2016 Winter Inversion PM Study Weber State University HARBOR Aerostat Final Report
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Overview:

The Measurement Protocol:

The original proposal was to measure the air from ground level to 500 feet in two locations in Ogden: 1. The Utah Division of Air Quality (UDAQ) Ogden station O2 and on the Weber State University campus, which is roughly 200 feet higher in elevation. Measurements were to be done twice a day for as many days as possible during the winter inversion season.

It was decided by the consortium (UDAQ, Univ. of Utah, Utah State Univ., WSU) that it would be better to have the measurements done all day long and in the Salt Lake Basin closer to the other measurements of the study. This change put a significant constraint on student staffing and availability. We were able to obtain seven days of sunrise to sunset vertical air column monitoring. The first two were during a minor inversion event, the next four were during a strong inversion and the last measurement was with the inversion mixing out.

The measurements were made under a tethered balloon system called an aerostat. The target altitude was 500 feet (152 meters) and with coordination with all the local helicopter operations we actually measured the bottom 200 meters above ground level for 660 feet AGL. The duration above 500 feet was minimized for air traffic safety. Flights were scrubbed if visibility became an issue, again, in coordination with local helicopter flight operations and the SLC FAA Air Traffic Control operations. There were zero close calls, no unexpected events, and smooth communication between all airborne parties.

Final Results:

A total of forty flights were completed. There are clear correlations with these *in situ* measurements and measurements taken at the Hawthorne Elementary location. For consistency this report will compare the WSU data with the U of U lidar data which provide remote sensing of the vertical air column. Future comparisons will be made with other data sets such as the ceilometer and the flights made by the KSL Chopper 5.

The particle counts show a clear altitude dependence for smaller particulates but complete mixing for larger (≥ 5.0 µm) particles.

The ozone data show both the expected diurnal pattern of increased ozone in the early afternoon but also an altitude dependence during the inversion. Outside of the inversion the ozone is much more uniform in the vertical columns of air that we measured.

The data are all available at:
http://harbor.weber.edu/FlightData/2016/WinterInversion/WinterPM2016.html

Instrumentation Suite:

The instrumentation suite consisted of three payload packages: a standard NOAA ozonesonde/radiosonde; a cleanroom particle counter that measured six channels of particle sizes (0.5 µm through 5µm); and the WSU AtmoSniffer which measured several gases, particulates ≤

2.5 µm, humidity, pressure, location, turbulence, and system health. Details on these instruments are below. Due to the challenging flight conditions, the instruments required constant maintenance and not all instruments were available on every flight.

The ozonesonde is a Droplet Measurement Technologies EN-SCI ECC (electro-chemical cell) that is coupled with a standard iMet NOAA/NWS radiosonde. This instrument is designed for a single flight followed by factory refurbishment. The main problem is the delicate external temperature and humidity sensors which can be easily damaged. Each flight day we did a complete calibration with a Droplet Measurement Technologies "Ozonesonde Test Unit" lab bench system that is the standard calibration method for these devices. Some days this calibration was done twice to verify that the system was remaining stable. There were no problems with calibration. We did lose the external sensors due to flight damage, but we used ground measurements to calibrate the instrument and compared those to measurements taken by the AtmoSniffer to make sure everything remained in agreement. The calculation of the ozone concentration is done via the NOAA SkySonde software which uses the most common algorithm for this calculation. (There is some disagreement in the ozonesonde ECC industry as to the best algorithm. The actual differences are in the noise for the ozone levels near the ground.)

We also compared ground measurements from the ozonesonde with a portable 2B ozone monitor. The agreement was excellent and was also consistent with the UDAQ values at the Hawthorne Elementary School located 6.34 km to the NNW of our location at Larry H. Miller Softball Complex, Big Cottonwood Regional Park.

The particle counter is a Met One Instruments, Inc., GT-526 six-channel laser backscatter handheld particle counter. It was factory calibrated and refurbished prior to the start of the Winter PM Study.

The particle counts were averaged over a 4-second interval then data logged on the instrument. The clock was set to GPS time at the start of each day. That time stamp was used to determine the altitude of the package from the onboard GPS systems on the AtmoSniffer and the radiosonde. This two-step process results in a measurement of particle counts per liter of air vs. altitude.

The six channels are: 0.3 µm, 0.5 µm, 0.7 µm, 1.0 µm, 2.0 µm, and 5.0 µm. The particle counts per channel are inclusive with the higher channels. For example, the 0.7 µm channel measured all particles flowing through the detector that are larger than or equal to 0.7 µm in diameter, including the counts in the 1.0 µm, 2.0 µm, and 5.0 µm channels. To obtain the number of particles in the size range of 0.7 µm to 1.0 µm is possible by subtracting the two values for those channels. In practice, except for the smallest two channels, the number of larger particles in the higher channels is so small as to be in the noise of the next smaller channel.

