2019 ANNUAL REPORT

UINTA BASIN AIR QUALITY RESEARCH

Seth Lyman
Marc Mansfield
Huy Tran
Trang Tran
Makenzie Holmes
Executive Summary

Background Information about Uinta Basin Air Quality

Ozone negatively impacts respiratory health, especially for those with lung diseases. During the wintertime inversion conditions that are common in basins and valleys throughout Utah, ozone in the Uinta Basin sometimes increases to levels that exceed the standard of 70 ppb set by the U.S. Environmental Protection Agency (EPA). Because of this, on 3 August 2018, portions of Uintah and Duchesne Counties below 6,250 feet in elevation were declared an ozone nonattainment area by EPA.

The Uinta Basin is one of only two places in the world that are known to experience wintertime ozone in excess of EPA standards (Wyoming’s Upper Green River Basin is the other). Ozone forms in the atmosphere from reactions involving oxides of nitrogen (NOx) and volatile organic compounds, and the majority of NOx and organic compound emissions in the Uinta Basin are from oil and gas development. Inversion conditions trap these pollutants near ground level, increasing their concentrations and allowing them to generate ozone. The mix of pollutants during inversion episodes in the Uinta Basin is very different from those on Utah’s urban Wasatch Front, leading to the formation of ozone, rather than PM2.5.

The number of ozone exceedance days and concentrations of ozone that occur each year are closely tied to meteorology. Years with persistent snow cover and high barometric pressure tend to have more days with strong winter inversions and high ozone. During inversion episodes, ozone concentrations tend to be higher at lower elevations where inversion conditions are stronger and last longer. In the absence of snow cover and winter inversions, ozone concentrations in the Basin are similar to those in other rural, high-elevation locations around the western United States.

Purpose of Uinta Basin Air Quality Research

Because wintertime ozone is relatively new to science, many aspects of the meteorology, chemistry, and emissions that allow ozone to form during winter are still poorly understood. Federal and state agencies are required by law to promulgate regulations that reduce ozone-forming emissions in the Uinta Basin. These regulations will mostly target the local oil and gas industry, which is the basis for the majority of the Basin’s economy. Scientific research to better elucidate the causes and characteristics of winter ozone can help industry and regulators craft emissions reductions that maximize effectiveness and minimize costs to the local industry and economy. Since 2010, we (scientists at Utah State University’s Bingham Research Center) have conducted research to improve understanding of winter ozone in the Uinta Basin. This research includes the following:

- Collection and analysis of ambient air measurements of meteorology and chemistry,
- Improvement of air quality computer models that are used by industry and regulators to develop emissions control strategies, and
- Characterization of emission sources through measurements and analysis.

We have produced a summary of all the air quality research that has been conducted in the Uinta Basin to date. This summary is available at binghamresearch.usu.edu/cumulativeresearchsummary.
Highlights from This Document

This document reports on Uinta Basin air quality research we carried out during the past year, as well as our research plans and performance. The majority of the work presented here was funded by the Utah legislature and the Uintah Impact Mitigation Special Service District, but some projects were also supported by the Utah Division of Air Quality and the Utah Clean Air Partnership (UCAIR). Here we provide some highlights and key findings:

- **High ozone last winter:** During winter 2018-19, ozone in the Uinta Basin exceeded the EPA standard of 70 ppb on 16 days. Because of this high ozone, the Uinta Basin’s non-attainment status is very likely to be changed from marginal to moderate, triggering additional emission control requirements and other regulatory actions. The status change to moderate will occur in 2021. More information about air quality during the past winter is available in Section 2.

- **Industry changes result in less ozone:** As the oil and gas industry changes, concentrations of ozone and its precursors around the Uinta Basin also change. Concentrations of ozone-forming pollutants in the atmosphere are decreasing in the eastern Basin, which is dominated by natural gas development because prices are low and natural gas production is declining. In the western Basin, where oil production is dominant, ozone precursor concentrations appear to be increasing. Ozone precursor concentrations have decreased in the Basin overall, and statistical analyses show that ozone during winter 2018-19 would have been higher if oil and gas production were still at former levels. Information about how ozone precursor levels are changing over time is presented in Section 4, and information about how this may be impacting ozone is presented in Section 12.

- **Pumpjack engines appear to be a large source of alkenes:** We measured 76 organic compounds in ambient air at a network of portable measurement stations across the Uinta Basin. These measurements showed that concentrations of alkenes, a class of hydrocarbons that are very active in ozone production, are relatively high in the western Basin, and evidence points to natural gas-fueled pumpjack engines as the probable source. Future work, made possible by funding from the Utah Division of Air Quality, will provide additional measurements and explore how these measurements compare against the results of computer simulations of air quality. This work is described in Section 5.

- **Improvements to estimates of emissions composition:** We worked with the Utah Division of Air Quality to collect new measurements of organic compound emissions from liquid storage tanks and other oil and gas sources. Some of these measurements were made with a new, unique system we developed to measure emissions directly. A summary of this work is presented in Section 6, and a final report will be released soon.

- **Aldehydes emitted from snow:** Under some conditions, snow can release formaldehyde and acetaldehyde, two important ozone precursors, into the atmosphere. The snowpack may even be converting less reactive organic compounds into formaldehyde and acetaldehyde, enhancing the ability of the atmosphere to produce wintertime ozone. More research is needed to fully understand the importance of this process in the Uinta Basin atmosphere. This work is summarized in Section 7.
- **New method improves simulations of inversion meteorology:** We used data assimilation of surface-level and vertical meteorological measurements to produce a much more accurate model of winter inversion meteorology than was possible in the past. This model leads to realistic day-upon-day buildup of ozone during inversion episodes. Find out more in Section 8.

- **Improvements to winter ozone models:** Computer models of wintertime air quality will be used by regulatory agencies in emissions reduction plans. Thus, the effectiveness and cost-effectiveness of emissions reduction plans depend on having accurate computer models. Improvements to meteorological simulations (see the previous bullet) and emissions models have improved computer simulations of ozone in the Uinta Basin. The models are more accurate than ever before, but more work is still needed, especially to improve information about the composition of organic compound emissions. More information is available in Section 10.

- **Ozone alert program:** USU issues email alerts to subscribers when high ozone is expected in the Uinta Basin. The purpose of this program is to provide the oil and gas industry with information that allows them to reduce emissions when it matters most, though any interested party is welcome to subscribe. USU issues alerts when current and forecast conditions appear conducive to the formation of high wintertime ozone and when ozone episodes are expected to end. During winter 2018-19, the program had 102 subscribers, among which 32% were from industry (mostly oil and gas producers); 21% were from regulatory agencies; 21% were private citizens; 11% were from other agencies/organizations; 11% were academic researchers; 4% were working in media, and 2% were from environmental groups. Information about this program can be found in Section 13.

- **Stakeholder workshop:** We hosted a workshop for stakeholders, including representatives from the oil and gas industry, academia, and all levels of government, to discuss the most important needs for improving computer simulations of wintertime ozone. A summary document that describes the findings from the workshop is presented in Section 14.

- **Research priorities, performance, and plans:** Sections 16, 15, and 16 provide information about our performance over the past year, research priorities, and plans for the coming year, respectively. We developed the priorities and plans with help from a stakeholder committee, which includes representatives from the oil and gas industry, public health agencies, local government representatives, and regulators.
17.4. Interact More Frequently With Stakeholders ................................................................. 129
17.5. Make Fact Sheets to Summarize Study Results for Lay Readers ............................... 129
17.6. Operate Ambient Air Monitoring Stations ................................................................. 130
17.7. Continue Investigation of Carbonyl Fluxes at the Air-snow Interface ......................... 131
17.8. Drone Deployments to Characterize Vertical Structure of Inversion Episodes .............. 133
17.9. Cooperation with BLM in Their Measurements of Vertical Inversion Structure .......... 133
17.10. Online Coupling of Meteorology and Chemistry in Photochemical Simulations of Winter Ozone ................................................................. 134
17.11. Sensitivity Tests of Different Organic Compound Emissions Composition Scenarios ... 134
17.12. Processing of 2017 Utah Air Agencies Emissions Inventory for Photochemical Modeling ... 135
17.13. Comparison of the 2017 Utah Air Agencies Inventory against Top-down Estimations of Basin-Wide Emissions ....................................................................................................................................................................................................................................................................................................................................................................................... 136
17.15. Continued Development of Tools to Predict Wintertime Ozone ................................. 138
17.16. Organic Compound Measurements from Portable Collection Stations ....................... 139
17.17. Improving WRF/CAMx model Performance with Satellite Data Assimilation Techniques .... 140
17.18. Other Funded Activities for 2019-20 ........................................................................... 140

18. Acknowledgments .............................................................................................................. 141

19. References ......................................................................................................................... 142
List of Tables

Table 2-1. Air quality monitoring stations that operated during winter 2018-19........................................4
Table 2-2. Eight-hr average ozone concentrations around the Uinta Basin, winter 2018-19......................7
Table 2-3. Ozone summary statistics for five sites in the Uinta Basin over eight calendar years............14
Table 2-4. Average of the 4th-highest 8-hr daily maximum ozone values during three consecutive calendar years for several monitoring stations in the Uinta Basin (a.k.a., ozone design values).........15
Table 2-5. PM$_{2.5}$ summary statistics for the Uinta Basin from 2010 through March 2019.........................19
Table 7-1. Temperature ranges in the chamber runs..................................................................................56
Table 10-1. Uinta Basin total emissions of VOC and formaldehyde from various categories of engines. .77
Table 10-2. Speciation profile of TOG and NHAPTOGa applied for engines/turbines using SMOKE (i.e., the PROF scenario).......................................................................................................78
Table 10-3. Comparisons of formaldehyde emissions over the Uinta Basin estimated using various approaches........................................................................................................................................78
Table 10-4. Summary of NO$_x$ and VOC emissions as estimated by the SMOKE emissions model for Duchesne and Uintah Counties (moles hr$^{-1}$).........................................................................................................83
Table 10 5. CAMx model performance metrics for simulating hourly ozone in the BASE emissions scenario......................................................................................................................................................87
Table 12-1. Predictors used in our ozone regression models.................................................................100
Table 12-2. Natural gas and oil emissions have an impact on estimates of ozone attainment. ...........104
Table 13-1. Results of survey questions that asked respondents to rate their level of agreement with given statements......................................................................................................................................109
Table 15-1. Results of survey questions that asked respondents to rate their level of agreement with given statements......................................................................................................................................122
Table 15-2. Data quality summary for ozone, NO$_x$, carbon monoxide (CO), and organic compound data collected during 2018-19............................................................124
Table 15-3. Outcomes of annual project objectives for the current reporting period..............................125
List of Figures

Figure 2-1. Horsepool daily maximum ozone, average snow depth, and daytime average total UV radiation (incoming + reflected) .............................................................. 6

Figure 2-2. 8-hr average ozone from all sites listed in Table 2-1 during winter 2018-19 .................. 7

Figure 2-3. Daily maximum 8-hr average ozone on 21 February 2019 ............................................. 8

Figure 2-4. Daily maximum 8-hr average ozone on 23 February 2019 .............................................. 9

Figure 2-5. Daily maximum 8-hr average ozone on 25 February 2019 .............................................. 9

Figure 2-6. Daily maximum 8-hr average ozone on 27 February 2019 .............................................. 10

Figure 2-7. Daily maximum 8-hr average ozone on 1 Mar 2019 ..................................................... 10

