Utah Winter Fine Particulate Study

January 15 – February 14, 2017, Salt Lake City and adjacent air basins

A twin otter aircraft investigation of the factors governing high PM2.5 events in mountain basins of northern Utah
Winter Particulate Matter in Northern Utah

Ogden - Salt Lake City – Provo urban area has a population of 2.4 million (80% of Utah’s total) in a 120 mile corridor.

PM2.5 in this region exceeds the NAAQS (35 µg m\(^{-3}\), 24 hours) an average of 18 days per year, exclusively during Nov 15 – Feb 15.
Meteorology leading to high winter PM events has been well studied.
Major constituent of PM$_{2.5}$ during pollution episodes

- Secondary sources dominate
- Dominated by secondary NH$_4$NO$_3$ (50 – 75% of the total)
- Secondary NH$_4$Cl may also be a significant contributor (10-15% of the total PM$_{2.5}$) (Kelly et al., 2013)

Emissions and the interaction of chemical mechanisms with boundary layer dynamics that leads to formation of NH$_4$NO$_3$ not well understood

Contribution of organic aerosol from residential wood combustion also poorly characterized
Secondary Aerosol and Boundary Layer Dynamics

Near surface measurements are consistent with secondary PM formation in upper layer of inversion, with entrainment to surface

### Average Winter PM2.5, 2009-2014

<table>
<thead>
<tr>
<th>Hour of day (MST)</th>
<th>PM2.5 &gt; 35</th>
<th>All Winter Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>4</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>6</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>8</td>
<td>50</td>
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<tr>
<td>10</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>12</td>
<td>70</td>
<td>70</td>
</tr>
</tbody>
</table>

Whiteman et al., Atmos. Environ. (2014)

### One Day Event from Hawthorne Site

**PM$_{2.5}$**
- 24 hr
- Hourly
- NAAQS

- **NO$_2$**
- **NO$_x$**
- **O$_3$**

**O$_3$** ppb
- 0
- 10
- 20
- 30
- 40

**NO$_2$** ppb
- 0
- 50
- 100
- 150
- 200

**NO$_x$** ppb
- 0
- 50
- 100
- 150
- 200

**O$_3$** ppb
- 0
- 50
- 100
- 150
- 200

**PM$_{2.5}$**
- 0
- 5
- 10
- 15
- 20

**O$_3$**
- 0
- 5
- 10
- 15
- 20

**NO$_2$**
- 0
- 5
- 10
- 15
- 20

**NO$_x$**
- 0
- 5
- 10
- 15
- 20

**Figure 3**

At night
- **O$_3$** is depleted
- High “NO$_x$”, CO (!!)
- PM constant or slowly decreasing

Morning Hours
- **PM$_{2.5}$** and **O$_3$** both show an increase
- Sharp decrease in “NO$_x$”, CO
- PM2.5 decrease in afternoon

No secondary chemistry at surface at night (no **O$_3$**)

Daytime PM growth = photochemistry + residual layer mixing
Science Questions

For details, please see
http://esrl.noaa.gov/csd/groups/csd7/measurements/2017uwfps/whitepaper.pdf

- What is the spatial distribution 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?
- How do these distributions and the associated chemistry vary as a function of time of day?
- What is the role of the Great Salt Lake and Utah Lake, both chemically and meteorologically, in regional air quality?
- Are there significant aerosol sources other than ammonium nitrate? What is the role of residential wood combustion as a source for organic aerosol?
- What are the key emission sectors for aerosol precursors? What is the role of agricultural, industrial, urban, home heating, and natural emissions?
# Atmospheric Chemistry Instrument Payload

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Instrument</th>
<th>Investigator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aerosol Composition</td>
<td>Aerosol Mass Spectrometer</td>
<td>Ann Middlebrook, NOAA</td>
</tr>
<tr>
<td>Acid Gases</td>
<td>Iodide TOF CIMS</td>
<td>Joel Thornton, U. Washington</td>
</tr>
<tr>
<td>NO$_x$, NO$_y$, O$_3$</td>
<td>Custom CRDS</td>
<td>Steve Brown, NOAA</td>
</tr>
<tr>
<td>NH$_3$</td>
<td>Infrared QCL absorption</td>
<td>Jennifer Murphy, U. Toronto</td>
</tr>
<tr>
<td>CO, CH$_4$</td>
<td>Picarro CRDS</td>
<td>Loaned from Colm Sweeney, NOAA</td>
</tr>
<tr>
<td>PM distributions</td>
<td>UHSAS</td>
<td>Loaned from Jon Abbatt, U. Toronto</td>
</tr>
</tbody>
</table>

