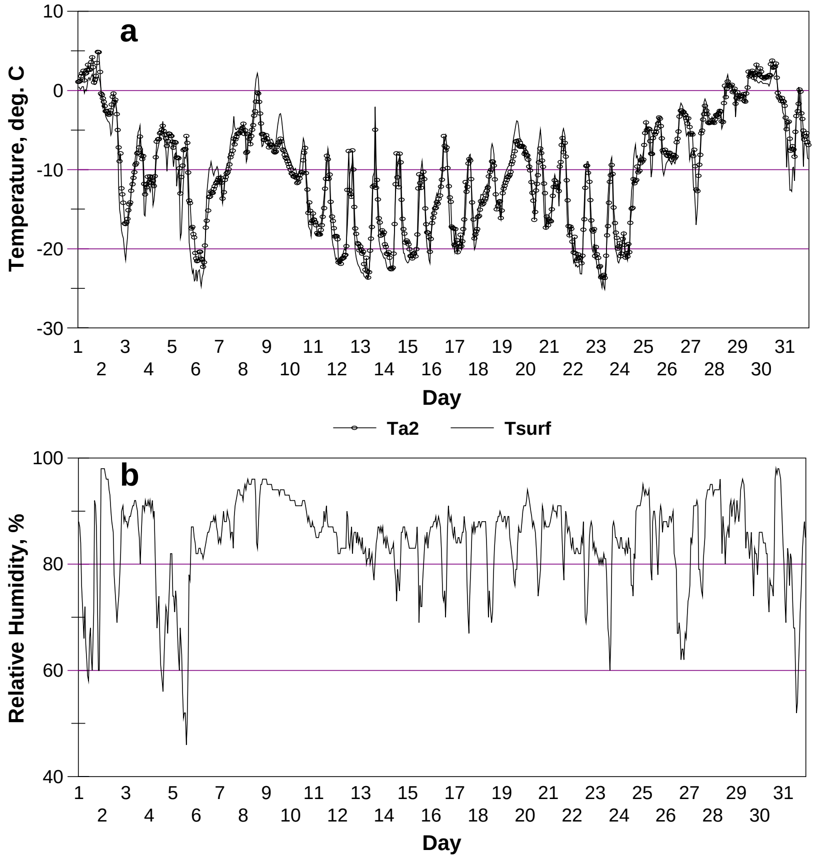

Fig. 8. The hourly values of a) surface and 2-m air temperatures and b) the 2-m relative humidity in Cache Valley during the month of January, 2004.

Valley throughout the month of January, 2004. Frequent occurrence of near-surface inversion, especially during the middle of this the month, is evident. The combination of temperature inversion, very cold temperatures, and lack of enough precipitation and/or strong winds, resulted in stagnant air in the valley with no tendency for vertical movement. This phenomenon was observed frequently in the valley during the months of January and February, 2004.

The high ground level $PM_{2.5}$ concentrations and visual evidence suggested that significant inversion layers existed mostly in January and February, 2004, in the valley. Climbing the surrounding mountains to reach the clear sky during these winter-inversion episodes showed that concentration of pollutants ended at a height range of 250 to 350 m above the valley floor. Fig. 10 shows an example of the winter time inversion in the valley. The pictures were taken on 6 February, 2004. Background shows the Wellsville Mountains under the clear sky. The Cache Logan Airport does not launch radiosonde for sounding the air and consequently to evaluate the depth of inversion in the valley.

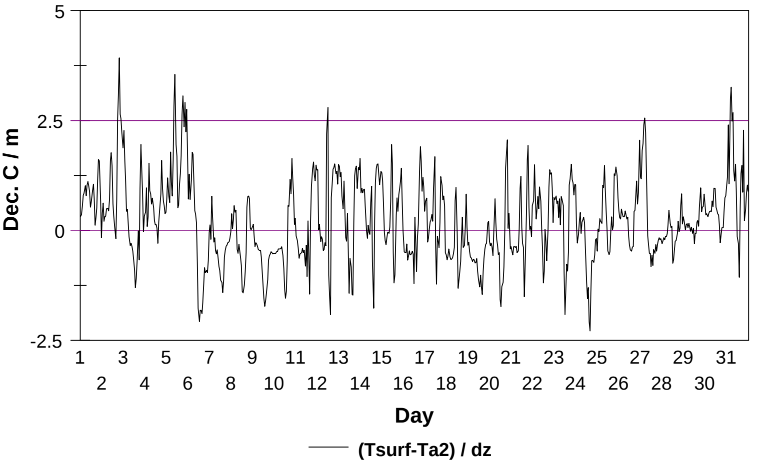

Fig. 9. Lapses or inversions Episodes in Cache Valley throughout the month of January, 2004.