This instrument provided the most detailed data for particle size and concentration. No attempt was made to convert these data to µg/m^3 as measured at Hawthorne. (This conversion was done with the AtmoSniffer data as described below.) This conversion process assumes an average density of the particulates and an assumed size distribution based on the measurement channel. This process is under intense debate in the research literature and we decided it would be best to stay with the actual measurement rather than an assumed conversion.

The AtmoSniffer is a prototype air monitoring system being developed at Weber State University. It has a wide range of sensors that are data logged onboard and downloaded after each flight. The sensor suite includes: particle filter (≤ 2.5 µm Anderson cascade filter) and optical dust sensor, temperature, humidity, pressure, O3, NO2, SO2, NH3, CO, GPS (UTC time, altitude, lat., long.), inertial measurement (6-axis accelerometers, 3-axis gyroscope, 3-axis magnetic field), air mass flow rate, and system health monitoring (battery voltage, CPU temperature, etc.). The system is powered with a LiPo battery which has excellent low temperature performance and is lightweight for flight. The AtmoSniffer has been flown repeatedly to the stratosphere under high altitude weather balloons. As such, the AtmoSniffer has proven to be robust, but still has design flaws.

As the system is still under development, some of the sensors were not yet adequately calibrated. The main issue for the AtmoSniffer seems to be zero drift of the gas sensors. The result is that we can use these data for patterns in the air, but not actual concentrations. The system was attached to a broadband pollutant destruction filter before most flights to filter the air. Some flights had "zero air" from a compressed air tank run through the instrument prior to flight. Attempts were made to calibrate the gas sensors at the UDAQ Air Monitoring Center (AMC) in West Valley City. The calibration trends were good for NO_2 and CO but were crippled by zero drift problems.

The O3 sensor also has zero-drift issues, but the trends were in excellent agreement with the independent measurements made by the ECC ozonesonde. This provides both additional verification of the ozonesonde data and more confidence in the AtmoSniffer sensors.

Likewise, the dust counter on the AtmoSniffer is in good agreement with the Met One particle counter. We used the AtmoSniffer as a validation of the particle counter data but do not include it in the data plots below as it is effectively redundant. We also used a common conversion for particle counts to $\mu g/m^3$ density measurements. When the AtmoSniffer was placed near the Ogden UDAQ air quality measurement station (O2), the multiday measurement comparison with the UDAQ online reports was excellent. This results in an additional verification of the data quality of the AtmoSniffer's dust counter and hence the Met One particle counter with UDAQ measured data. The result is that we have excellent confidence in the Met One particle counter and so report those data below.

Data:

Complete data sets are posted online at

http://harbor.weber.edu/FlightData/2016/WinterInversion/WinterPM2016.html

All raw data are currently available at that location as well as combined data (from the three flight payloads) in the form of .csv files. We continue to process the data and will update the website with additional graphics as they become available.

Important Note: The data compilations shown below in figures 3-7 are for seeing the trends in the air column. The axes are too small to read in a document like this. Rather than create forty pages of graphics, all these are available in an easier to read format at the link above.