- **AMS**
- **NH$_3$**
- **NOx**
- **CH$_4$, CO**
- **CRDS**

Emerg. Exit

I$^-$ TOF CIMS
Flight Planning Logistics

• Twin Otter to be based at TAC Aviation at Salt Lake International Airport

• Aircraft endurance / flight time constraints
  Payload = ~1500 lbs of instruments + 2 scientific operators and 2 pilots
  Aircraft endurance (Payload + Passangers + Fuel) = 2 hours 45 minutes

• Survey Northern Utah region using two back to back flights with 1 hour refueling stop at Salt Lake International, total duration (flight time + refueling) of 6.5 hours

• Total flight hours available for research flights in Salt Lake City 78-80
  5.5 hours per flight day = 14.5 research flight days / 29 flights
  Total available flight days during study period = 27

• Takeoff times will be staggered day to day to capture early morning, midday and nighttime periods

• Weather conditions expected to be ~80% clear, but fog may be a limitation for some flight days, especially during the later stages of inversion periods

• Inversion days will have low boundary layer heights
  Aircraft cruise altitude is 1000’ AGL; can request lower during daylight hours
  Make use of missed approaches to airfields to probe boundary layer structure
Ceilometer data suggest 400 – 600 m BL depths during periods when inversions are building

Consistent with aircraft cruise altitude of 1000’ AGL, and possibly lower during daylight hours

Probe vertical structure of boundary layer with missed approaches to airfields to ~20 m AGL
Flight Plan #1

Survey flight to the north of Salt Lake city including Ogden, Cache Valley, Beaver River Valley, Great Salt Lake and Tooele Valley.
Flight Plan #2

Focused survey of urban areas of Salt Lake and Utah Valleys
Current Aircraft Schedule

January 2: Twin Otter arrives at NCAR Research Aviation Facility (RAF), Broomfield CO

January 3 – 14: Integration and test flights

January 15: Transit to Salt Lake City. Twin Otter based at TAC Air, Salt Lake City International Airport

January 17 – February 12: Research flights in Great Salt Lake basin

27 Flight days, approximately 78-80 flight hours

February 13: Transit back to Colorado

February 14: De-installation at RAF

February 15: Twin Otter departs for next mission
• Overview of 2015 – 2016 study
• Plans for Ground Based Observations

Rooftop measurements of chemistry and met parameters

**Atmospheric Sciences Building**

**MiniVol PM$_{2.5}$ samplers on WBB roof**

**Spatial measurements**

**Vertical measurements**

**Rooftop Measurements:**
- CO$_2$, CH$_4$, NO$_3$, N$_2$O$_5$, NOx,
- O$_3$, CO, PM$_{2.5}$, H$_2$O,
- Particle Size Distribution, particle composition
- Isotopes ($^{13}$C$^{18}$O$_2$, $^2$H$_2$$^{18}$O), met observations

Winter (Dec – Feb) 2015 - 2016
Measurements at Valley Floor and Higher Elevations

- Detailed observation of chemical and met parameters

Winter (Dec – Feb) 2015 - 2016
Time Series of PM$_{2.5}$, Heat deficit, O$_3$, NOx, N$_2$O$_5$: A Close Correlation Between PM$_{2.5}$ Episodes and Atmospheric Stability

**PM$_{2.5}$:**
- PM$_{2.5}$ varies from 0 to 76 ug/m$^3$
- ~ 6 CAPs events
- PM enhancements are closely associated with heat deficit.
- 8 exceedances; all occurred during Feb 7 – 14 episodes

**Primary pollutants:**
- Enhanced during pollution events
- NOx: <10 -200 ppb; max CO 1 ppm

**O$_3$:**
- Low, especially during the PM pollution episodes.

**N$_2$O$_5$:**
- detectable most night. max 1.5 ppb; average 0.076 ppb
**Conditions During Pollution Episodes**

**PM\(_{2.5}\)**
- Daytime high
- **O\(_3\)**
  - Titrated at night

**NO\(_x\)**
- Morning peak ~10 AM due to transport
- A sharp decrease coincides with increase in PM
- NO\(_2\) is high and persists through out the day. ~ 35 ppb

