# 1. Introduction

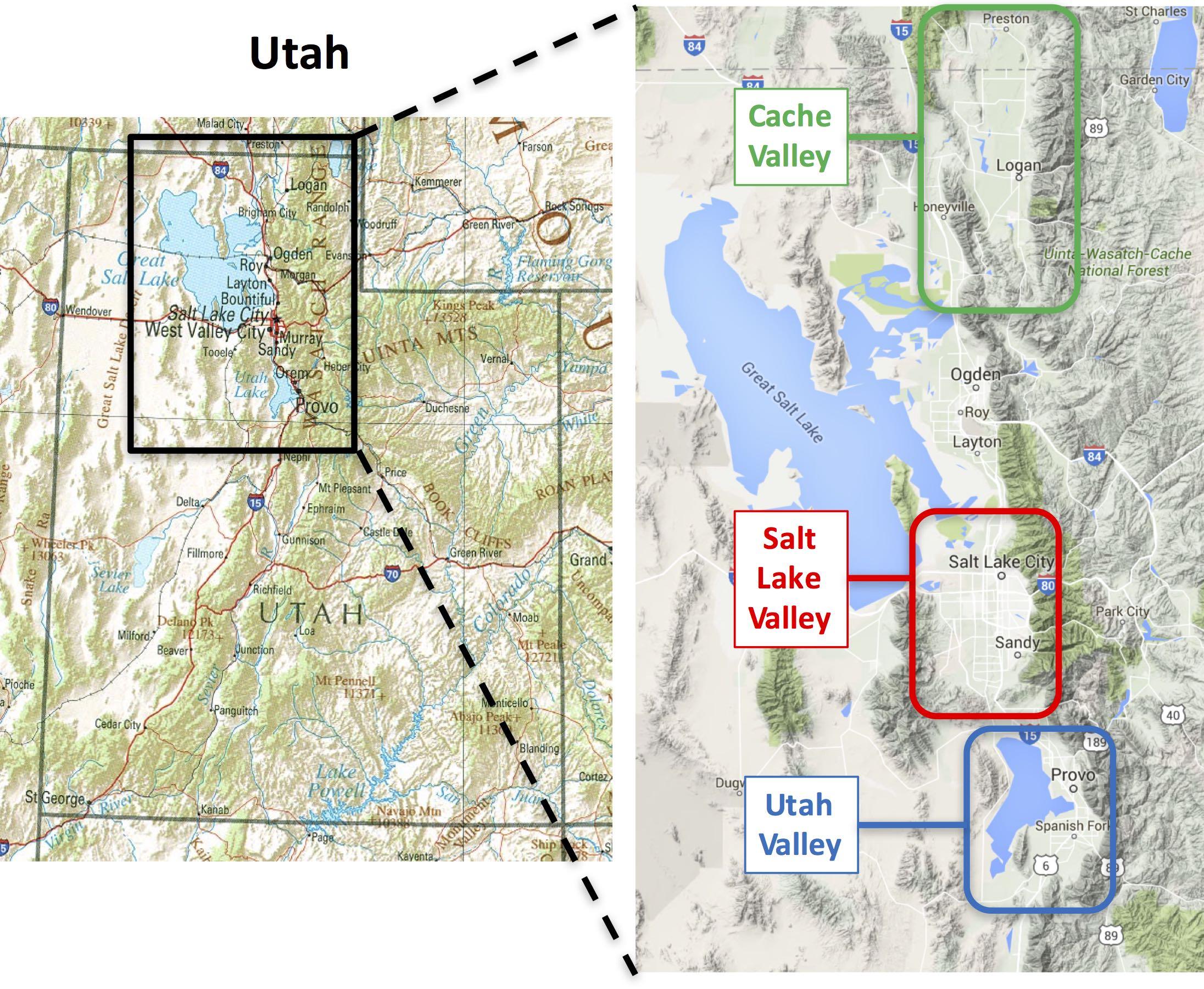
Working Group: Munkh Baasandorj, Steve Brown, Sebastian Hoch, Erik Crosman

## 1.1 PM Exceedances in Great Salt Lake Region

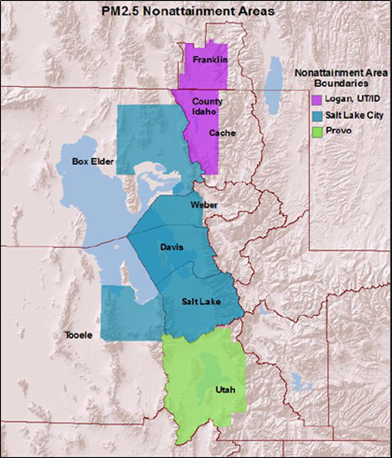
Munkh Baasandorj & Steve Brown

The air basins along and adjacent to Utah’s Wasatch Front, a region with 2.4 million residents (2010 Census), experience some of the most severe particulate matter (PM) air pollution in the United States. Although there is considerable inter-annual variability in the number, severity and duration of pollution events, analysis of historical data shows that the region exceeds the National Ambient Air Quality Standard (NAAQS, 35 µg m–3, 24 hours) for particulate matter with aerodynamic diameter smaller than 2.5 µm (PM2.5) on average 18 days out of the year. The majority of exceedance days occur in December, January and early February during a period when passages of high pressure systems lead to stably stratified valley atmospheres, or persistent cold air pools (PCAPs), that trap urban emissions within a shallow boundary layer (Whiteman *2*014). Particulate matter exceedances in northern Utah are similar to those seen in urban mountain valleys across the western United States, but Salt Lake City is by far the largest urban area subject to these air quality issues in the intermountain west, and it experiences the highest PM concentrations (Green2015). Particulate matter accumulates at rates of 6-10 µg m–3 day-1 during PCAP events to reach maximum daily average concentrations of 70-80 µg m–3 (Silcox 2012, Whiteman 2014) in the Salt Lake City area, and up to 132.5 µg m–3 in Logan, UT (Malek 2006). Hourly PM2.5 at Logan has been reported as high as 182 µg m–3 in January of 2004.