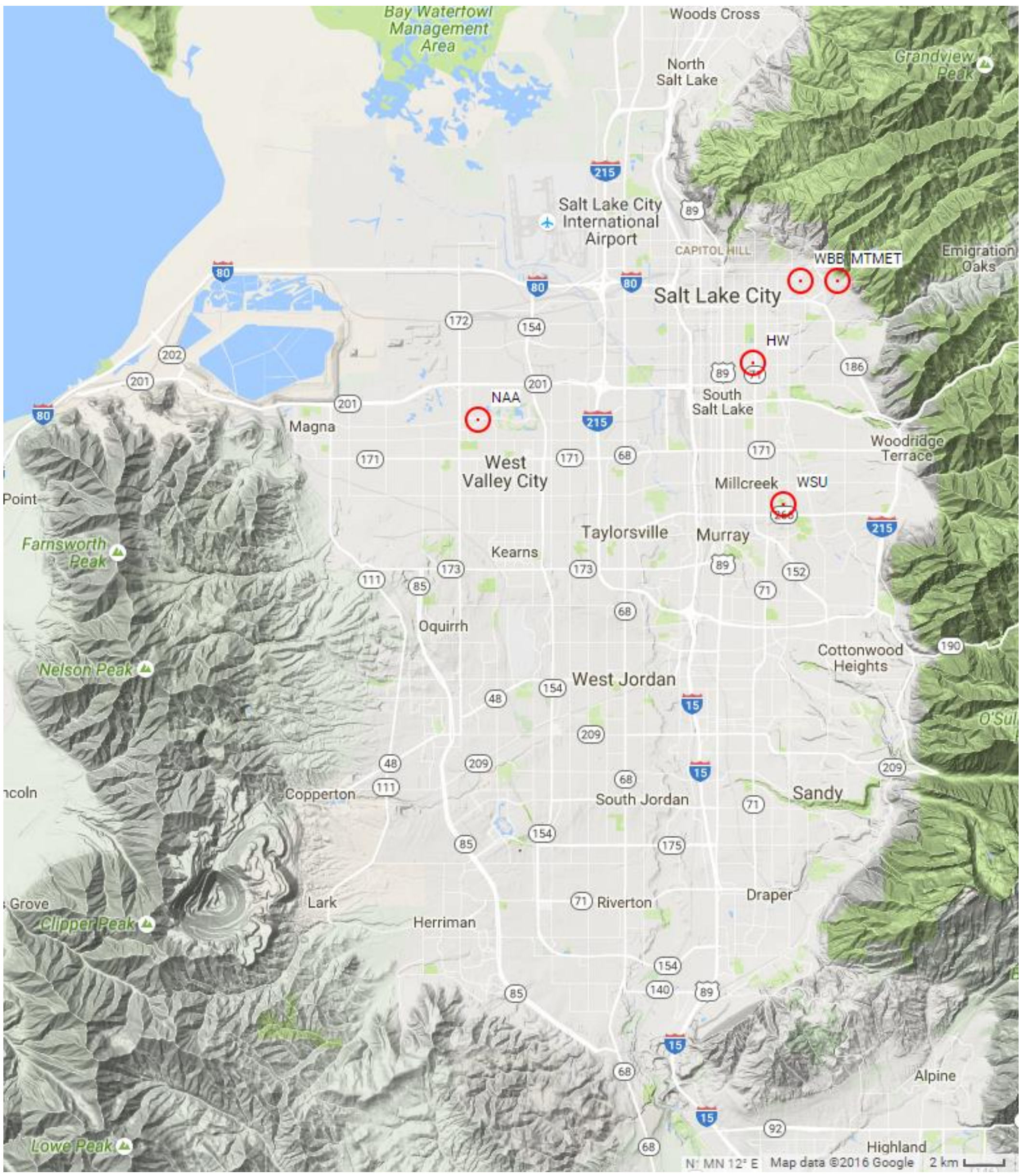

Figure 1. The Salt Lake Basin showing the locations of several of the primary monitoring sites. WBB and MTMET are on the University of Utah campus. HW is the Hawthorne Elementary School UDAQ and Lidar site. NAA is the Neil Armstrong Academy. WUS is the aerostat.