**RH & T**
- Average RH: ~ 75%
- Low T <0

PM\(_{2.5}\) episodes are characterized by:
- High PM
- Low O\(_3\)
- High NO\(_x\)
- High RH
- Low T <0
Conditions During February 6 – 16 Episode

8 Exceedances

Middle of the episode

- PM$_{2.5}$ increase rate ~ 7 ug/m$^3$
- Reaches a plateau, ~ 60 ug/m$^3$ Same levels at both UU and HW

Towards the end
What is the Altitude to Which the Surface Level O3 Titration Persists?

- Consistent O3 levels at U and top of LDS office building ~ 100 m agl
- Complete titration at 100 m agl
- Occasional spikes likely due to drainage flows from City Creek Canyon.
Time Evolution of Aerosol Layer During Feb 6 –16 Event:
Morning and Nighttime Chemistry Aloft and Daytime Mixing

- Activities at night and early morning
- Mixing happens ~ 10 am– 12 noon.
- Unstable in the afternoon; aerosol well mixed within the inversion layer.

- Depth increases with time
- Stable @ night; unstable during the day within lowest few 100 m’s.
- But capping inversion is still present.
• very different chemical condition with high ammonia and low NOx in Cache
Levels of HNO3, NH3, and HONO at HW

Jan 2009 – Feb 2009

Near Surface Measurements
- HONO<0.5 ppb
- HNO3<1 ppb
- NH3 in 10’s of ppb

Kuprov et al. 2014
### Ground Site Measurements: Plan A

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Species Measured</th>
<th>PI</th>
</tr>
</thead>
<tbody>
<tr>
<td>VAPs--Aerosol Mass Spectrometer</td>
<td>Speciated PM 1 ; speciated organics</td>
<td>Dr. Brent Williams (Washington University in St. Louis)</td>
</tr>
<tr>
<td>Iodide Time of Flight Chemical Ionization Mass Spectrometer</td>
<td>HONO, HNO₃, N₂O₅, CINO₂, other species</td>
<td>Dr. Hans Osthoff (University of Calgary)</td>
</tr>
<tr>
<td>Proton Transfer Reaction Time of Flight Mass Spectrometer</td>
<td>Volatile Organic Compounds (aromatics, carbonyls etc)</td>
<td>Dr. Dylan Millet (University of Minnesota)</td>
</tr>
<tr>
<td>Nitrogen Oxide CRDS</td>
<td>NO, NO₂, NO₃, N₂O₅, NO₃, O₃</td>
<td>Dr. Steve Brown (NOAA)</td>
</tr>
<tr>
<td>Others</td>
<td>PM$_{2.5}$, CO, CO$_2$, CH₄</td>
<td>Munkh/Lin group (University of Utah)</td>
</tr>
<tr>
<td>Doppler wind lidar, ceilometers, radiosondes and Hobos</td>
<td>Depth, dynamics and time evolution of CAPs, vertical structure, forecasting</td>
<td>Dr. Sebastian Hoch, Dr. Erik Crossman (University of Utah)</td>
</tr>
<tr>
<td>AIM-IC</td>
<td>PM inorganics, HNO3, NH3</td>
<td>Jen Murphy, U Toronto?</td>
</tr>
<tr>
<td>&gt; 6</td>
<td></td>
<td>EPA ORD</td>
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</tbody>
</table>
Ground Site Measurements: Plan A

Atmospheric Sciences Building

Cylinder storage with connection lines

Cloud Physics Lab

Opening between the two labs

Roof
### Plan B: Ground Site Measurements

**Atmospheric Sciences Building**

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Species Measured</th>
<th>PI</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEOM</td>
<td>PM2.5, O₃, NOₓ, CO</td>
<td>DAQ/UU</td>
</tr>
<tr>
<td>LGR CRDS</td>
<td>CO₂, CH₄</td>
<td>University of Utah</td>
</tr>
<tr>
<td>Depth and time</td>
<td>ceilometers, and Hobos</td>
<td>University of Utah</td>
</tr>
<tr>
<td>evolution of CAPs,</td>
<td></td>
<td></td>
</tr>
<tr>
<td>vertical structure</td>
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<td></td>
</tr>
<tr>
<td>AIM-IC</td>
<td>PM inorganics, HNO₃, NH₃</td>
<td>Jen Murphy, U</td>
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<td></td>
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<td>Toronto?</td>
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<tr>
<td>&gt; 6</td>
<td></td>
<td>EPA ORD</td>
</tr>
</tbody>
</table>