Figure 2-8. Daily maximum 8-hr average ozone on 2 Mar 2019 ..................................................... 11

Figure 2-9. Daily maximum 8-hr average ozone on 3 Mar 2019 ..................................................... 11

Figure 2-10. Fourth-highest daily maximum 8-hr average ozone versus station elevation for winter 2018-19. ............................................................................................................. 12

Figure 2-11. Time series of daily maximum 8-hr average ozone concentration at five sites in the Uinta Basin from July 2009 through March 2019 ........................................................................................................... 13

Figure 2-12. Number of annual ozone exceedances at five sites from 2010 through March 2019. ....... 16

Figure 2-13. Annual 4th-highest 8-hr average ozone at five sites from 2010 through March 2019. ........ 16

Figure 2-14. 24-hr average PM$_{2.5}$ at monitoring stations around the Uinta Basin during winter 2018-19. ............................................................................................................................ 17

Figure 2-15. Box-and-whisker plot of 24-hr average PM$_{2.5}$ at four monitoring stations during winter 2018-19. ............................................................................................................................ 18

Figure 2-16. Time series of daily 24-hr average PM$_{2.5}$ concentrations at nine sites in the Uinta Basin, October 2009-March 2019 ........................................................................................................... 18

Figure 2-17. Hourly average NO$_x$ measured at Roosevelt, Horsepool, and Castle Peak during winter 2018-19. ............................................................................................................................ 21

Figure 2-18. Hourly average NO$_x$ measured at Roosevelt and Horsepool during winter 2018-19 ....... 22

Figure 2-19. Hourly average ozone measured at Roosevelt, Horsepool, and Castle Peak during winter 2018-19. ............................................................................................................................ 23
Figure 2-20. Average ozone at Roosevelt, Horsepool, and Castle Peak during each hour of the day during inversion episodes that occurred during winter 2018-19. .......................................................... 23

Figure 2-21. Average NOx at Roosevelt, Horsepool, and Castle Peak during each hour of the day during inversion episodes that occurred during winter 2018-19. .......................................................... 24

Figure 2-22. Hourly average methane measured at Roosevelt and Horsepool during winter 2018-19. .......................................................... 24

Figure 2-23. Hourly average total NMHC measured at Roosevelt and Horsepool during winter 2018-19. 25

Figure 2-24. Percent by volume of measured organics at Horsepool and Roosevelt measured during winter 2018-19 that were comprised of alkanes, alkenes, aromatics, and alcohols ................................. 25

Figure 2-25. Percent by volume of measured NMHC at Horsepool and Roosevelt during winter 2018-19 comprised of compounds containing 2-9 carbon atoms (i.e., C2-C9; excluding alcohols). .............................................. 26

Figure 2-26. Time series of total NMHC (measured as the sum of individual NMHC) at Roosevelt and Horsepool during winter 2018-19.......................................................... 26

Figure 2-27. Heptane versus toluene at Horsepool and Roosevelt. .......................................................... 27

Figure 3-1. Daily maximum 8-hr ozone concentrations measured at Dinosaur (DINO), Myton (MYTON), Ouray (OURAY) Roosevelt (ROOSE), Vernal (VERNA), Whiterocks (WHITE), and Red Wash (REDWA) from 1 May to 31 August 2019. .................................................................................. 28

Figure 4-1. Average NOx at Horsepool and Roosevelt (top panel) for each winter season (15 November through 31 March), and basin-wide February oil and gas production (bottom panel)............................................. 30

Figure 4-2. Average total NMHC, ethane, and toluene at Roosevelt (top panel) and Horsepool (bottom panel) .......................................................... 31

Figure 4-3. Maximum 8-hr average ozone concentrations for all sites in the Uinta Basin, 26 January 2013. ........................................................................................................................................ 32

Figure 4-4. Daily maximum 8-hr average ozone on 1 February 2017. ........................................................................................................ 32

Figure 5-1. Locations of sample collection stations used in this study.......................................................... 34

Figure 5-2. Organic compound concentrations at all measurement stations on 27 February 2019 during an inversion episode (top panel) and on 17 April 2019 when snow had melted and no inversion existed (bottom panel).................................................................................. 36

Figure 5-3. Composition (percent by volume) of organic compounds measured at stations in a transect across the Uinta Basin on 23 February 2019 from 10:00 to 16:00. ........................................................................................................ 37

Figure 5-4. Composition (percent by volume) of organic compounds measured at stations in a transect across the Uinta Basin on 25 February 2019 at 22:00 to 26 February 2019 at 4:00. ........................................................................ 38
Figure 5-5. Composition (percent by volume) of organic compounds measured at stations in a transect across the Uinta Basin on 27 February 2019 from 10:00 to 16:00. .................................................. 38

Figure 5-6. Composition (percent by volume) of organic compounds measured at stations in a transect across the Uinta Basin on 15 March 2019 from 10:00 to 16:00. ................................................................. 39

Figure 5-7. Composition (percent by volume) of organic compounds measured at stations in a transect across the Uinta Basin on 17 April 2019 at 22:00 to 18 April 2019 at 4:00. ................................................. 39

Figure 5-8. Average composition (percent by volume) of measured organic compounds at measurement stations, grouped by compound type. .............................................................. 40

Figure 5-9. Average composition (percent by mass) of measured organic compounds at measurement stations multiplied by compound-specific incremental reactivities (Carter, 2009) and grouped by compound type .............................................................. 41

Figure 5-10. Ratio of heptane to toluene (ppb:ppb) at measurement stations. ............................................. 42

Figure 5-11. Map of natural gas and diesel-fueled stationary engines in the Uinta Basin oil and gas industry. ........................................................................................................ 43

Figure 5-12. Ethylene versus propylene in all transect measurements.................................................. 44

Figure 5-13. Total alkanes versus total alkenes+alkyne in all transect measurements......................... 45

Figure 6-1. Comparison of gas-oil ratios of flash gas measured from pressurized liquid samples we analyzed in our laboratory and gas-oil ratios modeled by AST ........................................... 48

Figure 6-2. Average carbonyl composition of gas flashed from oil samples. ........................................ 48

Figure 6-3. Formation-averaged hydrocarbon composition of flash gas............................................. 49

Figure 6-4. Ozone that would be formed from emissions of 100 g of total organics from the flash gas speciation profiles indicated. ................................................................................................. 50

Figure 6-5. Diagram of the high flow measurement system. ................................................................. 51

Figure 6-6. Box and whisker plot of emissions from well pad sources measured with the high flow system. ......................................................................................................................... 52

Figure 6-7. Emissions composition by carbon number for oil tank emissions measured with the high flow system, flash gas modeled by AST ......................................................................... 53

Figure 7-1. Under conditions of strong insolation, a greenhouse effect leads to heating of the air under the dome of the flux chamber. ................................................................. 55

Figure 7-2. Fluxes of total non-methane hydrocarbons (TNMHC), alcohols (methanol and ethanol), and water vapor through the air-snow surface as measured by the flux chamber. ......................... 57
Figure 7-3. Fluxes of formaldehyde, acetaldehyde, and acetone through the air-snow interface as functions of temperature, as measured by the flux chamber ................................................................. 59

Figure 7-4. Simulated emissions (mole hr⁻¹) of formaldehyde, acetaldehyde, and acetone from (left column) oil and gas and (right column) snow ................................................................................................................ 61

Figure 8-1. WRF modeling domains ........................................................................................................................................................................ 64

Figure 8-2. Time series of simulated (ONU and G4) and observed (O3_obs) surface ozone concentrations at Ouray and Vernal .................................................................................................................................................................. 67

Figure 8-3. Simulated and observed relative humidity vertical profiles at Horsepool (dashed lines) and Fantasy Canyon (solid lines) .................................................................................................................................. 68

Figure 8-4. Simulated and observed vertical temperature profiles at Horsepool (dashed lines) and Fantasy Canyon (solid lines) .................................................................................................................. 70

Figure 8-5. Simulated and observed relative humidity vertical profiles at Horsepool (dashed lines) and Fantasy Canyon (solid lines) .................................................................................................................. 71

Figure 8-6. ONU, G4, and G4_plus-simulated column-sum cloud mixing ratio averaged over the Uinta Basin ............................................................................................................................................................................ 72

Figure 8-7. Time series of simulated (ONU, G4, and G4_plus) and observed surface ozone (O3_obs) concentrations at Ouray and Vernal .................................................................................................................................................. 72

Figure 10-1. Uinta Basin formaldehyde emissions in the BASE and PROF scenarios. ............................................................. 79

Figure 10-2. NOₓ emissions from all source categories and from oil and gas production activities as calculated by the SMOKE emissions model in the BASE and OLD scenarios .......................................................... 81

Figure 10-3. VOC emissions (VOC excludes methane and ethane) from all source categories and from oil and gas production activities as calculated by the SMOKE emissions model in the BASE and OLD scenarios .......................................................................................................................... 82

Figure 10-4. Comparisons of observed ozone (OBS) with ozone simulated by CAMx at several stations in the BASE, FALSE, and OLD scenarios ............................................................................................................. 85

Figure 10-5. Spatial distribution of observed (colored circles) and simulated daily 8-hr maximum ozone by CAMx in the BASE scenario on 5 and 6 February 2013 ........................................................................................................... 86

Figure 10-6. Comparison of observed NO and NOₓ concentrations (OBS) with those simulated in the BASE scenario (SIM) at several monitoring stations ....................................................................................................... 89

Figure 10-7. Ozone simulated by CAMx in the BASE and 7/3NOₓ scenarios .................................................................................................................. 90

Figure 10-8. Comparison of observed (OBS) vs. simulated formaldehyde, acetaldehyde, benzene, toluene, xylenes, methanol, and VOC by CAMx in the BASE scenario at Horsepool monitoring station. . 92
Figure 10-9. Comparison of simulated primary (directly emitted from sources) and secondary (formed via chemical reactions in the atmosphere) methanol and formaldehyde as obtained in the BASE (left column) and woPWP (right column) scenarios on 5 February 2013. ................................................................. 94

Figure 10-10. Highest 8-hr average ozone in the BASE scenario and the differences between the BASE and woPWP scenarios on 5 February 2013. .................................................................................. 95

Figure 10-1. Highest 8-hr average ozone simulated on 5 February 2013 in the BASE scenario and BASE + emissions from snow fluxes. ......................................................................................... 95

Figure 11-1. Comparison of surface albedo as processed from MODIS satellite data (left) and as estimated by the WRF model (right) on 21 February 2019. .............................................................................. 98

Figure 12-1. Random-forest model comparisons. ......................................................................................... 101

Figure 12-2. Uinta Basin annual oil and natural gas production. ................................................................. 102

Figure 13-1. Screenshot from the ozone alert program web page. .............................................................. 105

Figure 13-2. Ozone alerts that were issued during the winter 2018-19 season. ......................................... 108

Figure 15-1. Funding received by our research group since 2011, categorized by type of funding source. ........................................................................................................................................ 118

Figure 15-2. All funding sources for our research team, from 2011 to the present. ............................... 118

Figure 15-3. Sources of funding for our research team for wintertime ozone projects, from 2011 to the present. ........................................................................................................................................ 119

Figure 15-4. Users of the ubair.usu.edu real-time data website per day over the past 12 months. ....... 121

Figure 17-1. Air quality monitoring stations that will operate in the Uinta Basin during winter 2019-20. ........................................................................................................................................ 130

Figure 17-2. Laboratory apparatus to determine snowpack effects on atmospheric chemistry. .......... 132
1. Background and Introduction

Ozone has been measured continuously in Utah’s Uinta Basin since summer 2009 when air quality monitoring stations were established in Ouray and Red Wash. During winter 2009-10, and during the majority of the winters since then, ozone concentrations measured at Ouray and Red Wash, as well as other locations, have exceeded Environmental Protection Agency (EPA) standards. Ozone in excess of EPA standards is more typically found in urban areas during summer and has only been observed during winter months in two places in the world: the Uinta Basin and Wyoming’s Upper Green River Basin. In 2010, Uintah and Duchesne Counties (through the Uintah Impact Mitigation Special Service District) engaged our team at Utah State University to investigate the extent and causes of wintertime air pollution in the Uinta Basin, and we have carried out a wide variety of air quality research projects since that time. The results of most of these studies can be found in reports available at http://binghamresearch.usu.edu/reports.