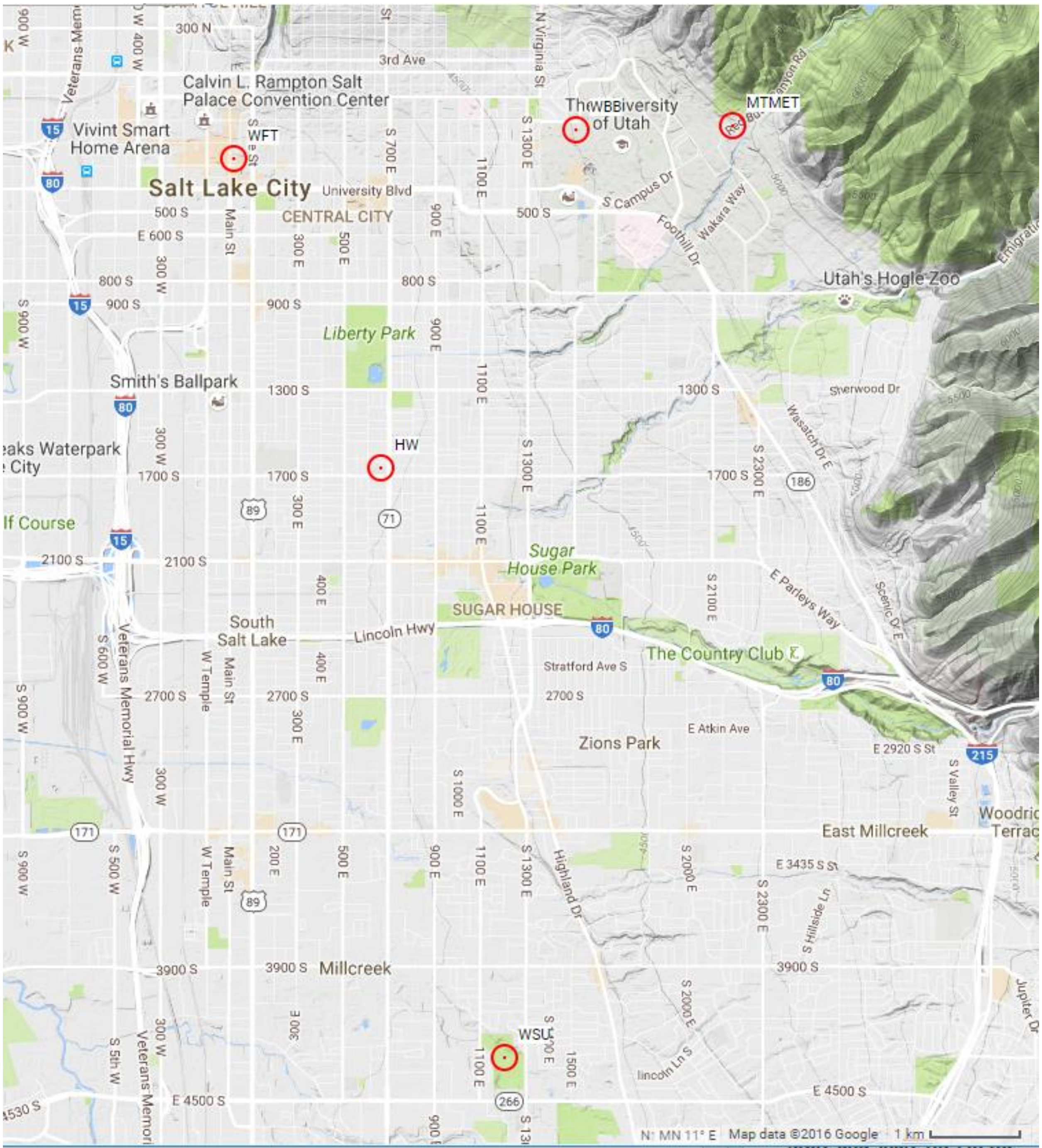

Figure 2. Detail map showing the locations of the main air study sites. Also shown in this map is the WFT (Wells Fargo Tower) site.

The WSU HARBOR data for the weak January 2016 inversion will be posted online. The data below are for the main inversion event taking place approximately February 7, 2016 through midday on February 15, 2016. By mid-day on February 15 the inversion had mixed out. We were able to complete forty flights starting slightly into the beginning of the inversion and ending with flights through the mix out to clear air.

Table I. Flight and Data Summary

Date	Number of Flights	Notes
Feb 6, Saturday	3	Winds generally from the SW.
Feb 9, Tuesday	10	Winds generally from the WNW.
Feb 11, Thursday	4	Winds generally from the NW.
Feb 13, Saturday	13	Winds generally from the NW.
Feb 15, Monday (Presidents' Day)	10	Winds started from the SE gradually changing to the WNW.

For this analysis, the aerostat data are being compared with the University of Utah lidar data collected at Hawthorne Elementary School (HW on map) located 6.34 km to the NNW of our location at Larry H. Miller Softball Complex, Big Cottonwood Regional Park ("WSU" on maps in Figures 1 and 2). Based on Table I, we expect the air measured at HW to flow towards WSU. With typical wind speeds being 1 to 2 m/s (3 to 7 kph) we might expect an hour delay between the conditions at HW and WSU as a first-order approximation.

The data in figures 3 through 7 are plotted in two ways. The images superimposed on the lidar data are logarithmic color scale maps all plotted to the same scale. The data have also been scaled in both altitude and time to match the lidar plots. Wider shaped (inverted V) flight profiles were done by moving the aerostat in approximately 50 foot intervals with approximately one-minute of dwell time at each altitude step to allow for averaging of the data. The narrower flight profiles were nearly continuous flights up then down, pausing only for a couple seconds at 50 foot intervals to attach a warning flag on the tether. Below the lidar data are plots of three data sets that are characteristic of the overall data: "large" particulates (5.0 µm and larger), "small" particulates (0.5 µm and larger), and ozone. These are scaled to the data in each plot and, thus, the horizontal axes are not to the same scale. This allows layers and patterns to be visible in the data. These plots are arranged "in order" so that the individual plots line up sequentially with the plots shown against the lidar data. (Note that that required many of the plots to be stacked in a staggered horizontal pattern.)

The individual plots are color coded with blue indicating the ascent phase ("heading to the sky") and green indicating descent ("heading to the grass"). This provides a sense of time as well since you can read the plots as starting at the ground with blue markers, progressing upward then returning back to ground with the green markers. Times shown on the plots are the start times of each flight.

Several obvious trends can be seen in these data. The larger particles generally have no pattern or layering with altitude. The smaller particles often have altitude dependence. These plots were selected from the six channels of particulate sizes as being representative of the pattern. If you look at the channels in order there is a smooth trend from zero altitude dependence for the 5.0 μm particles to a clear altitude dependence for the 0.3 μm diameter particulates.

Also note that the ozone data range from no real altitude dependence to strong dependence, all superimposed on the expected diurnal ozone rise and fall pattern.