High PM2.5 mass loadings in northern Utah are a significant public health concern. They have been specifically associated with adverse health effects in the region, including a 42% higher rate of emergency room visits for asthma during the latter stages of air pollution events (Beard 2012) and a 4.5% increase in the risk for acute ischemic coronary events per 10 µg m–3 particulate concentration (Pope 2006). The US EPA declared three regions, including part or all of 7 counties in northern Utah, as non-attainment areas (NAA) in 2009 (Silcox *et al.* 2012; SIP 2XXX) as shown in **Figure 1.2**. Two nonattainment regions are located along Utah’s Wasatch Front (Salt Lake City Utah NAA, Provo Utah NAA), where 80% of Utah’s population lives, while one region (Logan Utah-Idaho NAA) consists of the Cache Valley in the northernmost part of the state. Because of recent failures to bring these areas back into attainment with the standard, the two NAAs along the Wasatch Front have been redesignated in December 2016 as “serious” NAA, a designation more critical than “moderate”. Under the Federal Clean Air Act, The State of Utah is mandated to demonstrate attainment of the federal standard at a future date; usually five-years out from a present-day “base” year and required to develop more stringent regulations to reduce PM2.5. The demonstration of federal attainment is determined by using regional air quality modeling. At this moment, there is a high level of uncertainty in the scientific understanding of these pollution episodes that propagates into air quality models and limits the model’s usefulness for assessing emission control strategies. Hence, detailed measurements of the atmospheric composition and meteorological conditions are essential to improve the scientific understanding of these events and provide constraints on the air quality models.



**Figure 1.1 A** Map of Utah (left) with area of detail (right) showing the three major valleys subject to wintertime particulate matter pollution. The Cache Valley in the north spans northern Utah and southern Idaho and is primarily rural, while the Salt Lake and Utah Valleys to the south include the major urban areas of Salt Lake City and Provo.



**Figure 1.1 B** Map of the three federal Daily PM2.5 nonattainment areas in Utah. The Salt Lake (blue) and Utah (green) nonattainment areas have recently been designated as “serious”.

The chemical composition of PM2.5 in northern Utah, and the mechanisms by which it forms, have received less attention than in other regions of the U.S. despite the severity of the problem in Utah. Chemically speciated PM2.5 measurements come from EPA and UDAQ monitoring sites in the Cache, Salt Lake and Utah Valleys (Hansen 2010, Kelly 2013, Kuprov 2014, Mangelson 1997, Silcox 2012, Whiteman et al. 2014). Much of the database is based on 24-hour filter measurements, but is augmented by intensive operating periods in different years that produce data at hourly time resolution for major primary trace gases, inorganic acids and bases, inorganic PM2.5 ions, and organic matter.

The principal component of PM2.5 during winter air pollution events is ammonium nitrate, which is responsible for up to 70% of PM2.5 mass during PCAPS and 40% outside of PCAPs (Kuprov 2014). Ammonium chloride may also contribute up to 15% of PM2.5 mass during periods of high concentrations, although the source of the aerosol chloride is unclear (Kelly 2013). Nearly all studies within the last 20 years find sulfate to be a minor contributor to PM2.5 during PCAPS (Hansen 2010, Kelly 2013, Kuprov 2014, Long 2003, Long 2005a, Long 2005b, Mangelson 1997, Silcox 2012, Whiteman et al. 2014). The contribution of organics is more difficult to estimate. Residential wood combustion (RWC) is in general thought to be an important source of organic aerosol during wintertime in a number of western mountain basins (Green 2015). Several studies in the Salt Lake City area have inferred organic mass from the difference between total mass and the sum of all inorganic ions (e.g., Kuprov 2014). Other studies have determined organic mass from filter samples and a total organic carbon measurement following IMPROVE protocols (Green 2015). Most studies find a dominant contribution from ammonium nitrate during PCAP events, although some suggest a substantial contribution from organic carbon.

Because ammonium nitrate is generally the single largest component of PM2.5 mass, it is subject to the greatest scrutiny with respect to its sources and potential control strategies. There are several important research questions with respect to ammonium nitrate production within polluted winter boundary layers. The first and most obvious is the limiting reagent within any given region. Most studies that have considered the balance between reduced nitrogen (the sum of gas phase ammonia, NH3(g), and particulate ammonium, NH4+(p)) and oxidized nitrogen (the sum of gas phase nitric acid, HNO3(g), and particulate nitrate, NO3-(p)) suggest that oxidized nitrogen is the limiting reagent. Measurement of total inorganic ions in PM2.5 suggests that NH4+ is balanced by the sum of sulfate and nitrate, providing evidence for excess NH3 since a cation deficit would be expected in the NH3 limited case (Kelly 2013). Surface level data from a site in the center of Salt Lake City also suggested a slight excess of reduced nitrogen, although oxidized and reduced nitrogen are nearly equal (Kuprov 2014). As discussed further below, attribution of the limiting reagent in the ammonium nitrate equilibrium may be a complicated question, since there may be considerable horizontal and vertical variation in the distribution of each reagent that has not been adequately probed from surface level measurements.