In general, wintertime air quality in the Uinta Basin becomes impaired when strong, multi-day inversion events occur. Strong, multi-day inversions only occur when (1) stagnant, high-pressure meteorological conditions exist, and (2) sufficient snow cover exists to reflect incoming sunlight, which keeps the ground from absorbing sunlight and warming. Snow also increases the amount of sunlight available to provide energy for the chemical reactions that form ozone. Numerous exceedances of EPA’s ozone standard have occurred during winters with adequate snow cover and sustained high-pressure conditions, and no wintertime exceedances have ever been observed without snow cover.

Ozone forms in the atmosphere from reactions involving oxides of nitrogen (NO₃) and organic compounds, and the majority of NO₃ and organic compound emissions in the Uinta Basin are due to oil and gas development. Inversion conditions trap these pollutants near ground level, increasing their concentrations and their ability to generate ozone. During strong, multi-day inversion episodes, high ozone first forms in the low-elevation center of the basin and builds day-upon-day in concentration while expanding towards the basin’s margins. The highest ozone occurs primarily in areas at the lowest elevation and secondarily in areas with the most oil and gas development. Longer episodes and episodes that occur late in the winter season (because of increased sunlight) tend to lead to higher ozone.

On 3 August 2018, portions of Uintah and Duchesne Counties below 6,250 feet in elevation were officially designated an ozone nonattainment area by EPA. This designation formalizes a process already begun by the Utah Division of Air Quality, the Ute Indian Tribe, EPA, the oil and gas industry, and other stakeholders to mitigate the winter ozone problem by reducing NO₃ and organic compound emissions in the Uinta Basin. Efforts by USU and many other entities have improved understanding of the causes and impacts of elevated ozone during Uinta Basin winters, allowing industry and regulators to make more efficient and effective decisions relating to air quality. Much about this issue remains poorly understood, however, and additional research is needed to provide information that will allow industry and regulators to continue to develop sound, cost-effective air emissions reduction strategies.

This annual report provides information about Uinta Basin air quality research conducted by Utah State University over the past 12 months. Sections 2, 3, and 4 report on the status of Uinta Basin air quality during 2018-19, while the remaining sections provide the results of specific air quality research projects in which our team engaged during the past year. Sections 15, 16, and 17 present a report of our
performance for the past year, our research priorities, and our project objectives for the coming year, respectively.

As part of our annual reporting process, we have revised our management plan for our group’s operations. It is available here: https://usu.box.com/s/19t1dj3t1ztb49ix0aav7p8i5p18ewaf. Additionally, we have updated our cumulative summary of all significant research findings that relate to Uinta Basin air quality, from 2010 through the present. It is available here: http://binghamresearch.usu.edu/cumulativeresearchsummary.

Authorship is indicated at the beginning of each section. Seth Lyman edited all sections of the document.
2. **Winter 2018-19 Air Quality and Meteorology**

*Author: Seth Lyman*

### 2.1. Introduction

This section provides an analysis of air quality and meteorology data from monitoring sites that operated around the Uinta Basin during winter 2018-19, as well as an analysis of all years of available ozone and particulate matter data. In this chapter, “winter 2018-19,” “winter,” “winter season,” or other similar phrases refer to the period from 15 November through 31 March.

### 2.2. Methods

Quality assurance results for the methods described here are available in Section 15.6.2.

#### 2.2.1. Ozone Measurements

During winter 2018-19, fourteen monitoring stations that measured ozone operated in the Uinta Basin. Table 2-1 contains a list of all monitoring stations, including locations, elevations, and operators. We obtained data for stations operated by organizations other than USU from the U.S. Environmental Protection Agency (EPA)'s AQS database ([https://aqs.epa.gov/api](https://aqs.epa.gov/api)) or, when data had not yet been entered into the AQS database, from EPA's airnow real-time database ([https://www.airnowtech.org](https://www.airnowtech.org)). We utilized an Ecotech Model 9810 ozone analyzer and a Thermo 49i at the Horsepool and Rabbit Mountain sites, respectively, and 2B Technology Model 205 ozone monitors at all other stations operated by USU. We performed calibration checks at all USU stations at least every other week using NIST-traceable ozone standards. Calibration checks passed if monitors reported in the range of ±5 ppb when exposed to 0 ppb ozone, and if monitors were within ±7% deviation from expected values when exposed to higher concentrations of ozone. We only included data bracketed by successful calibration checks in the final dataset.
Table 2-1. Air quality monitoring stations that operated during winter 2018-19. All stations measured ozone and basic meteorological parameters. Stations that measured organic compounds, NOx, and/or PM2.5 are indicated. NOx* signifies NO2 measured with a photolytic NO2 (rather than molybdenum) converter. NPS is the National Park Service. UDAQ is the Utah Division of Air Quality. BLM is the Bureau of Land Management. AQS is the EPA AQS air quality database (https://aqs.epa.gov/api).

<table>
<thead>
<tr>
<th>Operator</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Elev. (m)</th>
<th>Organics</th>
<th>NOx, PM2.5</th>
<th>Data Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seven Sisters</td>
<td>USU</td>
<td>39.981</td>
<td>-109.345</td>
<td>1618</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Castle Peak</td>
<td>USU</td>
<td>40.051</td>
<td>-110.020</td>
<td>1605</td>
<td>N/A</td>
<td>NOx*</td>
</tr>
<tr>
<td>Willow Creek</td>
<td>USU</td>
<td>39.836</td>
<td>-109.579</td>
<td>1799</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Rabbit Mtn.</td>
<td>USU</td>
<td>39.869</td>
<td>-109.097</td>
<td>1879</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Dinosaur N.M.</td>
<td>NPS</td>
<td>40.437</td>
<td>-109.305</td>
<td>1463</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Red Wash</td>
<td>Ute Tribe</td>
<td>40.204</td>
<td>-109.352</td>
<td>1689</td>
<td>N/A</td>
<td>NOx</td>
</tr>
<tr>
<td>Vernal</td>
<td>UDAQ</td>
<td>40.453</td>
<td>-109.510</td>
<td>1606</td>
<td>N/A</td>
<td>NOx, PM2.5</td>
</tr>
<tr>
<td>Whiterocks</td>
<td>Ute Tribe</td>
<td>40.484</td>
<td>-109.906</td>
<td>1893</td>
<td>N/A</td>
<td>NOx</td>
</tr>
<tr>
<td>Ouray</td>
<td>Ute Tribe</td>
<td>40.055</td>
<td>-109.688</td>
<td>1464</td>
<td>N/A</td>
<td>NOx</td>
</tr>
<tr>
<td>Roosevelt</td>
<td>DAQ/USU</td>
<td>40.294</td>
<td>-110.009</td>
<td>1587</td>
<td>Yes</td>
<td>NOx*, PM2.5</td>
</tr>
<tr>
<td>Myton</td>
<td>Ute/USU</td>
<td>40.217</td>
<td>-110.182</td>
<td>1610</td>
<td>N/A</td>
<td>NOx</td>
</tr>
<tr>
<td>Fruitland</td>
<td>USU</td>
<td>40.209</td>
<td>-110.840</td>
<td>2021</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Horsepool</td>
<td>USU</td>
<td>40.144</td>
<td>-109.467</td>
<td>1569</td>
<td>Yes</td>
<td>NOx*, PM2.5</td>
</tr>
<tr>
<td>Rangely</td>
<td>NPS/BLM</td>
<td>40.087</td>
<td>-108.762</td>
<td>1648</td>
<td>N/A</td>
<td>NOx, PM2.5</td>
</tr>
</tbody>
</table>

2.2.2. Reactive Nitrogen Measurements

We measured NO, true NO2 (via a photolytic converter), and NOx (sum of NO, NO2, and other reactive nitrogen compounds) at Roosevelt and Horsepool with Teledyne-API and Ecotech systems, respectively. We measured NO and true NO2 with a Thermo 42i with a photolytic converter at Castle Peak. NOx is the sum of NO and NO2. All three photolytic converters were manufactured by Air Quality Design, Inc. We calibrated the systems weekly with NO standards and for NO2 via gas-phase titration using a dilution calibrator. Once during the season, we calibrated NOx instrumentation with nitric acid and n-butyl nitrate permeation tubes. All sites operated by other organizations measured NO and NO2 via a molybdenum converter-based system, a method known to bias NO2 and NOx results high due to NOx interference (Jung et al., 2017).

2.2.3. Organic Compound Measurements

We measured methane and total non-methane hydrocarbons (NMHC) at Horsepool and Roosevelt with a Chromatotec ChromaTHC and a Thermo 55i, respectively. We calibrated these systems every week with certified gas standards and a dilution calibrator.

To measure speciated C2-C10 NMHC, we collected whole-air samples with silonite-coated 6 L stainless steel canisters at Horsepool and Roosevelt. We collected one can per day via an automated sampling manifold (We filled some cans from 0:00 to 3:00 local standard time, and the others from 12:00 to 15:00). We used silonite-coated critical orifice-based flow regulators to regulate flow into the canisters, and we controlled sample collection with a nickel-plated brass manifold with solenoid valves (Clippard part number O-ET-2M-12).
We analyzed the canisters for 54 NMHC, methanol, ethanol, and isopropanol using a method similar to guidance provided by EPA for Photochemical Assessment Monitoring Stations (EPA, 1998). We used cold trap dehydration (Wang and Austin, 2006) with an Entech 7200 preconcentrator and a 7016D autosampler to preconcentrate samples. We analyzed samples with two Shimadzu GC-2010 gas chromatographs (GCs), a flame ionization detector (for C2 and C3 NMHC), and a mass spectrometer (for all other compounds). We used a Restek rtx1-ms column (all compounds; 60 m, 0.32 mm ID), a Restek Alumina BOND/Na₂SO₄ column (C2 and C3 NMHC; 50 m, 0.32 mm ID), and another Restek rtx1-ms column (all other compounds; 30 m, 0.25 mm ID) to separate compounds in the GC.

We used a 5-point curve to calibrate the flame ionization detector and mass spectrometer before each analyzed batch of samples. We also analyzed a duplicate sample, at least one blank, and at least one calibration check during each batch. We accepted data if calibration curves had r² values greater than 0.99, if all values for blanks were less than 1 ppb, if duplicate values for each compound were within 10% of each other, and if calibration checks were within 20% of expected values. We also collected field spikes at Horsepool and Roosevelt by adding calibration gas to the sampling manifold from a certified compressed gas standard and a dilution calibrator, and we collected blanks by adding air scrubbed of organics to the manifold.