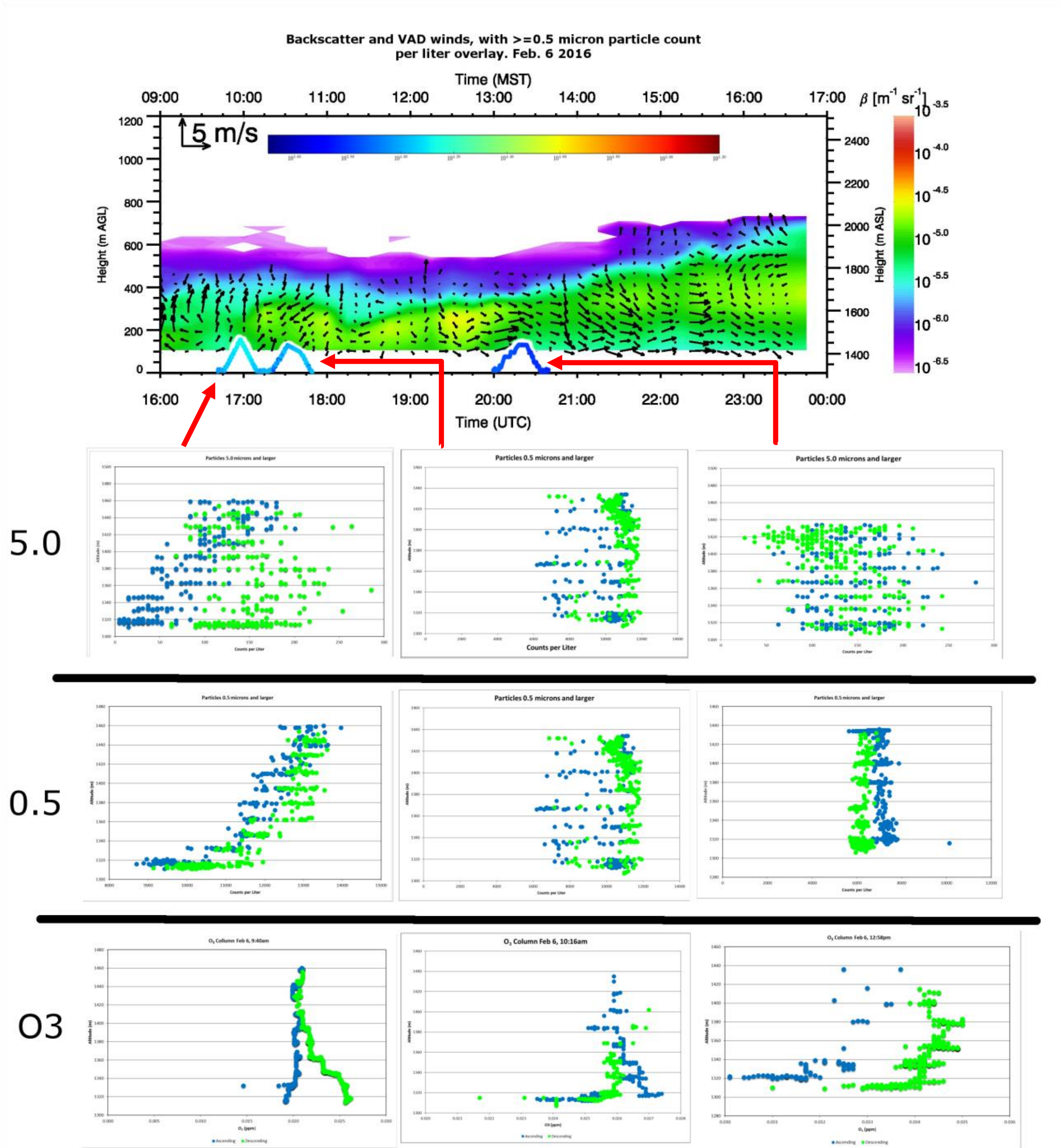

Figure 3. February 6 data with red arrows indicating which plots match which lidar overlay flights. (For clarity the arrows are only shown on this figure.)