A second important question is the role of residual layer atmospheric chemistry and transport in determining surface level PM2.5 levels. Diurnal cycles of aerosol mass at surface level typically exhibit a rise during morning hours, somewhat prior to maximum photochemical activity. This time dependence is consistent with overnight production of aerosol in the residual layer, followed by mixing from the residual layer to the surface during morning breakup of the nocturnal boundary layer as indicated by observations in the SLV of Baasandorj et al. (2017) . Long term monitoring in Salt Lake City suggests that primary pollutants, such as CO and NOx, undergo characteristic weekday-weekend cycles seen in other locations, but that PM2.5 does not have a strong weekday-weekend cycle (Whiteman et al. 2014). This observation is consistent with a PM2.5 reservoir buildup that lags primary NOx emissions. Together, these observations indicate that the composition of and transport within the residual layer is important to understanding the mechanism for winter PM2.5 formation in northern Utah. Residual layer chemistry and transport has been identified as a factor in the buildup of ammonium nitrate aerosol in other regions, such as California’s San Joaquin Valley (Watson and Chow 2002, Chow 2006, Brown 2006, Lurman 2006, Pusede 2016, Prabhakar 2017).

A third question is the source of oxidants that convert NOx emissions to soluble nitrate and the rate at which this oxidation occurs. Because NOx is primarily emitted as nitric oxide (NO), two molecules of oxidant are required to convert NOx to HNO3 by daytime photochemical reactions, R1 and R2 below.

NO + HO2 → NO2 + OH, or NO + O3 → NO2 + O2 (R1)

NO2 + OH → HNO3 (R2)

Alternatively, 1.5 molecules of oxidant are required to convert NO to soluble nitrate via nighttime processes, with N2O5 as the intermediate.

2NO + 3O3 → N2O5 + 3O2 (R3)

N2O5 + H2O (het) → 2HNO3 (R4)

Sources of oxidants include background ozone or photochemical reactions of VOC and NOx that produce oxidants including OH and O3. If entrainment of background O3 is the major source, then the oxidant limitation depends on the dynamics of the PCAP and the mixing efficiency with background O3 from the free troposphere. If photochemistry is the major oxidant source, then its response to both VOC and NOx emissions becomes important, as is the case for summertime urban boundary layers. Oxidant sources may also be influence by the interaction between the reactive nitrogen and aerosol chloride. Nighttime NOx oxidation occurs simultaneously with activation of photolabile halogen in the form of nitryl chloride (ClNO2) in regions rich in aerosol chloride (Osthoff 2006, Thornton 2010).

N2O5 + Cl- (het) → NO3- + ClNO2 (R5)

The recent analysis from Salt Lake City showing several µg m–3 attributable to ammonium chloride aerosol, accounting for 15% of PM2.5 mass, suggests that this chemistry may be particularly active in that region. If so, the atmospheric chemistry of winter PM2.5 in northern Utah may be complex, with a nighttime residual layer component and a daytime photochemical component due to atomic chlorine. Baasandorj et al. recently suggested that the nighttime processes in the upper part of PCAPs and subsequent daytime transport of PM2.5 rich air down to the surface play an important role contributing to the near surface PM2.5 enhancements during these pollution episodes.

The 2017 Utah Winter Fine Particulate Study (UWFPS) was designed to address these and other questions with respect to ammonium nitrate aerosol formation in the stable, polluted boundary layers associated with the valleys of northern Utah. The study design was based on the use of a light aircraft, the NOAA Twin Otter, to probe the horizontal and vertical distribution of trace gases and aerosols important to ammonium nitrate. Ground based measurements within the different valleys augmented the aircraft data and provided continuous measurements during both clean and polluted conditions. The goals of the study, as articulated through a set of science questions, as outlined below

**Scientific Questions and Study Goals**

1. What is the spatial distribution, both vertically and horizontally, of key trace gases and aerosols related to PM formation? What are the limiting and excess reagents in ammonium nitrate formation, and what are the key source regions? What are the limiting and excess reagents in oxidant and nitric acid formation? Do these limitations and / or sources vary significantly across the region?

Emissions within the three major valleys of the Wasatch Front are expected to be heterogeneous, with the largest urban emissions in the Salt Lake Valley and the largest agricultural emissions in the Cache Valley. Aircraft flights across all 3 valleys at different times of day characterize the spatial distribution of NH3, HNO3 and NOx, together with intermediates in NOx oxidation. Aircraft measurements at different times of day characterize transport of trace gases and aerosols, to assess the efficiency of residual layer transport in the distribution of pollutants and / or inter-valley coupling.

2. How do these distributions and the associated chemistry vary as a function of time of day? What are the most important chemical mechanisms for ammonium nitrate aerosol?

Morning, afternoon and night flights characterize the chemical and meteorological evolution of boundary layer breakup, re-establishment, and overnight residual layer chemistry and transport. Rates of chemical reactions may vary with altitude and time of day. Vertical profiles probe this chemical composition and boundary layer structure.

3. What is the role of the Great Salt Lake and Utah Lake, both chemically and meteorologically, in regional air quality? Are they significant sources of aerosol chloride that interacts with nitrogen oxide chemistry? Do they play a role in transport and or storage of polluted air masses?

Flights over the region’s lakes at various altitude characterize the transport of pollutants and chemical composition at different altitudes.

4. Are there significant aerosol sources other than ammonium nitrate? What is the role of, for example, residential wood combustion as a source for organic aerosol?