2.2.4. Particulate Matter Measurements

We measured particulate matter with a diameter smaller than 2.5 micrometers (PM₂.₅) at Horsepool with a BAM 1020 monitor. We operated the instrument according to manufacturer protocols, with leak checks, flow and mass calibrations, detector calibrations, and cleanings performed at regular intervals. We obtained particulate matter values for other sites from the EPA AQS database (https://aqs.epa.gov/api) or, when data had not yet been entered into the AQS database, from EPA’s airnow real-time database (https://www.airnowtech.org).

2.2.5. Meteorological Measurements

We deployed solar radiation sensors at Horsepool (incoming and outgoing shortwave and longwave with a Kipp and Zonen CNR-4 and UV-A and UV-B with Kipp and Zonen UV radiometers) and Roosevelt (incoming and outgoing shortwave with a Kipp and Zonen CNR-4). We have these sensors calibrated at the factory or check them against a recently-calibrated sensor every three years.

We operated a suite of comprehensive, research-grade meteorological instruments at all sites operated by USU. We checked wind speed and direction, temperature, humidity, and barometric pressure against a NIST-traceable standard once annually. We checked snow depth sensors against a height standard annually. We also obtained meteorological data from the EPA AQS database or, when data had not yet been entered into the AQS database, from EPA’s airnow real-time database.

2.3. Results and Discussion

2.3.1. Ozone

Even though NOₓ and organic compound emissions into the Uinta Basin atmosphere are relatively constant, significant ozone production from NOₓ and organic compounds only occurs when certain
meteorological conditions exist. Ozone stays well below the EPA standard of 70 ppb during winter except when adequate snow cover and multi-day temperature inversions exist (a temperature inversion occurs when the air temperature aloft is warmer than the temperature at the surface). Sunlight is the energy that fuels ozone production and, since snow reflects sunlight, snow cover increases the amount of energy available to produce ozone. By the same process, snow limits the amount of energy absorbed by the earth’s surface, keeping the surface and the air immediately above it cooler than the air aloft, which promotes inversion formation and persistence. Inversions trap NO_x and organic compounds near their emission sources, allowing them to build up to concentrations that allow for rapid ozone production.

Plentiful snow cover existed in the Uinta Basin during the second half of winter 2018-19 (Figure 2-1). Snow cover increased available radiation and allowed for several multi-day inversion episodes. These conditions led to ozone in excess of EPA standards at many sites throughout the Uinta Basin (Figure 2-2).

![Figure 2-1](image)

Figure 2-1. Horsepool daily maximum ozone, average snow depth, and daytime average total UV radiation (incoming + reflected) during winter 2018-19. Inversion periods are shown as light blue boxes.
Table 2-2 provides information about ozone observed at all monitoring stations in the Uinta Basin during winter 2018-19. Many stations experienced exceedances of the EPA standard during the winter, with the Ouray monitoring station having the most exceedances. An exceedance occurs when the daily maximum 8-hr average ozone value at a station is greater than the EPA standard. The average of the fourth-highest daily maximum 8-hr average ozone value over three consecutive calendar years is used to determine compliance with the standard.

Table 2-2. Eight-hr average ozone concentrations around the Uinta Basin, winter 2018-19.

<table>
<thead>
<tr>
<th>Station</th>
<th>Mean</th>
<th>Maximum</th>
<th>Minimum</th>
<th>4th Highest Daily Maximum</th>
<th>Number of Exceedances</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seven Sisters</td>
<td>41.1</td>
<td>116.4</td>
<td>9.9</td>
<td>98.8</td>
<td>15</td>
</tr>
<tr>
<td>Castle Peak</td>
<td>39.0</td>
<td>82.7</td>
<td>14.8</td>
<td>77.4</td>
<td>7</td>
</tr>
<tr>
<td>Willow Creek</td>
<td>41.9</td>
<td>86.6</td>
<td>19.1</td>
<td>80.6</td>
<td>6</td>
</tr>
<tr>
<td>Rabbit Mtn.</td>
<td>44.4</td>
<td>61.5</td>
<td>28.2</td>
<td>57.9</td>
<td>0</td>
</tr>
<tr>
<td>Dinosaur N.M.</td>
<td>37.7</td>
<td>80.4</td>
<td>9.8</td>
<td>70.5</td>
<td>2</td>
</tr>
<tr>
<td>Red Wash</td>
<td>40.8</td>
<td>88.9</td>
<td>14.3</td>
<td>74.4</td>
<td>6</td>
</tr>
<tr>
<td>Vernal</td>
<td>36.5</td>
<td>76.4</td>
<td>7.1</td>
<td>64.8</td>
<td>1</td>
</tr>
<tr>
<td>Whiterocks</td>
<td>41.5</td>
<td>74.4</td>
<td>17.9</td>
<td>67.3</td>
<td>3</td>
</tr>
<tr>
<td>Ouray</td>
<td>39.1</td>
<td>110.5</td>
<td>7.7</td>
<td>98.1</td>
<td>16</td>
</tr>
<tr>
<td>Roosevelt</td>
<td>38.1</td>
<td>96.4</td>
<td>5.0</td>
<td>87.5</td>
<td>10</td>
</tr>
<tr>
<td>Myton</td>
<td>35.7</td>
<td>86.1</td>
<td>5.8</td>
<td>79.1</td>
<td>9</td>
</tr>
<tr>
<td>Fruitland</td>
<td>40.8</td>
<td>65.9</td>
<td>12.1</td>
<td>61.3</td>
<td>0</td>
</tr>
<tr>
<td>Horsepool</td>
<td>41.7</td>
<td>93.9</td>
<td>12.6</td>
<td>86.2</td>
<td>11</td>
</tr>
<tr>
<td>Rangely</td>
<td>29.0</td>
<td>70.8</td>
<td>4.3</td>
<td>59.0</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 2-3 through Figure 2-9 show the spatial distribution of ozone around the Uinta Basin during an ozone episode that persisted from 21 February through 3 March. Figure 2-3 shows conditions on 21 February at the end of a stormy period that resulted in relatively low ozone across the basin (ozone at...
Seven Sisters and Horsepool remained elevated above background levels. By 23 February (Figure 2-4), ozone had increased above the 70 ppb standard at Seven Sisters and Ouray, and from 25 February (Figure 2-5) through 1 March (Figure 2-7) concentrations had reached a maximum. These figures show the highest ozone centered around the area between Ouray, Seven Sisters, and Horsepool, as has been observed in previous years. Unlike previous years, however, ozone at Roosevelt was at least as high as at Horsepool. Lyman and Tran (2015a) showed that ozone concentrations during inversion episodes depend primarily on elevation and secondarily on proximity to oil and gas sources. The area around Seven Sisters and Horsepool has the highest density of oil and gas wells of any part of the Uinta Basin, and Ouray is nearby and is the site at the lowest elevation. Ozone may be increasing in the Roosevelt area because of increased oil development there (Section 4).

By 1 March, clean air from the east began pushing polluted air to the west (Figure 2-7), and by 2 March the entire Basin was again below the EPA ozone standard, except for the Ouray station, which is the lowest-elevation station in the Basin (Figure 2-8). It took one more day before polluted air was flushed from the Ouray station (Figure 2-9).

![Figure 2-3. Daily maximum 8-hr average ozone on 21 February 2019. The color indicates ozone concentration and was interpolated using ArcGIS software. The black bar on the ozone color scale indicates 70 ppb. Arrows indicate wind direction, and arrow size indicates wind speed.](image)
Figure 2-4. Daily maximum 8-hr average ozone on 23 February 2019. The color indicates ozone concentration and was interpolated using ArcGIS software. The black bar on the ozone color scale indicates 70 ppb. Arrows indicate wind direction, and arrow size indicates wind speed.

Figure 2-5. Daily maximum 8-hr average ozone on 25 February 2019. The color indicates ozone concentration and was interpolated using ArcGIS software. The black bar on the ozone color scale indicates 70 ppb. Arrows indicate wind direction, and arrow size indicates wind speed.
Figure 2-6. Daily maximum 8-hr average ozone on 27 February 2019. The color indicates ozone concentration and was interpolated using ArcGIS software. The black bar on the ozone color scale indicates 70 ppb. Arrows indicate wind direction, and arrow size indicates wind speed.

Figure 2-7. Daily maximum 8-hr average ozone on 1 Mar 2019. The color indicates ozone concentration and was interpolated using ArcGIS software. The black bar on the ozone color scale indicates 70 ppb. Arrows indicate wind direction, and arrow size indicates wind speed.
Figure 2-8. Daily maximum 8-hr average ozone on 2 Mar 2019. The color indicates ozone concentration and was interpolated using ArcGIS software. The black bar on the ozone color scale indicates 70 ppb. Arrows indicate wind direction, and arrow size indicates wind speed.

Figure 2-9. Daily maximum 8-hr average ozone on 3 Mar 2019. The color indicates ozone concentration and was interpolated using ArcGIS software. The black bar on the ozone color scale indicates 70 ppb. Arrows indicate wind direction, and arrow size indicates wind speed.

Figure 2-10 shows 4th-highest daily maximum ozone versus station elevation for all ozone monitoring stations that operated during winter 2018-19. As has been observed in previous winters, ozone concentrations were dependent on elevation. Lower elevation locations have more, longer, and
stronger inversions than higher elevations, and we have shown that this is the reason for the relationship between elevation and ozone during inversion episodes (Lyman and Tran, 2015a). The relationship between elevation and ozone is weak in Figure 2-10 because (1) proximity to sources also influences ozone levels and (2) the average elevation in an area around the measurement location is a better predictor of ozone levels than the actual site elevation (Lyman and Tran, 2015a).

Figure 2-10. Fourth-highest daily maximum 8-hr average ozone versus station elevation for winter 2018-19.

Figure 2-11 shows a time series of ozone concentrations at several sites in the Uinta Basin from July 2009 (when continuous measurements began) through March 2019. As Figure 2-11 shows, exceedances of the standard have occurred during seven of the ten winters (70%) in the Uinta Basin for which continuous ozone monitoring data are available. Utah DAQ also measured ozone in Vernal during 2006 and 2007, but those data are not publicly available and are not included here. No wintertime exceedances of the ozone standard were measured in Vernal during that period. Summertime exceedances are considered in Section 3 of this document.
Figure 2-11. Time series of daily maximum 8-hr average ozone concentration at five sites in the Uinta Basin from July 2009 through March 2019. The red dashed line shows 70 ppb, the EPA standard for ozone.

Ozone statistics from the five sites shown in Figure 2-11 are summarized in Table 2-3. The three-year average of annual 4th-highest 8-hr averages for a given site (using calendar years) is referred to as a design value. The design value is the value EPA uses to determine whether an airshed is in attainment of the 70 ppb ozone standard (design values of 71 and above are out of attainment). EPA used the 2014-16 period in their recent decision to designate the Uinta Basin a nonattainment area for ozone. Table 2-4 shows the ozone design value for 2013-15, 2014-16, 2015-17, 2016-18, and 2017-19 for the same monitoring stations shown in Figure 2-11, as well as for the Whiterocks station. The design value for 2017-19 shown in Table 2-4 only includes 2019 data through March.
Table 2-3. Ozone summary statistics for five sites in the Uinta Basin over eight calendar years. All values were calculated from daily maximum 8-hr average concentrations. For 2019, only data through 31 March are shown.