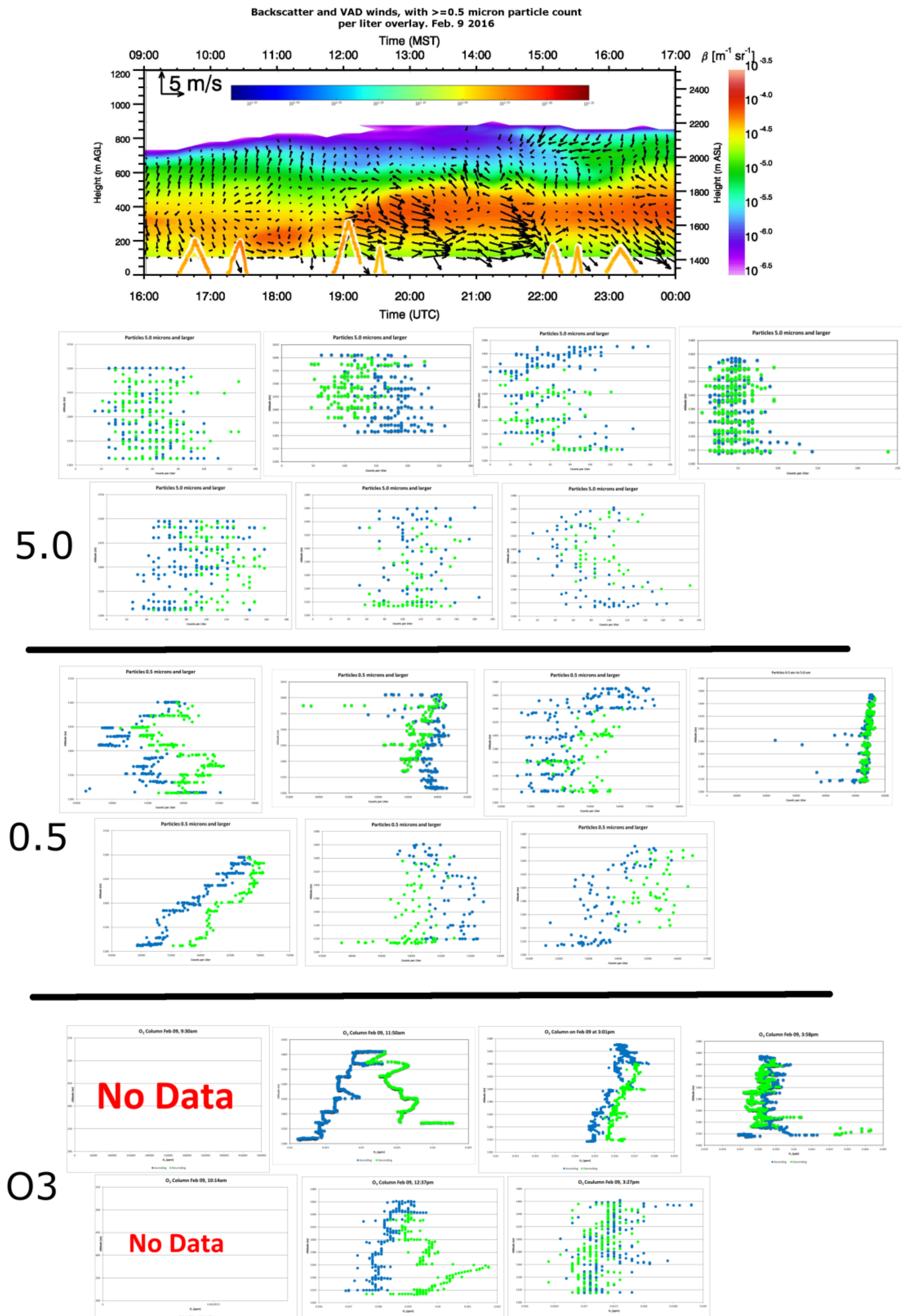

Figure 4. February 9, 2016 data. Notice the lack of altitude dependence for the 5.0 micron particles but strong dependence for the 0.5 micron counts.