Aircraft based aerosol composition data provides new detail to the measurement of organic aerosol composition to the northern Utah valleys. Iodide CIMS measurements provide organic and nitrogen containing compounds characteristic of residential wood combustion.

5. What are the key emission sectors for aerosol precursors? What is the role of agricultural, industrial, urban, home heating, and natural emissions?

Aircraft measurements can be compared to emissions inventories developed by UDAQ to assess the emission sources responsible for PM2.5. This comparison will benefit from local 3D air quality modeling capabilities of investigators in Utah, at the EPA or at NOAA.

## 1.2 Meteorology of PCAPs and exchange processes

[Sebastian Hoch & Erik Crosman]

The Salt Lake Valley (SLV) and other Utah basins experience persistent cold-air pool (PCAP) episodes under high-pressure synoptic conditions during the wintertime (Lareau et al. 2013, Whiteman et al. 2014). Under the stable atmospheric PCAP conditions, vertical mixing is inhibited and particulate pollutants accumulate and affect the population along the Wasatch Front. Typical winters see exceedances of the National Ambient Air Quality Standard for PM2.5 on 18 days during an average of 6 multi-day pollution episodes (Whiteman et al. 2014). A major field study funded by the National Science Foundation, the Persistent Cold-Air Pool Study (PCAPS), was conducted in the SLV in 2010-2011. The goals of PCAPS were to improve understanding of the meteorological formation, maintenance, and decay of cold-air pools (Lareau et al. 2013). PCAPS data and subsequent scientific analysis resulted in improved understanding of PCAP boundary-layer structure and climatology of wintertime particulate pollution in the SLV (Silcox et al. 2012, Whiteman et al. 2014, Whiteman and Hoch 2014, Young and Whiteman 2015, Crosman and Horel 2016), improved understanding of the interactions between synoptic weather systems and PCAP events (Lareau and Horel 2015a, Lareau and Horel 2015b), and improved numerical simulations of PCAP episodes (Lu and Zhong 2014, Foster et al. 2016, Crosman and Horel 2017). The following meteorological ingredients, of which only some may be present during any given PCAP, have been found to play an important role in the lifecycle of PCAPs (Lareau et al. 2013):

1. PCAP formation and maintenance mechanisms:

* Cold-air emplacement in the Great Salt Lake Basin from a cold low pressure system prior to PCAP onset;
* High pressure and associated subsidence temperature inversion that initially forms above mountaintop and descends over time;
* Deep snow cover and resulting enhanced nocturnal radiative cooling and decreased absorption of incoming daytime solar radiation at the land surface;
* Cold air from over the Great Salt Lake returning to engulf the Salt Lake Valley following partial pollution mix-out events after the passage of weak weather systems;
* Persistent stratus cloud decks that limit incoming solar radiation and redistribute radiative cooling from the surface to cloud top.

1. PCAP decay mechanisms:

* Synoptic westerly and southwesterly flows that slowly erode the PCAP from the top down;
* Modification of PCAP through absorption of solar radiation at the land surface;
* Cooling aloft associated with approaching storm system;
* Rapid increase in winds and decrease in temperature associated with a strong cold front (results in complete removal of PCAP in 1-2 hours).

The intensity of PCAPS is often described through the use of heat deficit (see Section 1.2.2)

While the various meteorological ingredients associated with PCAPs are well-known, the relative importance of these various factors varies from PCAP episode to episode and is difficult to quantify with limited meteorological observations during non-field study periods. In addition, the relationship and complex interactions between meteorology, flow patterns within the PCAP, and the complex chemistry in the SLV remains a major unanswered scientific question (Baasandorj et al. 2017.)

Meteorological transport and mixing processes such as horizontal and vertical advection are inhibited due to the overall stable stratification within PCAPs. Nevertheless, thermally driven flows such as downvalley and downslope, and upvalley and upslope flows (Zardi and Whiteman 2012) can be triggered by thermal contrasts within and amongst the basins and surrounding topography affected by PCAPs. Further, the thermal inertia of the Great Salt Lake results in lake breeze circulations (Lareau et al. 2013, Crosman and Horel 2016), while inter-basin thermally and pressure-driven flows resulting from slope drainages and horizontal gradients in temperature between the Utah and Salt Lake Valleys are commonly observed.

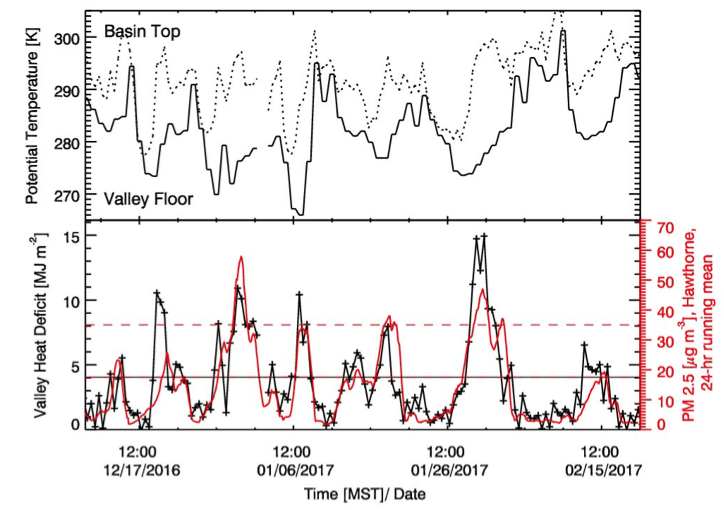
The *Cold-Air Pool Exchange Processes* resulting from diurnal mountain wind systems, interbasin exchange, and lake breeze circulations are often weaker under PCAP than under non-PCAP conditions. Nevertheless, they are expected to influence pollutant and precursor concentrations and thus to modify chemical processes within PCAPs.