<table>
<thead>
<tr>
<th>Year</th>
<th>Site</th>
<th>Mean</th>
<th>Median</th>
<th>Max</th>
<th>Min</th>
<th>4th High Daily Max</th>
<th>Exceedance Days (&gt;70 ppb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009 (July-Dec)</td>
<td>Ouray</td>
<td>46</td>
<td>47</td>
<td>101</td>
<td>23</td>
<td>67</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Fruitland</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>Vernal</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>Roosevelt</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>Rangely</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>2010</td>
<td>Ouray</td>
<td>56</td>
<td>54</td>
<td>123</td>
<td>20</td>
<td>117</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>Fruitland</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>Vernal</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>Roosevelt</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>Rangely</td>
<td>41</td>
<td>42</td>
<td>67</td>
<td>11</td>
<td>58</td>
<td>--</td>
</tr>
<tr>
<td>2011</td>
<td>Ouray</td>
<td>53</td>
<td>52</td>
<td>138</td>
<td>18</td>
<td>119</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td>Fruitland</td>
<td>48</td>
<td>50</td>
<td>71</td>
<td>24</td>
<td>65</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Vernal</td>
<td>55</td>
<td>55</td>
<td>95</td>
<td>33</td>
<td>84</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>Roosevelt</td>
<td>55</td>
<td>54</td>
<td>116</td>
<td>29</td>
<td>103</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>Rangely</td>
<td>48</td>
<td>50</td>
<td>88</td>
<td>21</td>
<td>73</td>
<td>4</td>
</tr>
<tr>
<td>2012</td>
<td>Ouray</td>
<td>48</td>
<td>50</td>
<td>76</td>
<td>18</td>
<td>67</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Fruitland</td>
<td>49</td>
<td>49</td>
<td>71</td>
<td>26</td>
<td>70</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Vernal</td>
<td>45</td>
<td>46</td>
<td>68</td>
<td>14</td>
<td>64</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Roosevelt</td>
<td>49</td>
<td>51</td>
<td>70</td>
<td>14</td>
<td>67</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Rangely</td>
<td>46</td>
<td>47</td>
<td>71</td>
<td>15</td>
<td>69</td>
<td>2</td>
</tr>
<tr>
<td>2013</td>
<td>Ouray</td>
<td>57</td>
<td>54</td>
<td>141</td>
<td>24</td>
<td>132</td>
<td>52</td>
</tr>
<tr>
<td></td>
<td>Fruitland</td>
<td>49</td>
<td>50</td>
<td>75</td>
<td>18</td>
<td>69</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Vernal</td>
<td>52</td>
<td>52</td>
<td>114</td>
<td>20</td>
<td>102</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>Roosevelt</td>
<td>56</td>
<td>54</td>
<td>110</td>
<td>25</td>
<td>104</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>Rangely</td>
<td>50</td>
<td>50</td>
<td>106</td>
<td>22</td>
<td>91</td>
<td>13</td>
</tr>
<tr>
<td>2014</td>
<td>Ouray</td>
<td>48</td>
<td>50</td>
<td>91</td>
<td>17</td>
<td>79</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>Fruitland</td>
<td>47</td>
<td>49</td>
<td>65</td>
<td>16</td>
<td>64</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Vernal</td>
<td>43</td>
<td>45</td>
<td>64</td>
<td>12</td>
<td>62</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Roosevelt</td>
<td>46</td>
<td>49</td>
<td>63</td>
<td>16</td>
<td>62</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Rangely</td>
<td>44</td>
<td>46</td>
<td>66</td>
<td>14</td>
<td>62</td>
<td>0</td>
</tr>
<tr>
<td>2015</td>
<td>Ouray</td>
<td>45</td>
<td>47</td>
<td>71</td>
<td>21</td>
<td>68</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Fruitland</td>
<td>46</td>
<td>46</td>
<td>77</td>
<td>23</td>
<td>69</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Vernal</td>
<td>43</td>
<td>43</td>
<td>67</td>
<td>10</td>
<td>64</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Roosevelt</td>
<td>42</td>
<td>42</td>
<td>66</td>
<td>14</td>
<td>60</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Rangely</td>
<td>43</td>
<td>45</td>
<td>70</td>
<td>15</td>
<td>66</td>
<td>0</td>
</tr>
<tr>
<td>2016</td>
<td>Ouray</td>
<td>49</td>
<td>48</td>
<td>120</td>
<td>20</td>
<td>96</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>Fruitland</td>
<td>47</td>
<td>47</td>
<td>67</td>
<td>30</td>
<td>62</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Vernal</td>
<td>47</td>
<td>46</td>
<td>78</td>
<td>20</td>
<td>73</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Roosevelt</td>
<td>47</td>
<td>47</td>
<td>96</td>
<td>20</td>
<td>81</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Rangely</td>
<td>45</td>
<td>45</td>
<td>67</td>
<td>18</td>
<td>61</td>
<td>0</td>
</tr>
</tbody>
</table>
Table 6-3 Continued.

<table>
<thead>
<tr>
<th>Year</th>
<th>Site</th>
<th>Mean</th>
<th>Median</th>
<th>Max</th>
<th>Min</th>
<th>4th High Daily Max</th>
<th>Exceedance Days (&gt;70 ppb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2017</td>
<td>Ouray</td>
<td>50</td>
<td>50</td>
<td>111</td>
<td>20</td>
<td>103</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>Fruitland</td>
<td>41</td>
<td>42</td>
<td>57</td>
<td>26</td>
<td>53</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Vernal</td>
<td>48</td>
<td>49</td>
<td>69</td>
<td>25</td>
<td>68</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Roosevelt</td>
<td>48</td>
<td>48</td>
<td>86</td>
<td>24</td>
<td>78</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>Rangely</td>
<td>47</td>
<td>48</td>
<td>69</td>
<td>25</td>
<td>64</td>
<td>0</td>
</tr>
<tr>
<td>2018</td>
<td>Ouray</td>
<td>48</td>
<td>48</td>
<td>72</td>
<td>18</td>
<td>67</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Fruitland</td>
<td>47</td>
<td>46</td>
<td>68</td>
<td>22</td>
<td>64</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Vernal</td>
<td>48</td>
<td>50</td>
<td>81</td>
<td>20</td>
<td>69</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Roosevelt</td>
<td>49</td>
<td>49</td>
<td>79</td>
<td>18</td>
<td>71</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>Rangely</td>
<td>47</td>
<td>48</td>
<td>73</td>
<td>17</td>
<td>68</td>
<td>2</td>
</tr>
<tr>
<td>2019</td>
<td>Ouray</td>
<td>58</td>
<td>57</td>
<td>110</td>
<td>26</td>
<td>98</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>Fruitland</td>
<td>50</td>
<td>50</td>
<td>67</td>
<td>34</td>
<td>63</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Vernal</td>
<td>49</td>
<td>50</td>
<td>76</td>
<td>24</td>
<td>64</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Roosevelt</td>
<td>56</td>
<td>56</td>
<td>96</td>
<td>21</td>
<td>87</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Rangely</td>
<td>44</td>
<td>47</td>
<td>70</td>
<td>22</td>
<td>59</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 2-4. Average of the 4th-highest 8-hr daily maximum ozone values during three consecutive calendar years for several monitoring stations in the Uinta Basin (a.k.a., ozone design values). Only 2019 data collected through 31 March are used. Values in exceedance of the EPA standard are in bold font.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Ouray</td>
<td>93</td>
<td>81</td>
<td>89</td>
<td>88</td>
<td>89</td>
</tr>
<tr>
<td>Fruitland</td>
<td>67</td>
<td>65</td>
<td>61</td>
<td>59</td>
<td>60</td>
</tr>
<tr>
<td>Vernal</td>
<td>76</td>
<td>66</td>
<td>68</td>
<td>70</td>
<td>67</td>
</tr>
<tr>
<td>Roosevelt</td>
<td>75</td>
<td>67</td>
<td>73</td>
<td>76</td>
<td>78</td>
</tr>
<tr>
<td>Rangely</td>
<td>73</td>
<td>63</td>
<td>62</td>
<td>64</td>
<td>63</td>
</tr>
<tr>
<td>Whiterocks</td>
<td>66</td>
<td>71</td>
<td>71</td>
<td>72</td>
<td>67</td>
</tr>
</tbody>
</table>

Figure 2-12 and Figure 2-13 show the number of annual ozone exceedances and the annual 4th-highest 8-hr average ozone, respectively, at the same monitoring stations shown in the previous tables and figures. These figures show that air quality is extremely variable from year to year and across measurement stations in the Uinta Basin. Ouray experienced more than 40 exceedance days in 2010 and 2013 but had only one in 2012 and 2018 and two in 2015. Exceedance days in 2012, 2015, and 2018 occurred during summer, not winter, and were due to intrusions of ozone-rich stratospheric air and/or wildfires (see Section 3).
Figure 2-12. Number of annual ozone exceedances at five sites from 2010 through March 2019.

Figure 2-13 shows that the 4th-highest 8-hr average ozone at the five sites shown is always at least 60 ppb (except 2019, which only has data through 31 March). Between 60 and 70 ppb is the natural summertime background ozone level in the Uinta Basin region. During years with no winter inversions and low wintertime ozone (2012, 2015, and 2018), the highest ozone is observed during summer and is usually in the range of 60-70 ppb.

The portion of the Uinta Basin that lies below 6,250 ft in elevation above sea level is currently a marginal non-attainment area for ozone. In 2021, EPA will use ozone data from calendar years 2018, 2019, and 2020 to update the attainment status. Clean Air Act regulations stipulate that if the design value for those years is 71 ppb or higher, the area will become a moderate non-attainment area. If the design value is 94 ppb or higher, the area will become a serious non-attainment area. Ozone was relatively low during 2018, but ozone exceedances during winter 2018-19 make it all but certain that the basin will become a moderate non-attainment area. Figure 2-13 shows that the lowest annual 4th-highest 8-hr
average ozone values for sites in the Uinta Basin, even in the absence of winter inversions, is 60 ppb. The average of the 4\textsuperscript{th}-highest 8-hr average ozone at Ouray for 2018, 2019, and an assumption of 60 ppb for 2020, is 75 ppb, which is above the threshold required to avoid moderate non-attainment. A serious non-attainment designation is unlikely (Section 12.4).

2.3.2. Particulate Matter

PM\textsubscript{2.5} concentrations stayed below the EPA standard of 35 $\mu$g m\textsuperscript{-3} during winter 2018-19, though PM\textsubscript{2.5} increased during stagnant and inverted conditions at all monitoring stations (Figure 2-14).

![Figure 2-14. 24-hr average PM\textsubscript{2.5} at monitoring stations around the Uinta Basin during winter 2018-19. The red dashed line indicates the EPA PM\textsubscript{2.5} standard.](image)

Figure 2-15 shows box and whisker plots of PM\textsubscript{2.5} at monitoring stations around the Uinta Basin. As has been observed in previous years, higher PM\textsubscript{2.5} occurred in the urban areas of the basin than in the oil and gas-dominated area of Horsepool, likely because emissions from traffic and home heating enhance PM\textsubscript{2.5} in urban areas.
Figure 2-15. Box-and-whisker plot of 24-hr average PM$_{2.5}$ at four monitoring stations during winter 2018-19. X’s indicate average values. Lines in the middle of boxes indicate medians. Tops and bottoms of boxes indicate the third and first quartiles. Top and bottom whiskers indicate maximum and minimum values. Circles indicate outliers.