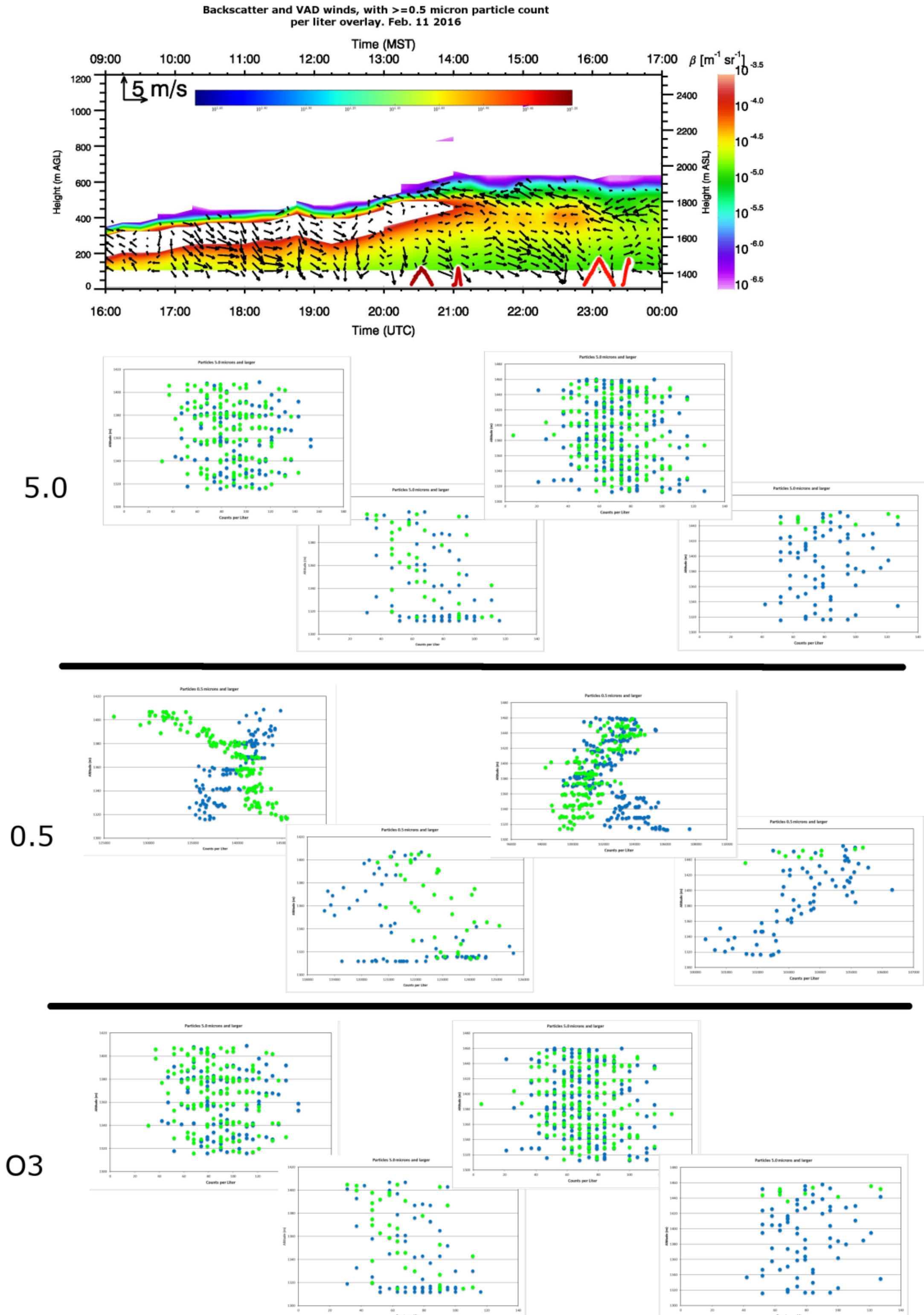

Figure 5. February 11, 2016 data.

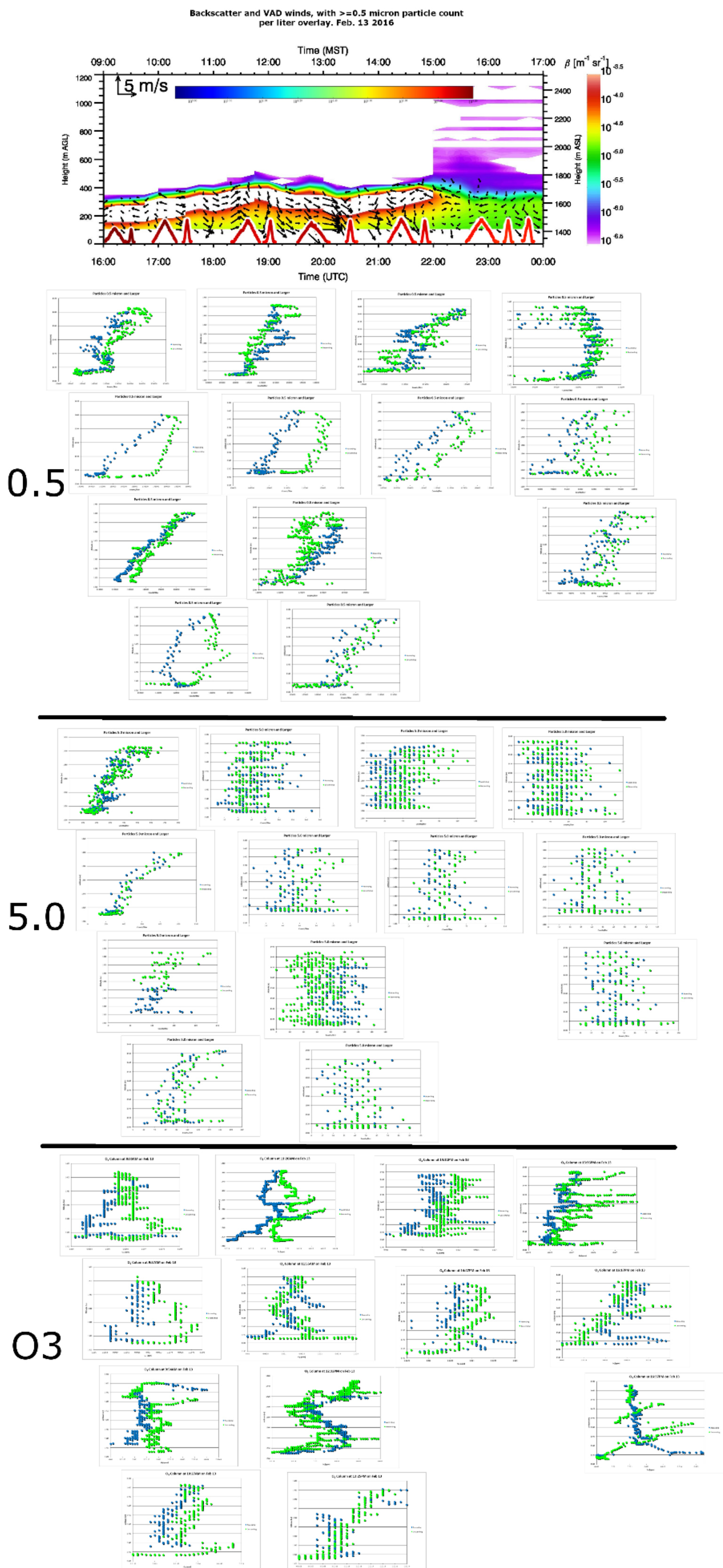

Figure 6. February 13, 2016 data. This is deep into the inversion event and there are very strong altitude dependencies for the smallest particulates.