A meteorological experiment, funded by NSF (Grant # AGS-1723337) and the Utah Department of Air Quality, was conducted in January and February 2017 to allow the characterization of *Cold-Air Pool Exchange Processes* and PCAP evolution and to complement the chemical observation of UWFPS.

## 1.3 Overview of 2016-17 winter

Here we explore the key meteorological and chemical variables during the 2016-2017 winter in **Figure 1.3 A, B, C, and D** and give a brief overview of the meteorological and chemical evolution of two primary PCAP episodes sampled by the NOAA Twin Otter research flights. **Figure 1.3 A** explores the relationship between the Valley Heat Deficit (VHD) and PM2.5 in the SLV and helps identify 7 pollution episodes with elevated PM2.5, while **Figure 1.3 B, C** compare the levels of PM2.5 and other species measured in three valleys. The valley heat deficit (VHD) is a measurement of the amount of energy that would be needed to bring a valley or basin atmosphere to a neutral stratification (see section 2.2.2.b). The upper panel of **Figure 1.3 A** shows the time series of potential temperatures at the valley floor (~1300 m MSL) and at the mean top height of the Salt Lake City Basin, ~2200 m MSL, derived from radiosonde observations by the National Weather Service from the Salt Lake City Airport. The difference between the two curves indicates the bulk stability of the valley atmosphere. When the two curves meet, the atmosphere is referred to as neutral for dry adiabatic processes and there is no resistance to vertical mixing. The further the two curves deviate, the higher is the stability and the harder it is to mix pollutants emitted at the surface. These time series further illustrate that the strong wintertime cold pool episodes are often caused by warm air advection aloft rather than through enhanced cooling near the surface. The bottom panel of **Figure 1.3 A** shows the VHD together with smoothed PM2.5 pollution concentrations (red curve). The good correlation between VHD and PM2.5 becomes evident, and has previously been reported by Whiteman et al. (2014).

Persistent cold air pools or PCAPs in the Salt Lake Valley can be defined as periods when the VHD exceeds a threshold value of 4.04 MJ m-3 for at least three consecutive 12-hourly atmospheric soundings (Whiteman et al. 2014). This VHD threshold value corresponds to PM2.5 concentrations of 17.5 μg m-3, which is half of the NAAQS for PM2.5. After a VHD value of 4.04 MJ m-3 is reached, pollution concentrations tend to increase monotonically at a rate of approximately 10 μg m-3 day-1 (Whiteman et al. 2014).