4.1.4. Ground-based vertical temperature profile

Fig. 11 shows the vertical temperature profiles determined by traveling approximately 13 km up the adjacent Logan River Canyon. The profiles were obtained at roughly the same time on two different days (12 and 15 January, 2004). As can be seen, on both days, a clear inversion started at around 1520 m above msl (approximately 150 m above the lowest elevation shown). The strong inversions shown on both days are also supported by persistent high barometric pressures (Fig. 3a), low surface temperatures (Fig. 8a), and strong negative net radiation (Fig. 6b).

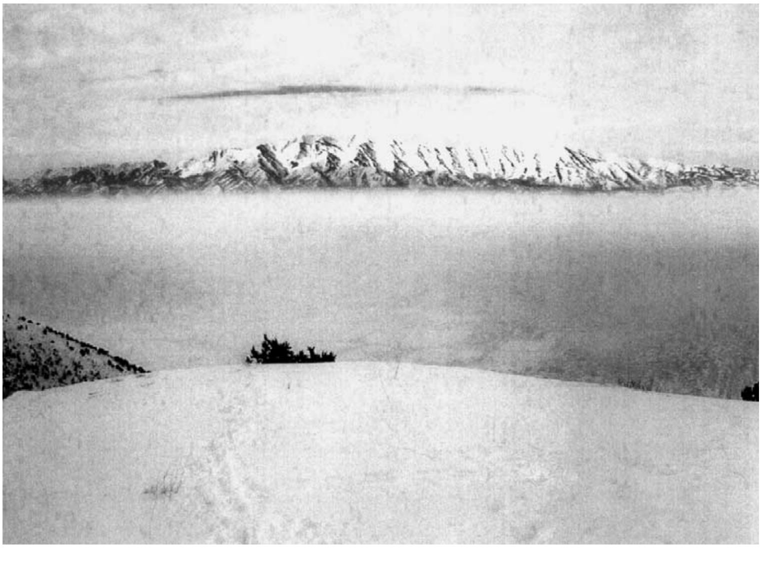

Fig. 10. An example of inversion in Cache Valley.

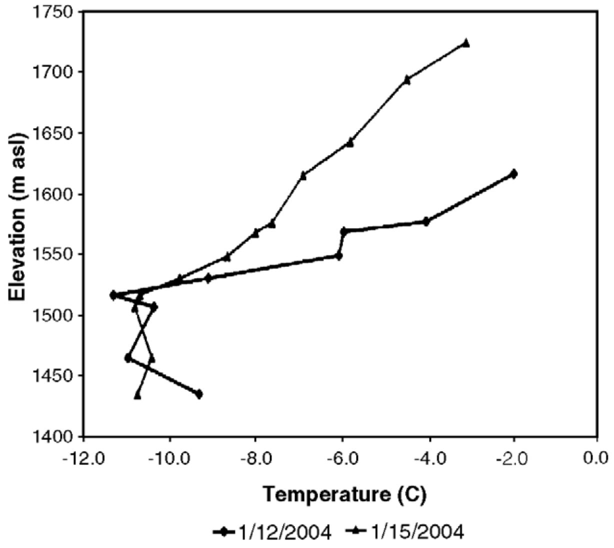

Fig. 11. The vertical temperature profiles determined by traveling approximately 13 km up the adjacent Logan River Canyon.

Furthermore, it can be seen that the portion of the atmosphere above the measured inversion heights can be classified as extremely stable, or Pasquill–Gifford Stability Class G. This infrequent classification occurs when the measured ambient lapse rate is greater than +4.0 °C/100 m (NCR, 1980); under these conditions vertical mixing is negligible, although horizontal dispersion beneath the inversion may be significant, depending on the underlying lapse rate and wind conditions. As can be derived from Fig. 12, the sub-inversion-layer lapse rates on 12 January, 2004, were extremely unstable (starting from the surface), then slightly stable to extremely unstable for the measured periods on 12 January, 2004. The sub-inversion-layer temperature profiles were slightly different on 15 January, 2004. The near-surface variations of lapses and inversions, illustrated in Fig. 9, confirm the sub-inversion-layer conditions, shown in Fig. 11.