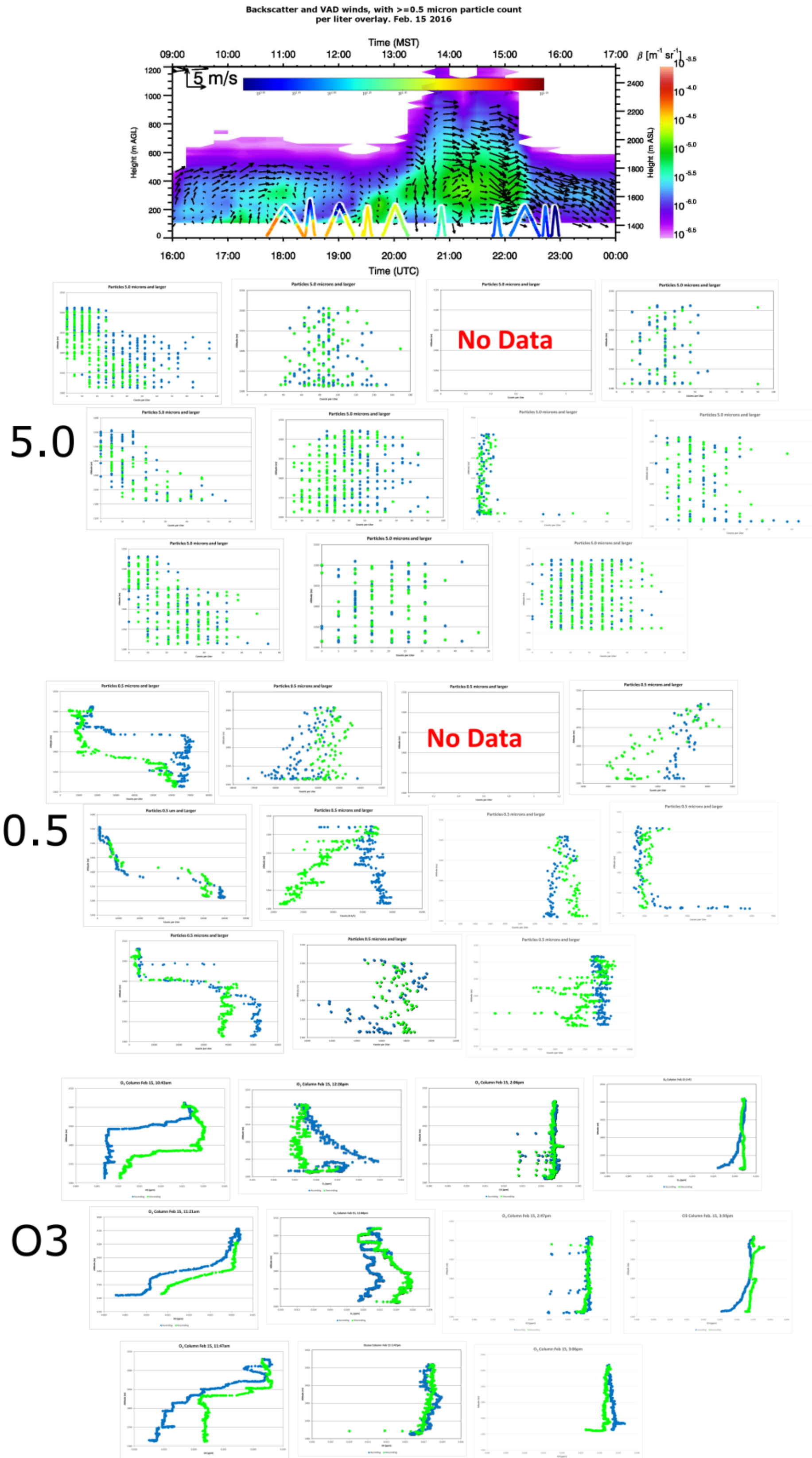

Figure 7. February 15, 2016. The last day of the inversion. Notice that the morning data have strong altitude dependence to the particulates and ozone concentrations, but when the inversion mixes out in the early afternoon the air column becomes very uniform.

Conclusions:

The most noticeable pattern is that the distribution of particulates has a strong dependence on particle size. The largest particles have no reliable altitude dependence in the lower 500 feet of our atmosphere during an inversion. But, as the particles get smaller in diameter there is a strong likelihood of layering or at least altitude dependence on the particle counts per liter.
Likewise, there are patterns in the ozone with altitude. Outside of the inversions the ozone is more uniform with altitude, but during inversion events there is a lot of variation with altitude. Further analysis will be completed and shared with the Utah Division of Air Quality as those plots and comparisons with other data are developed.