Figure 2-16 shows a time series of all PM$_{2.5}$ measurements that have been collected in the Uinta Basin. Exceedances of the EPA PM$_{2.5}$ standard have occurred most often during winter. However, summertime PM$_{2.5}$ exceedances occurred in the Uinta Basin during summers 2012 and 2018, and spikes in PM$_{2.5}$ have occurred during every summer. These summertime spikes in PM$_{2.5}$ concentrations tend to be caused by wildfire smoke.

Figure 2-16. Time series of daily 24-hr average PM$_{2.5}$ concentrations at nine sites in the Uinta Basin, October 2009-March 2019. The red dashed line shows 35 µg m$^{-3}$, the EPA standard for PM$_{2.5}$.

Table 2-5 is a summary of PM$_{2.5}$ values at sites around the Uinta Basin from 2010 through March 2019. PM$_{2.5}$ values in Vernal and Roosevelt have exceeded EPA standards more than other sites. To determine compliance with its 35 µg m$^{-3}$ PM$_{2.5}$ standard, EPA uses the three-year average of annual 98th percentile
The Uinta Basin has only had two years wherein the 98th percentile of annual PM$_{2.5}$ data exceeded the EPA standard (Myton in 2011 and Roosevelt in 2013). The highest 3-year average of annual 98th percentile data was 31.5 µg m$^{-3}$ in Vernal for years 2012 through 2014.

Table 2-5. PM$_{2.5}$ summary statistics for the Uinta Basin from 2010 through March 2019. All values shown were calculated from daily 24-hr average concentrations.

<table>
<thead>
<tr>
<th>Year</th>
<th>Site</th>
<th>Winter Mean</th>
<th>Winter Max</th>
<th>Winter Min</th>
<th>Annual # of Exceedance Days</th>
<th>Annual 98th Percentile Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>Roosevelt</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>Vernal</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>Ouray</td>
<td>8.8</td>
<td>22.5</td>
<td>1.0</td>
<td>0</td>
<td>19.0</td>
</tr>
<tr>
<td></td>
<td>Red Wash</td>
<td>7.2</td>
<td>22.7</td>
<td>0.0</td>
<td>0</td>
<td>16.0</td>
</tr>
<tr>
<td></td>
<td>Myton</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>Rabbit Mtn</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>Horsepool</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>2011</td>
<td>Roosevelt</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>Vernal</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>Ouray</td>
<td>9.9</td>
<td>30.0</td>
<td>1.1</td>
<td>0</td>
<td>22.5</td>
</tr>
<tr>
<td></td>
<td>Red Wash</td>
<td>7.8</td>
<td>23.7</td>
<td>1.0</td>
<td>0</td>
<td>17.8</td>
</tr>
<tr>
<td></td>
<td>Myton</td>
<td>11.8</td>
<td>48.2</td>
<td>1.0</td>
<td>8</td>
<td>36.7</td>
</tr>
<tr>
<td></td>
<td>Rabbit Mtn</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>Horsepool</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>2012</td>
<td>Roosevelt</td>
<td>5.7</td>
<td>22.2</td>
<td>0.0</td>
<td>3</td>
<td>28.2</td>
</tr>
<tr>
<td></td>
<td>Vernal</td>
<td>7.9</td>
<td>25.6</td>
<td>1.2</td>
<td>0</td>
<td>22.0</td>
</tr>
<tr>
<td></td>
<td>Ouray</td>
<td>6.1</td>
<td>14.0</td>
<td>1.3</td>
<td>3</td>
<td>27.4</td>
</tr>
<tr>
<td></td>
<td>Red Wash</td>
<td>4.9</td>
<td>10.6</td>
<td>1.0</td>
<td>0</td>
<td>16.0</td>
</tr>
<tr>
<td></td>
<td>Myton</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>Rabbit Mtn</td>
<td>2.7</td>
<td>10.7</td>
<td>0.4</td>
<td>4</td>
<td>20.3</td>
</tr>
<tr>
<td></td>
<td>Horsepool</td>
<td>4.0</td>
<td>10.7</td>
<td>0.0</td>
<td>0</td>
<td>10.4</td>
</tr>
<tr>
<td>2013</td>
<td>Roosevelt</td>
<td>18.7</td>
<td>41.7</td>
<td>1.3</td>
<td>5</td>
<td>35.1</td>
</tr>
<tr>
<td></td>
<td>Vernal</td>
<td>20.0</td>
<td>55.7</td>
<td>2.6</td>
<td>18</td>
<td>42.1</td>
</tr>
<tr>
<td></td>
<td>Ouray</td>
<td>13.4</td>
<td>32.0</td>
<td>2.3</td>
<td>0</td>
<td>26.5</td>
</tr>
<tr>
<td></td>
<td>Red Wash</td>
<td>10.9</td>
<td>26.7</td>
<td>3.0</td>
<td>0</td>
<td>26.0</td>
</tr>
<tr>
<td></td>
<td>Myton</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>Rabbit Mtn</td>
<td>5.0</td>
<td>13.9</td>
<td>1.4</td>
<td>0</td>
<td>18.0</td>
</tr>
<tr>
<td></td>
<td>Horsepool</td>
<td>13.7</td>
<td>28.3</td>
<td>0.7</td>
<td>0</td>
<td>27.8</td>
</tr>
<tr>
<td>2014</td>
<td>Roosevelt</td>
<td>7.1</td>
<td>35.3</td>
<td>1.7</td>
<td>1</td>
<td>29.8</td>
</tr>
<tr>
<td></td>
<td>Vernal</td>
<td>9.6</td>
<td>32.1</td>
<td>2.2</td>
<td>0</td>
<td>30.3</td>
</tr>
<tr>
<td></td>
<td>Ouray</td>
<td>9.2</td>
<td>34.4</td>
<td>2.4</td>
<td>0</td>
<td>31.6</td>
</tr>
<tr>
<td></td>
<td>Red Wash</td>
<td>6.0</td>
<td>26.8</td>
<td>3.2</td>
<td>0</td>
<td>15.1</td>
</tr>
<tr>
<td></td>
<td>Myton</td>
<td>--</td>
<td>--</td>
<td>0.2</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>Rabbit Mtn</td>
<td>2.0</td>
<td>5.0</td>
<td>0.0</td>
<td>0</td>
<td>5.1</td>
</tr>
<tr>
<td></td>
<td>Horsepool</td>
<td>5.5</td>
<td>22.3</td>
<td>1.5</td>
<td>0</td>
<td>21.6</td>
</tr>
</tbody>
</table>
Table 2-5 Continued.

<table>
<thead>
<tr>
<th>Year</th>
<th>Site</th>
<th>Winter Mean</th>
<th>Winter Max</th>
<th>Winter Min</th>
<th>Annual # of Exceedance Days</th>
<th>Annual 98th Percentile Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>Roosevelt</td>
<td>8.7</td>
<td>46.7</td>
<td>2.7</td>
<td>1</td>
<td>21.2</td>
</tr>
<tr>
<td></td>
<td>Vernal</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>Myton</td>
<td>6.7</td>
<td>25.5</td>
<td>0.1</td>
<td>0</td>
<td>19.8</td>
</tr>
<tr>
<td></td>
<td>Rabbit Mtn</td>
<td>1.7</td>
<td>3.8</td>
<td>0.0</td>
<td>0</td>
<td>3.7</td>
</tr>
<tr>
<td></td>
<td>Horsepool</td>
<td>7.0</td>
<td>15.2</td>
<td>3.0</td>
<td>0</td>
<td>14.4</td>
</tr>
<tr>
<td></td>
<td>Ft Duchesne</td>
<td>7.6</td>
<td>18.5</td>
<td>1.7</td>
<td>0</td>
<td>18.0</td>
</tr>
<tr>
<td></td>
<td>Randlett</td>
<td>9.4</td>
<td>34.6</td>
<td>1.4</td>
<td>0</td>
<td>21.3</td>
</tr>
<tr>
<td></td>
<td>Rangely</td>
<td>7.3</td>
<td>15.3</td>
<td>3.1</td>
<td>0</td>
<td>17.5</td>
</tr>
<tr>
<td>2016</td>
<td>Roosevelt</td>
<td>8.1</td>
<td>30.2</td>
<td>1.1</td>
<td>0</td>
<td>23.5</td>
</tr>
<tr>
<td></td>
<td>Vernal</td>
<td>8.1</td>
<td>30.0</td>
<td>1.2</td>
<td>0</td>
<td>25.0</td>
</tr>
<tr>
<td></td>
<td>Myton</td>
<td>8.9</td>
<td>31.9</td>
<td>1.1</td>
<td>0</td>
<td>22.5</td>
</tr>
<tr>
<td></td>
<td>Horsepool</td>
<td>6.8</td>
<td>21.9</td>
<td>0.4</td>
<td>0</td>
<td>21.8</td>
</tr>
<tr>
<td></td>
<td>Ft Duchesne</td>
<td>9.5</td>
<td>25.0</td>
<td>1.5</td>
<td>0</td>
<td>25.0</td>
</tr>
<tr>
<td></td>
<td>Randlett</td>
<td>10.1</td>
<td>26.1</td>
<td>1.3</td>
<td>0</td>
<td>26.1</td>
</tr>
<tr>
<td></td>
<td>Rangely</td>
<td>6.7</td>
<td>16.9</td>
<td>2.8</td>
<td>0</td>
<td>12.2</td>
</tr>
<tr>
<td>2017</td>
<td>Roosevelt</td>
<td>6.9</td>
<td>40.6</td>
<td>0.5</td>
<td>1</td>
<td>28.3</td>
</tr>
<tr>
<td></td>
<td>Vernal</td>
<td>6.5</td>
<td>23.8</td>
<td>2.1</td>
<td>0</td>
<td>20.7</td>
</tr>
<tr>
<td></td>
<td>Horsepool</td>
<td>3.4</td>
<td>22.1</td>
<td>0.0</td>
<td>0</td>
<td>21.6</td>
</tr>
<tr>
<td></td>
<td>Rangely</td>
<td>6.4</td>
<td>14.3</td>
<td>2.0</td>
<td>0</td>
<td>14.8</td>
</tr>
<tr>
<td>2018</td>
<td>Roosevelt</td>
<td>5.4</td>
<td>19.4</td>
<td>0.6</td>
<td>3</td>
<td>23.9</td>
</tr>
<tr>
<td></td>
<td>Vernal</td>
<td>4.9</td>
<td>16.1</td>
<td>1.1</td>
<td>0</td>
<td>19.2</td>
</tr>
<tr>
<td></td>
<td>Horsepool</td>
<td>2.5</td>
<td>13.0</td>
<td>0.0</td>
<td>0</td>
<td>9.6</td>
</tr>
<tr>
<td></td>
<td>Rangely</td>
<td>6.2</td>
<td>13.3</td>
<td>4.0</td>
<td>0</td>
<td>20.8</td>
</tr>
<tr>
<td>2019</td>
<td>Roosevelt</td>
<td>9.9</td>
<td>26.4</td>
<td>0.6</td>
<td>0</td>
<td>26.0</td>
</tr>
<tr>
<td></td>
<td>Vernal</td>
<td>7.7</td>
<td>19.5</td>
<td>1.7</td>
<td>0</td>
<td>19.2</td>
</tr>
<tr>
<td></td>
<td>Horsepool</td>
<td>5.3</td>
<td>17.2</td>
<td>0.3</td>
<td>0</td>
<td>16.7</td>
</tr>
<tr>
<td></td>
<td>Rangely</td>
<td>7.9</td>
<td>14.0</td>
<td>4.5</td>
<td>0</td>
<td>13.4</td>
</tr>
</tbody>
</table>

2.3.3. **Comparison of Roosevelt, Horsepool, and Castle Peak Data**

The Horsepool and Roosevelt monitoring stations began operating in winter 2011-12 and were designed to contain a nearly identical suite of instrumentation. At both stations, we measure NOx with instrumentation that doesn’t bias NO2 during winter inversion episodes, whereas all regulatory monitoring stations in the Uinta Basin use alternative, biased instrumentation. The areas surrounding the Horsepool and Roosevelt stations are very different from one another. The Horsepool station is on the northern edge of an area of dense oil and gas development (mostly gas), whereas the Roosevelt station is within a small city. Some oil and gas development exists within and near the city of Roosevelt (mostly oil). The two stations are at very similar elevations (Table 2-1).
In 2017 Utah DAQ donated a NOx analyzer that we upgraded with a photolytic converter and installed at our Castle Peak monitoring station. Castle Peak is in an area of dense oil development, and its elevation is less than 100 meters higher than the Roosevelt and Horsepool stations.