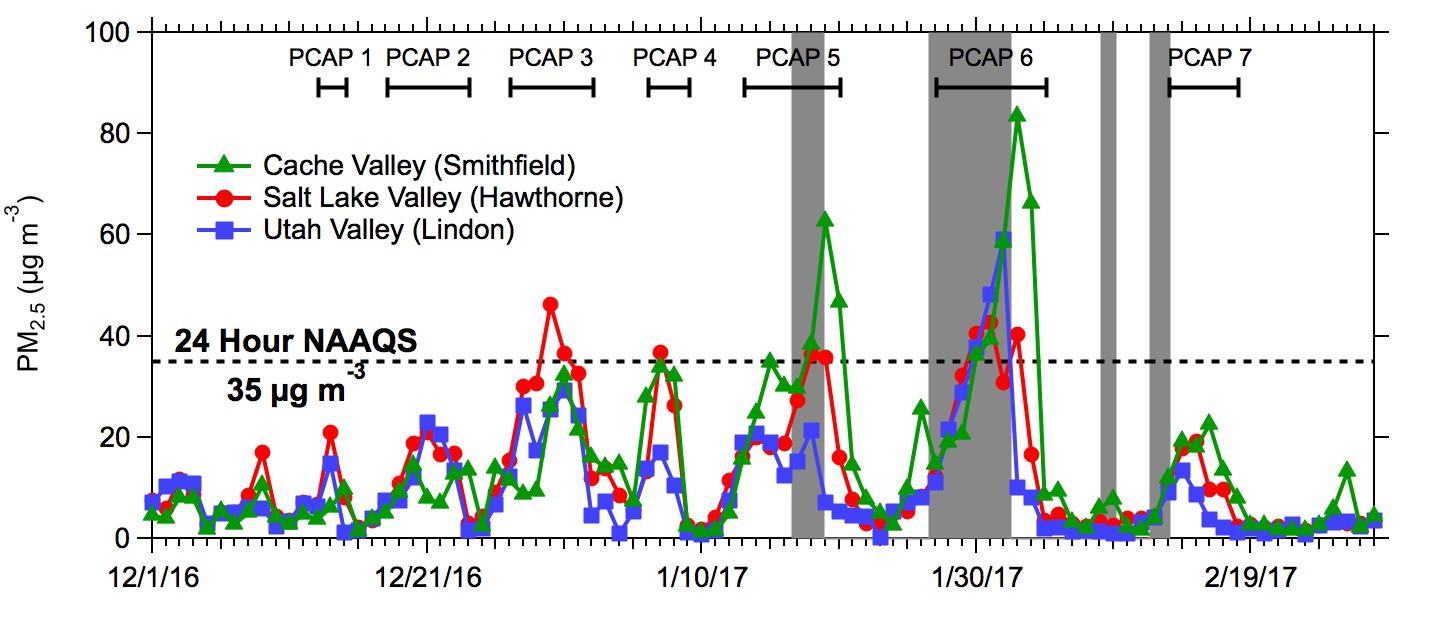


**Figure 1.3 A:** Potential temperature at the base and top of the Salt Lake City Basin from radiosonde observations by the National Weather Service (top), and the Valley Heat Deficit (VHD, black) and the smoothed observations of PM2.5 pollutant concentrations (red) from the UDAQ Hawthorne (HW) site. Data covers the main observational period of the experiment, from 15 December 2016 through 20 February 2017. Note that the horizontal dashed line marks the NAAQS for PM2.5 and the horizontal red-black dashed line marks the VHD threshold value of 4.04 MJ m-3 and a PM2.5 concentration of 17.5 μg m-3.

Seven multi-day pollution episodes with elevated PM2.5, associated with stagnant conditions, were observed during the 2016-17 winter (**Table 1.3 A**). Three of these episodes (13 - 15 December 2016, 18 - 24 December 2016, 13 - 18 February 2017) were short-lived episodes with PM2.5 levels below the NAAQS. There were four major pollution episodes (27 December 2016- 2 January 2017, 6 - 9 January 2017, 13 - 20 January 2017, 27 January - 4 February 2017) when PM2.5 levels built up to exceed the NAAQS, leading to a total of 7, 8, and 3 exceedances in Logan, Salt Lake City and Provo-NAAs, which encompass most of Cache, Salt Lake, and Utah valleys, respectively (Fig 1.3 B). **Figure 1.3 B** shows a time series of PM2.5 at representative sites, and shows the periods when the Twin Otter was operating in the region.

**Table 1.3 A:** Pollution episodes observed during the 2016-2017 winter

|  |  |  |
| --- | --- | --- |
| # | Date | Intensity |
| 1 | 13 – 15 December 2016 | moderate |
| 2 | 18 - 24 December 2016 | moderate |
| 3 | 27 December 2016- 2 January 2017 | severe |
| 4 | 6 - 9 January 2017 | severe |
| 5 | 13 - 20 January 2017 | severe |
| 6 | 27 January - 4 February 2017 | Most persistent and  severe |
| 7 | 13 - 18 February 2017 | Moderate |



**Figure 1.3 B** Daily average PM2.5 mass loadings for representative sites in each of the three valleys indicated in **Figure 1.1 A** during the 2016 - 2017 winter (December 1 2016 - February 28, 2017). Grey shaded regions indicate the times during which the Twin Otter research flights occurred. Bars across the top indicate the PCAP periods in Table 1.3 A.

January and February 2017 were characterized by above-average precipitation in northern Utah associated with several active storm track periods during these months (5.0 cm observed in January versus normal of 3.2 cm, 4.3 cm in February versus normal of 3.2). These active storm tracks resulted in less frequent PCAP conditions than is climatologically observed. However, the two dominating episodes during the 2016-2017 winter occurred during the UWFPS period when the NOAA Twin Otter was deployed in Utah: 13 - 20 January 2017, 27 January - 4 February 2017 as shown (**Figure 1.3 A-B**). Temperatures were below normal in January associated with the active storm track (mean January temperature of 27.15 F versus normal of 29.75 F). In February, warm storms and periods of high pressure without snow cover resulted in higher temperatures than average (39.95 F versus normal of 34.2 F).

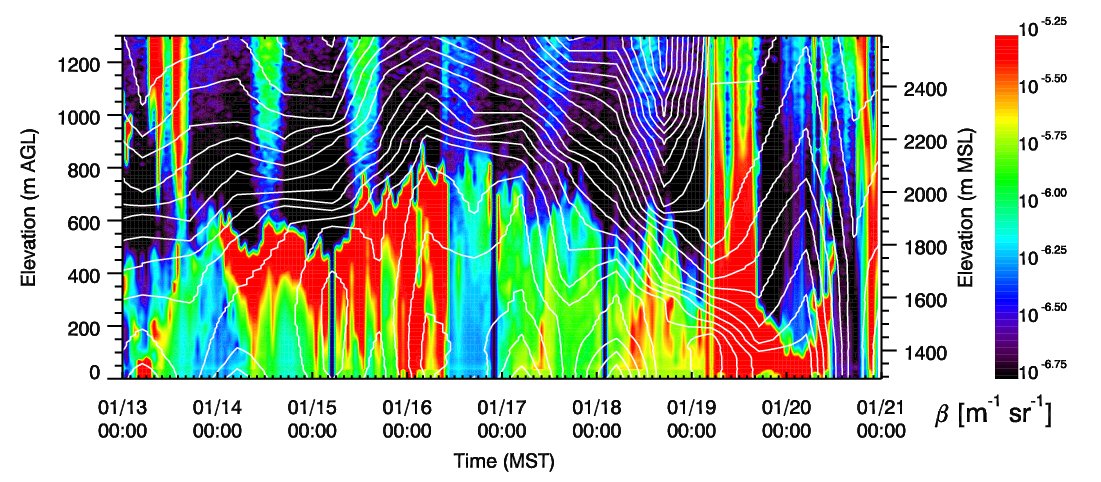
Snow cover is an important variable in PCAP occurrence and strength (**Table 1.3 B**). The Cache Valley saw the deepest and most persistent snow cover during the January-February 2017 period.