In another attempt during 12–15 January, 2004, the Cache Valley inversion was evaluated by measuring the air temperatures from Logan to a higher altitude at Mendon (see Fig. 1). The inversion depth during this trial was about 350 m (Wright, 2004, personal communications).

4.2. Air pollutants

Cache Valley's major air pollutant categories are listed by the US Air Quality Gradebook using emission data from the US Air Quality Gradebook (2004). During the winter season, motor vehicles, wood stove combustion, and agriculturally driven ammonia are the most important sources of local primary and secondary air pollutants. Emission from vehicles during very cold weather become more significant as engines warm up (cold start) and lengthy idling boosts the incomplete fuel combustion and emission of nitrogen

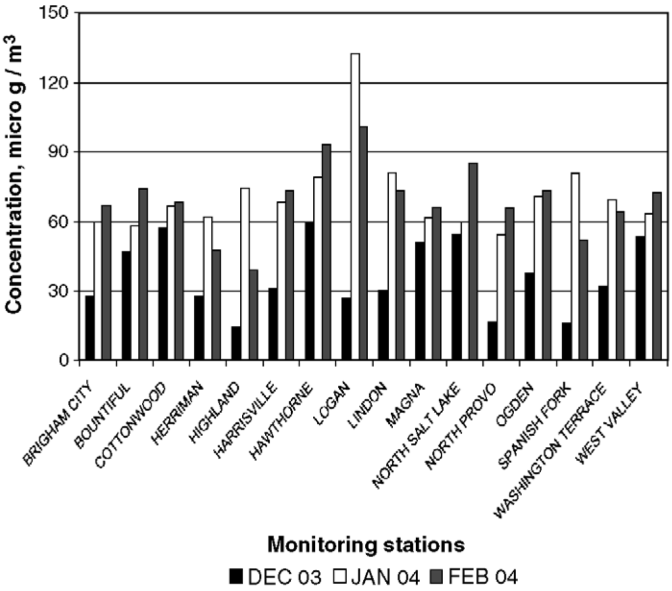

Fig. 12. Highest $PM_{2.5}$ throughout the state of Utah during December, 2003, and January and February, 2004.

oxides. Much of the organic hydrocarbons emissions are not characterized yet. With no major precipitation and/or wind, and existence of strong high surface pressure and frequent inversions, the particulate matter ($PM_{2.5}$ and PM_{10}) can build up, often making the air unhealthy to breathe. The combination of fog and photochemistry appear to aid in production of secondary chemical species in the particles (Silva et al., 2004). Fig. 12 shows the highest $PM_{2.5}$ throughout the state of Utah during December, 2003, and January and February, 2004 (Utah Air Monitoring, 2004c). As shown, Logan ranked first among monitoring stations in Utah, both in January and February, 2004. The elevated $PM_{2.5}$ levels in Logan during these months are in direct relationship with the high pressure, low temperatures, negative net radiation, shallow surface inversion episodes, and the valley topography previously described.

5. Conclusion

Local hospitals reported an increase in the number patients suffering from chronic obstructive pulmonary disease during the January, 2004, inversion in Cache Valley (The Salt Lake Tribune, 2004). What can be done to alleviate the wintertime high concentration of air pollutants in the valley? As mentioned previously, motor vehicles (especially when idling) and ammonia are the major sources of pollution. Voluntary or even mandatory shut down of banks' and fast food restaurants' drive-through windows during the inversion may reduce the pollutants entering the air. Driving as little as possible, car pooling, or using public transportation are some other ways to prevent more pollution of the air. Additionally, vehicle inspection and maintenance (I&M) programs in other regions have been shown to be effective for reducing emissions of primary and secondary particulate materials. Cache Valley is the State of Utah leader in dairy production (Utah Reach, 2004). The economic report to the Governor (USDA, National Agricultural Statistics Service, 2003) shows that there are 75,000 cattle, 13,000 hogs, and 4000 sheep on the Utah side of Cache Valley (Utah Statesman, 2004), providing a significant source of ammonia, which is a major contributor to the formation of particulate ammonium nitrate and, subsequently, to the high level of $PM_{2.5}$ in the valley. Research needs to be done to reduce ammonia from animal waste products.

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