PM mass concentration by TEOM

Back scattering by ceilometer
EPA Office of Research and Development: Ground-Based Observations (Plan A & B)

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Species Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRDS, UV Abs</td>
<td>NO2, O3</td>
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<tr>
<td>Chemiluminescence (?)</td>
<td>NOy</td>
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<tr>
<td>QCL (Aerodyne?)</td>
<td>HCHO</td>
</tr>
<tr>
<td>TSI OPC</td>
<td>PM$_{2.5}$ mass and size</td>
</tr>
<tr>
<td>3 x ceilometer</td>
<td>time evolution of aerosol layer</td>
</tr>
</tbody>
</table>
| 2 - 3 x PANDORA             | -Total column measurements of HCHO, NO2, and O3,  
                              | -Altitude profiles                |

Ideas:

• Co-located continuous measurements of NO2, NOy, HCHO, O3 and PM to study contribution of daytime component in Cache
• Remote sensing devices: inter-valley comparison of chemical conditions and aerosol layer
• In conjunction with UofU met observations, they can be used to study transport patterns:
  - Lake effects; drainage flows
  - Intrusion of cleaner air from the residual layer in 3 valleys
• Comparison of HCHO, and PM2.5 measurements; Pandora retrieval vs. aircraft
Mobile Laboratory Measurements: Plan A

Science Questions:
1. What is the contribution of emissions from wood stoves to VOCs and fine particles?
2. What are the emission sources of ammonia?

Other objectives:
1. Sample in the same basins on the flight days of the NOAA Twin Otter to provide perspective
2. Provide vertical and regional perspective by taking various roads out of the basin

Dates: January 15 – February 5 (3 weeks)
## Mobile Laboratory Measurements: Plan A

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Species Measured</th>
<th>Investigators</th>
</tr>
</thead>
<tbody>
<tr>
<td>H$_3$O$^+$ ToF-CIMS</td>
<td>Volatile Organic Compounds</td>
<td>Matt Coggon, Bin Yuan, Carsten Warneke, Joost de Gouw (NOAA &amp; CIRES)</td>
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<tr>
<td>LAS</td>
<td>Particle size (90nm-10µm)</td>
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<tr>
<td>LGR CRD</td>
<td>CO and N$_2$O</td>
<td>Joost de Gouw (NOAA &amp; CIRES)</td>
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<tr>
<td>PSAP</td>
<td>Absorption</td>
<td></td>
</tr>
<tr>
<td>LGR CRD</td>
<td>NH$_3$</td>
<td>Munkh Baasandorj (UDEQ; UofU)</td>
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</table>

**Comments:**

- CO$_2$/CH$_4$: would be good, but space and power may be too limited. Can be overcome by co-locating stationary measurements with Salt Lake City CO$_2$ network, or by coordinated drives with “Nerdmobile”
- Wish list: filter samples for aerosol composition during stationary measurements
- Wish list: Sunset Laboratory filter or semi-continuous OC/EC analyzer during stationary measurements
Mobile Laboratory Measurements: Plan A

Sampling strategy:

- Combination of drives and stationary measurements to determine diurnal variations
- Drives: sample in residential, industrial, business areas and along traffic corridors, and other targets of interest to UDEQ, UofU, Twin Otter, etc.
- Stationary measurements: select a few locations for the mobile laboratory in consultation with UDEQ and UofU to be parked at multiple times during the study and construct a diurnal variation (For example: mobile lab storage at UofU, Rose Park, Magna range from east to west in the SLC basin, not too far from base of operations)

Analysis:

- Use the drives to characterize specific emission sources
- Use the stationary measurements for source attributions of VOCs, fine particle volume, ammonia, BC and CO (using PMF, linear regression etc., and using the composition of individual sources for comparisons)