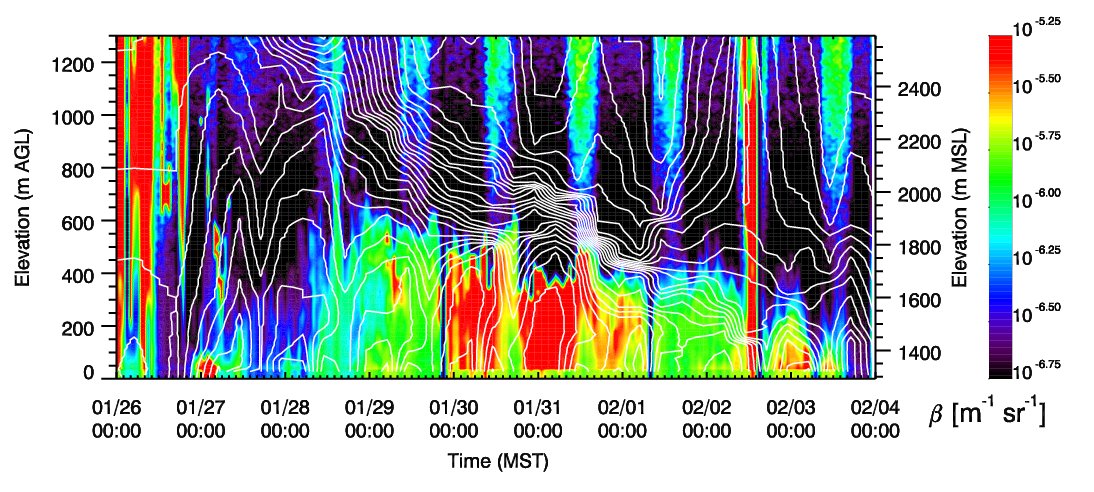
**Table 1.3 B** shows the snow depth in inches every three days in the three valleys during January 15th - February 15th (source cocorahs.org)

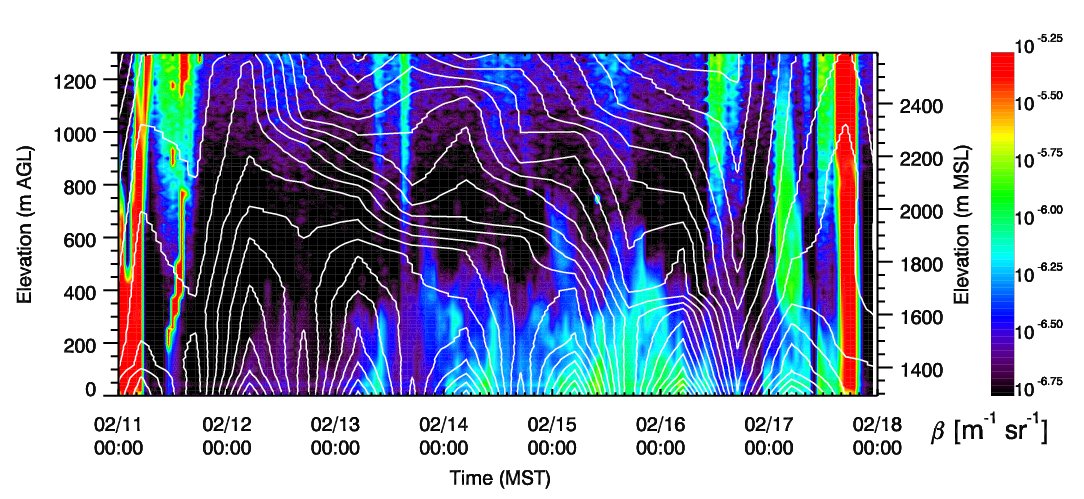
|  |  |  |  |
| --- | --- | --- | --- |
| Date | Salt Lake Valley | Utah Valley | Cache Valley |
| Jan 15th | 0-1” | 0 | 7-9” |
| Jan 18th | 0 | 0 | 6-8” |
| Jan 21st | 4-10” | 2-4” | 10-12” |
| Jan 24th | 4-8” | 2-4” | 21-27” |
| Jan 27th | 3-8” | 2-4” | 19-24” |
| Jan 30th | 3-7” | NA | 18-22” |
| Feb 2nd | 1-5” | 1-3” | 18-20” |
| Feb 5th | 0” | 0” | 11-15” |
| Feb 8th | 0” | 0” | 6-12” |
| Feb 11th | 0-1” | 0” | 3-8” |
| Feb 14th | 0” | 0” | 1-3” |

Meteorological summaries of the two primary episodes of the UWFPS study in the Salt Lake Valley are given below:

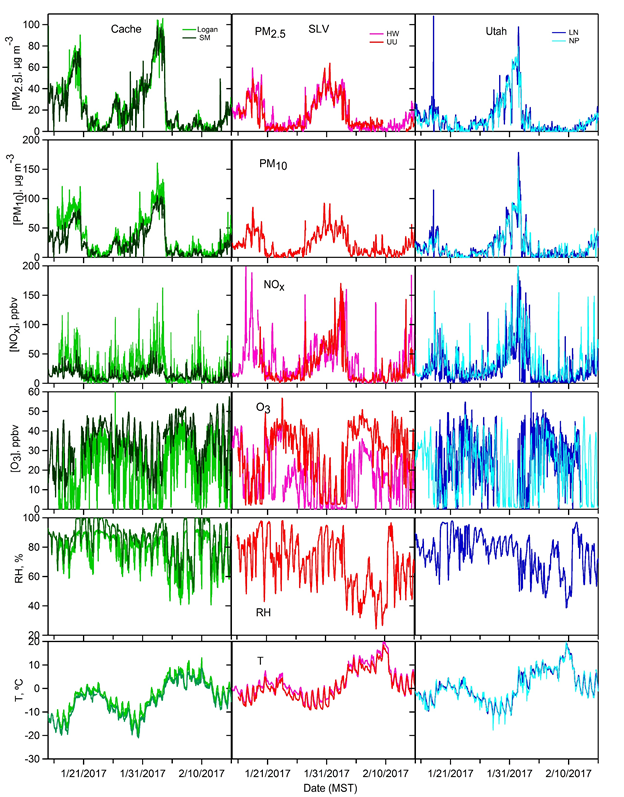
* 13 January – 21 January 2017. The pollution layer observed in this PCAP was between 400 – 800 m deep, which is significantly deeper than the typical mean depth of ~400 m for PCAPs in the Salt Lake Valley (Young and Whiteman 2014) (**Fig. 1.3 C**). The factors contributing to the ‘non-classical’ behavior of this PCAP were a lack of snow cover, the relatively weak subsidence inversion with a reduces capping stability, thick clouds and associated vertical mixing below the cloud base during more than half of the episode. Wind speeds aloft remained light during this episode until strong southwesterly flow ahead of two strong storm system resulted in top-down erosion of the CAP beginning on 19 January.
* 26 January – 3 February 2017. This episode was a classic PCAP, with an onset marked by cold air left in place by a storm system and several inches of fresh snow on the ground, followed by a large high pressure ridge over the Western USA. A subsidence inversion associated with the high pressure system descended from ~1200 m AGL on 27 January to near 400 m AGL by 1 February (**Fig. 1.3 C**). This capping layer confined the pollution layer below the base of the descending stable layer, as illustrated by ceilometer backscatter. A period of low clouds developed in the Great Salt Lake Basin and Salt Lake Valley in the middle of the episode (30 Jan – 1 February), decreasing nighttime stability and increasing sub-cloud turbulent mixing. Winds above the stable layer at 700 hPa were generally light from 27 January – 30 January, but increased above 10 m s-1 from the 31st January until the end of the episode, eroding the polluted stable layer in the Salt Lake Valley to only 100-200 m by the 3rd of February. The end of the episode was also complicated by lake breezes in the Salt Lake Valley (see Section 3.3).







**Figure 1.3 C**: Time-height cross sections of ceilometer backscatter profile and contours of isentropes at the Landfill Site (LFL) in the Salt Lake Basin for three of the pollution episodes in early 2017. Isentropes are from KSLC radiosonde dataset. Note that some intermittent power outages occurred at the site.

**Figure 1.3 D** provides an overview of the conditions for Logan (L4) and Smithfield (SM) in the Cache Valley, Hawthorne (HW) and University of Utah (UU) in the SLV, North Provo (NP) and Lindon (LN) located in Utah Valley during UWFPS (See method section for site description). 

**Figure 1.3 D** Times series of PM2.5, PM10, NOx, O3, RH and T for representative sites in each of the three valleys during the UWFPS (January 15 - February 15, 2017).

As shown, PM2.5, PM10, and NOx are enhanced at all measurement sites during the pollution episodes. Although the pollution typically starts building around same time in the three valleys, the end dates can vary due to the meteorological processes leading to a well-mixed atmosphere and the differences in the topographic sheltering of the three basins. Typically, the valley cold pools are first eroded in Utah Valley, followed by a mixout in the SLV, while the pollution episodes tend to persist the longest in Cache Valley. A consistent pattern was observed during the two major episodes of UWFPS. The pollution episodes were persistent and most severe in the Cache Valley where a steady, continuous buildup and the highest PM2.5 with 24-h values reaching up to 80 µg m–3 were observed. Similarly, PM2.5 in the Utah Valley built up steadily reaching up to 24-h value of 60 µg m–3 until the mixout that occurred first in the Utah Valley. In contrast, in the SLV PM2.5 reached a plateau around a 24-h value of 45 µg m–3 after a steady increase over first four days of 27 January - 4 February 2017 episode. This pattern appears to be quite common and seen in the long-lasting episodes of the past [Baasandorj et al. 2017]. PM2.5 and PM10 show a good correlation with PM2.5 constituting ~ 70 - 85% of PM10 during pollution episodes.

NOx levels as high as 200 ppb are observed in urban Utah and Salt Lake Valleys. They appear to be lower in the more rural Cache Valley as indicated by SM measurements, but values as high as 150 ppb are seen in Logan at the end of the 27 January - 4 February 2017 episode. As expected, O3 is lower and often depleted at night at more urban sites (Logan in Cache, sites in the SLV and Utah valley) during pollution episodes. Peak O3 during the day is 40 - 50 ppb outside the pollution episodes, consistent with the wintertime background O3 in Utah [Schnell et al 2009], but it decreases to values as low as 10 - 20 ppb later in the pollution episodes. Compared to Logan, higher O3 is observed at the more rural SM site. Similarly, O3 is higher at UU, a site on the valley sidewall, than that at HW, a site located in the urban corridor of the SLV. These observations indicate spatial, temporal and vertical variability of chemical conditions that exist within each valley and among the three valleys.

The remainder of this report is structured as follows. Section 2 provides the details of the methods employed for respective measurements and models. Section 3 explores this in detail by combining the aircraft and available ground-based observations to answer the key questions outlined above. Section 4 discusses the policy implications of the major findings of this study. Finally, Section 5 conclude the report by summarizing the unanswered questions and suggesting needs for future air quality studies in the region.

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