Figure 2-17 shows NOx measured at Roosevelt, Horsepool, and Castle Peak during winter 2018-19, and Figure 2-18 shows NOx at Roosevelt and Horsepool. NOx is the sum of NO and NO2, which are important precursors to ozone production. NOy (not shown in the figures) is the sum of NOx and all other reactive nitrogen compounds (i.e., nitric and nitrous acids, organic nitrates, and particulate-bound nitrogen compounds). NOz is the sum of all reactive nitrogen compounds except NOx (in other words, it is NOy minus NOx). While NOx is an ozone precursor, the compounds that comprise NOz are mostly generated along with ozone as a result of photochemical reactions and are byproducts and indicators of ozone production.

![Figure 2-17. Hourly average NOx measured at Roosevelt, Horsepool, and Castle Peak during winter 2018-19.](image-url)
During winter 2018-19, NO<sub>x</sub> was higher in Roosevelt than at Horsepool and Castle Peak (Figure 2-17) and was 5.6 times higher than Horsepool on average (during the previous winter, it was only 2.1 times higher). NO<sub>x</sub> in Roosevelt is likely emitted from urban sources like cars and home heating, as well as from oil and gas sources, while NO<sub>x</sub> in the vicinity of Horsepool and Castle Peak originates almost entirely from oil and gas activity. The 4<sup>th</sup>-highest daily maximum ozone values at Horsepool and Roosevelt were similar during winter 2018-19 (Table 2-2), while Horsepool ozone tended to be higher in previous winters (see previous annual reports). Section 4 discusses inter-annual changes in ozone precursor concentrations at these two sites.

The difference between daytime and nighttime ozone was greater in Roosevelt than at Horsepool and Castle Peak during winter 2018-19 (Figure 2-20), as has been observed in previous winters, likely because high NO<sub>x</sub> reacted with and destroyed ozone at night. In other words, the air at the Roosevelt site has more NO<sub>x</sub> than is needed for ozone production, and this excess NO<sub>x</sub> reacts with ozone at night, which can suppress ozone concentrations.
Figure 2-19. Hourly average ozone measured at Roosevelt, Horsepool, and Castle Peak during winter 2018-19.

Figure 2-20. Average ozone at Roosevelt, Horsepool, and Castle Peak during each hour of the day during inversion episodes that occurred during winter 2018-19. Whiskers represent 95% confidence intervals.

NOx concentrations were higher at Castle Peak than at Horsepool (Figure 2-17), in contrast to winter 2017-18 (when NOx was similar at both sites). NOx at Roosevelt exhibited a pronounced peak in the morning and a lesser peak in the late afternoon and early evening, probably due to morning and afternoon peaks in local traffic (Figure 2-21). Horsepool and Castle Peak did not show a pronounced peak. Instead, NOx at these sites built up slowly during the night and had a maximum in mid-morning, probably because the majority of NOx emissions at the sites were due to stationary, continuous sources, rather than traffic-related sources.
In contrast with NO\textsubscript{x}, methane was slightly higher at Horsepool than in Roosevelt (Figure 2-22; Horsepool methane was 9% higher), which is likely because more oil and gas sources, which emit methane, were near the Horsepool site. Total NMHC was not significantly different at Horsepool and Roosevelt (Figure 2-23).
Figure 2-23. Hourly average total NMHC measured at Roosevelt and Horsepool during winter 2018-19. ppmC is parts-per-billion of carbon atoms. Total NMHC in this figure was measured without speciation by methane/total NMHC analyzers (methods are described in Section 2.2.3).

2.3.4. Speciated Volatile Organic Compounds

As in previous years, organic compounds in the atmosphere at Roosevelt and Horsepool were dominated by alkanes, especially lighter alkanes (Figure 2-24 and Figure 2-25). Benzene, toluene, and xylenes were low, and C8 and larger aromatics were rarely observed. The organic compound speciation at both sites was similar, indicating that the two locations were influenced by the same general source type (oil and natural gas production).

Figure 2-24. Percent by volume of measured organics at Horsepool and Roosevelt measured during winter 2018-19 that were comprised of alkanes, alkenes, aromatics, and alcohols.
Hydrocarbon concentrations at Roosevelt and Horsepool generally tracked each other, with higher concentrations during inversion episodes, as was observed for other pollutants (Figure 2-26; also see Figure 2-18 and Figure 2-22). Total NMHC (measured as the sum of individual compounds measured in silonite-coated canisters. See Section 2.2.3 for more information) was 55% higher at Roosevelt than Horsepool, a statistically significant difference. Concentrations of pollutants at Horsepool have been decreasing year-upon-year, while pollution levels at Roosevelt have either stayed the same or increased. Inter-annual trends at the two stations are discussed in detail in Section 4.

Compared to Horsepool, NMHC in Roosevelt tended to include a slightly larger proportion of C5-C8 hydrocarbons. While the differences were small (see Figure 2-25), they were meaningful, and ratios of different compounds can be used to identify pollution from the two stations. Figure 2-27 shows an example of this, and more examples were given in previous annual reports (Lyman et al., 2017a; Stoeckenius et al., 2014).
Figure 2-27. Heptane versus toluene at Horsepool and Roosevelt.
3. Summertime Air Quality

Author: Huy Tran

The Uinta Basin had a quiet summer ozone season in 2019, with no exceedances of the U.S. Environmental Protection Agency (EPA) standard for ozone (Figure 3-1). The daily maximum 8-hr ozone concentration came close to the 70 ppb standard on several days (e.g., 23 May, 3 July), but we did not find evidence of influence from stratospheric ozone or wildfires on those days.

![Graph showing daily maximum 8-hr ozone concentrations](image)

Figure 3-1. Daily maximum 8-hr ozone concentrations measured at Dinosaur (DINO), Myton (MYTON), Ouray (OURAY) Roosevelt (ROOSE), Vernal (VERNA), Whiterocks (WHITE), and Red Wash (REDWA) from 1 May to 31 August 2019.

A number of ozone exceedances occurred during the previous summer (2018). Some of these exceedances were clearly due to wildfires, but the sources of others were more difficult to interpret. See Section 3 of Lyman et al. (2018a) for more information about ozone during summer 2018. EPA allows for ozone exceedances caused by influences reasonably outside of regulatory control to be classified as exceptional events, meaning that they are not included in regulatory decisions about non-attainment. To receive exceptional event designation, regulatory agencies are required to submit detailed documentation about the sources of ozone on proposed exceptional event days. Because of high ozone during winter 2018-19, it is very unlikely that the summer 2018 exceedance days will affect the non-attainment designation that will be made in 2021, and further analysis of these days is probably unnecessary. More information about the upcoming 2021 non-attainment designation is available at the end of Section 2.3.1.
4. Long-term Trends in Wintertime Air Chemistry

Author: Seth Lyman

We began measurements at the Horsepool and Roosevelt monitoring stations during winter 2011-12 to provide a long-term record of key chemical and physical characteristics of wintertime ozone. Section 2.3.3 presents a comparison of the two sites for the most recent winter season. Sections 2.3.1 and 2.3.2 show and discuss the long-term record of ozone and PM$_{2.5}$ as measured at these sites and other sites around the Uinta Basin. This section provides a more in-depth analysis of the entire record of data at the Horsepool and Roosevelt sites. The oil and gas industry and other sources of ozone-forming emissions in the basin change with time due to economic, technological, and regulatory drivers, and we attempt here to discern how those changes affect ozone and precursor concentrations in the Uinta Basin atmosphere. This section builds on the work described in Section 4 of Lyman et al. (2018a).

Measurement methodologies for the parameters presented in this section are discussed in Section 2.2.

In recent winters, maximum ozone levels and the number of exceedance days have been fewer than when ozone measurements first began in the basin (see Figure 2-12 and Figure 2-13). Inversion characteristics vary dramatically year-upon-year, however, making it impossible to determine, using ozone data alone, whether changes in maximum ozone from year to year are due to meteorological changes or changes in precursor emissions. Instead, in this section, we investigate changes in ozone precursor concentrations to determine how precursor emissions have changed over time. An analysis of how ozone concentrations may be changing over time is presented in Section 12.4.

Like ozone, precursor concentrations depend on meteorological conditions as well as emission rates, and interannual variations in meteorology confound attempts to observe how changes in emissions impact atmospheric concentrations. Pollutants tend to build up under low wind conditions and dilute out under high wind conditions. Also, during winter inversion episodes, pollutants become trapped near the surface. The level to which pollutant concentrations build under an inversion depends on the inversion’s spatial distribution, intensity, and duration, all of which can vary dramatically from episode to episode.

We tested several methods to account for meteorological impacts on ozone precursor concentrations, including (A) exclusion of data collected during ozone-forming winter inversions (defined here as periods with daily maximum hr-average ozone greater than 60 ppb), (B) multiplication of measured pollutant concentrations by wind speed to account for wind effects, (C) exclusion of data with low or high wind speeds, and (D), combinations of A, B, and C. Results varied among the methods used, but correlations with oil and gas industry data were strongest when we used method A. We tested a version of method A that used 50 ppb as the cutoff ozone value, but the results were similar.

Figure 4-1 shows trends in NO$_y$ for the Horsepool and Roosevelt stations. We show NO$_y$, rather than NO$_x$, since photochemical activity can convert some NO$_x$ to NO$_y$, making NO$_y$ more representative of the total amount of reactive nitrogen compounds emitted into the atmosphere. The figure shows that seasonal average NO$_y$ at Roosevelt increased from 2012 to 2014, remained relatively constant from 2014 through 2019, and increased again from 2018 to 2019. NO$_y$ at Horsepool, on the other hand, has declined significantly since 2012. Average NO$_y$ at Horsepool during the 2017-18 and 2018-19 winters was only 57% of average NO$_y$ during the 2011-12 and 2012-13 winters.
We investigated relationships between trends in NO\textsubscript{y} and trends in potential drivers of reactive nitrogen emissions, including basin-wide oil and gas production, county-level oil and gas production, and changes in population. Horsepool season-average NO\textsubscript{y} was well correlated with Uintah County gas production and basin-wide gas production ($r^2 = 0.71$, $p = 0.01$ for Uintah County; $r^2 = 0.70$, $p = 0.01$ for basin-wide). Roosevelt season-average NO\textsubscript{y} was correlated with Duchesne County oil production ($r^2 = 0.52$; $p = 0.04$). The eastern side of the Uinta Basin, where Horsepool is located, is dominated by gas production, and gas production during the 2017-18 and 2018-19 winters was only 60% of production during winters 2011-12 and 2012-13. This decrease in activity may be the primary cause of the observed NO\textsubscript{y} decrease at Horsepool. Oil production is dominant in the western Uinta Basin, where Roosevelt is located. As Figure 4-1 shows, oil production has been variable but has increased overall from 2012 to 2018. Season-average NO\textsubscript{y} at the two sites was not correlated with population.

Trends in organic compound concentrations at the two monitoring stations were similar to NO\textsubscript{y} trends. Figure 4-2 shows inter-annual trends in season-average total NMHC, ethane, and toluene at Roosevelt and Horsepool. At Roosevelt, concentrations of these compounds have been relatively constant since winter 2012-13, except that a large increase occurred in the 2018-19 winter. Concentrations have declined at Horsepool. Horsepool total NMHC during the two most recent winters was only 62% of values during the two earliest winters for which we have data. Since Roosevelt NMHC have increased as...
Horsepool values have declined, season-average total NMHC at Roosevelt is now 36% higher than at Horsepool.

Figure 4-2. Average total NMHC, ethane, and toluene at Roosevelt (top panel) and Horsepool (bottom panel) for each winter season (15 November through 31 March). Values are averages for the entire winter season, except that values during winter inversion episodes (days with maximum 1-hr average ozone greater than 60 ppb) are not included. Whiskers show 95% confidence intervals. 2012 and 2014 organic compound data at Horsepool were collected by Jessica Gilman of the National Oceanic and Atmospheric Administration.

While NO\textsubscript{x} and NMHC were higher at Horsepool when data collection began, they are now both higher at Roosevelt. During winter 2012-13, a year with many inversion episodes, the highest ozone was always observed at measurement stations in the eastern Uinta Basin, including Ouray, Seven Sisters, and Horsepool (see, for example, Figure 4-3). During winters 2016-17 and 2018-19, the most recent winters during which elevated wintertime ozone was observed, the spatial distribution of ozone appears to have changed, with high ozone distributed throughout the central Uinta Basin (Figure 4-4 and Figure 2-6). Since the spatial distribution of inversion conditions can be different for each episode and is not uniform across the Basin, these figures do not provide definitive evidence, but they provide an indication that the areas of highest ozone may be changing as petroleum production in the basin shifts to the west.
Figure 4-3. Maximum 8-hr average ozone concentrations for all sites in the Uinta Basin, 26 January 2013. The black line on the color scale indicates 75 ppb.

Figure 4-4. Daily maximum 8-hr average ozone on 1 February 2017. The black line on the color scale indicates 70 ppb.
5. Ambient Organic Compounds Measured in a Transect Across the Uinta Basin

Authors: Seth Lyman, Makenzie Holmes, Huy Tran, Trang Tran

5.1. Introduction

Official inventories of oil and gas-related emissions in the Uinta Basin are uncertain, and emissions measurements of local oil and gas sources are needed to reduce uncertainty and improve emissions estimates. Direct emissions measurements are labor-intensive and expensive, however (Section 6 provides information about a direct measurement study we participated in). Ambient measurements of ozone precursors can be collected more quickly and easily than direct emissions measurements and can provide indirect information about emission sources. For this project, we measured organic compound concentrations at fourteen locations in a transect across the Uinta Basin. We are using the collected data to determine how the current oil and gas emissions inventory for the Uinta Basin compares against measured organic compound concentrations. We are doing this by (1) comparing measurements against proximity to different types of oil and gas facilities, and (2) performing inverse modeling with three-dimensional photochemical models and the current emissions inventory for the Uinta Basin. Inverse modeling is a technique wherein modeled emissions are adjusted to minimize differences between measured and modeled organic compound concentrations. These analyses are allowing us to determine source types and/or geographical areas where more measurements are needed to improve the inventory.

This section discusses our work on this project thus far. Additional work is underway, as discussed in Section 17.16.

5.2. Methods

We deployed fourteen sample collection stations in a transect across the Uinta Basin from east to west (Figure 5-1). The stations were surrounded by an array of oil and gas operations, with facilities including but not limited to oil wells, gas wells, gas wells with glycol dehydrators, gas plants, compressor stations, and produced water ponds. Four of the measurement stations included comprehensive meteorological measurements, including wind speed, wind direction, ambient temperature, barometric pressure, and relative humidity. The other stations measured only temperature and humidity. Not every station collected a valid sample during each deployment.
The stations collected whole-air samples in silonite-coated stainless steel canisters, and we analyzed these for a suite of 57 ozone-forming organic compounds, including alkanes, alkenes, acetylene, aromatics, and alcohols. We used an Entech 7200 preconcentrator and 7016D autosampler to cryogenically concentrate organic compounds and introduce them to a Shimadzu GC-2010 gas chromatograph (GC) system for analysis. The GC system uses a flame ionization detector (FID) and a mass spectrometer (MS) to detect the target compounds (Lyman et al., 2018b). Duplicate samples were $1 \pm 1\%$ different (average ± standard deviation), blank checks contained $0.05 \pm 0.01$ ppb of the measured compounds, and calibration checks recovered $90 \pm 1\%$ of injected compounds.

The stations also collected carbonyls by passing air through trans-1,2-bis-(4-pyridyl) ethylene/2,4-dinitrophenylhydrazine (BPE-DNPH) cartridges. These cartridges retain carbonyl compounds but allow other compounds to pass through. We analyzed BPE-DNPH cartridges following Uchiyama et al. (2009). We kept used and unused BPE-DNPH cartridges refrigerated or on ice, except when installed for sampling. We analyzed cartridges within 14 days of sampling. To prepare samples for analysis, we flushed cartridges with a 5 mL solution of 75% acetonitrile and 25% dimethyl sulfoxide to release DNPH-carbonyls into solution. We collected the solution into 5 mL volumetric flasks and brought the flasks to a volume of 5 mL using 0.5-1 mL of the acetonitrile/dimethyl sulfoxide solution. Finally, we pipetted a 1
mL aliquot from the 5 mL flask into a 1.5 mL autosampler vial for analysis by High-Performance Liquid Chromatography (HPLC). We analyzed samples using a Hewlett Packard series 1050 HPLC with a Restek Ultra AQ C18 column and a diode array detector. We used a mixture of acetonitrile and water as the eluent. We prepared standards by diluting commercially available carbonyl-DNPH standards, and we calibrated the instrument on each analysis day with a five-point calibration curve. We ran an additional standard at the beginning and end of each analysis batch to check for retention time drift or other errors. Duplicate samples were $2 \pm 9\%$ different, blank checks were $0.03 \pm 0.01$ ppb, and calibration checks recovered $99 \pm 1\%$ of injected compounds.

5.3. Results

5.3.1. Impact of Inversion Conditions on Organic Compound Concentrations

Samples collected during the inversion episode that occurred from 23 February to 28 February 2019 revealed that organic compound levels were significantly elevated during the episode in comparison to samples taken outside of inversion periods, as others have shown (Lyman and Tran, 2015a). Samples collected during an inversion on 27 February had organic compound concentrations that were 8.7 times higher, on average, than during the 17 April deployment, which did not have inversion conditions (Figure 5-2). Helmig et al. (2014) found that alkane concentrations during inversions were consistently at least two times higher than periods without inversions, leading to higher ozone production rates.
Figure 5.2. Organic compound concentrations at all measurement stations on 27 February 2019 during an inversion episode (top panel) and on 17 April 2019 when snow had melted and no inversion existed (bottom panel). Stations in the figure are arranged from west to east (Figure 5-1). Blank spaces exist because some samples failed to collect at some stations.

5.3.2. Composition of Measured Organic Compounds

Figure 5-3 through Figure 5-7 show the composition of organic compounds at each measurement station for each deployment period. In general, alkanes comprised the dominant portion of total organics at the stations. At some measurement stations, alkenes and acetylene comprised a large portion of total organics. This was usually the case at the C1 station, and it was the case at almost all the stations on 15 March (Figure 5-6). It is not clear why alkenes comprised such a large portion of total organics on 15 March. Very small amounts of alkenes and acetylene are emitted from non-combustion oil and gas sources like tanks and raw gas leaks (Section 6), but combustion processes are the most important sources of these compounds. It is possible that a large fire or flare influenced organic compound concentrations across the basin on 15 March. If so, we expect the event to have occurred in the vicinity of the COR station, since it had a total alkene+acetylene concentration of 5700 ppb and a total alkane concentration of 989 ppb, which was much higher, and with a much larger proportion of alkenes, than any other station. Incident records from emergency response agencies in the Basin did not reveal any
combustion incident that could reasonably have led to the organic compound composition measured at station C0R on 15 March.

Figure 5-3. Composition (percent by volume) of organic compounds measured at stations in a transect across the Uinta Basin on 23 February 2019 from 10:00 to 16:00.
Figure 5-4. Composition (percent by volume) of organic compounds measured at stations in a transect across the Uinta Basin on 25 February 2019 at 22:00 to 26 February 2019 at 4:00.

Figure 5-5. Composition (percent by volume) of organic compounds measured at stations in a transect across the Uinta Basin on 27 February 2019 from 10:00 to 16:00.
Figure 5-6. Composition (percent by volume) of organic compounds measured at stations in a transect across the Uinta Basin on 15 March 2019 from 10:00 to 16:00.

Figure 5-7. Composition (percent by volume) of organic compounds measured at stations in a transect across the Uinta Basin on 17 April 2019 at 22:00 to 18 April 2019 at 4:00.
Figure 5-8 shows the average composition of organic compound groups at stations that had valid measurements for at least three of the deployments. Data for 17 April were not used to derive the averages in Figure 5-8 because emissions of organics may be different in winter versus spring. Including data from 17 April did not change the general trends in Figure 5-8. Data from Roosevelt and Horsepool from transect deployment days are also included in the figure even though we did not measure carbonyls at those stations.

With the exception of Roosevelt, the average volume-based organic compound composition at all the stations in the western and central Uinta Basin contained at least 10% alkenes+acetylene, while the percentage of alkenes+acetylene was lower, on average, in the eastern Uinta Basin. Compared to most other organic compounds, alkenes are extremely reactive, meaning that a given amount of these compounds is able to produce more ozone than a given amount of most other organics.

The impact of an organic compound on ozone formation can be estimated in computer models by changing the mass of that compound emitted in the model and recording the modeled change in ozone mass in the atmosphere. The amount of ozone produced per amount of organic compound emitted when other modeled conditions are optimized for ozone production is called maximum incremental reactivity (MIR) (Carter, 2009). MIR can be used to compare the ability of different compounds to produce ozone. For example, the MIR of ethane derived by Carter (2009) is 0.28 (meaning that a given mass of ethane can produce 28% of that mass of ozone in ideal conditions). In contrast, the MIR of ethylene for the same conditions is 9.00, 32 times higher than ethane. MIR values can also be applied to concentrations of individual compounds measured in ambient air to obtain MIR-weighted composition information.
We used MIR values from Carter (2009) to scale the data presented in Figure 5-8 by MIR, and the results are presented in Figure 5-9. The Carter (2009) MIR values were developed for urban, summertime ozone. Carter and Seinfeld (2012) calculated incremental reactivities for winter ozone episodes in Wyoming in 2008, but these values were not maximum incremental reactivities, but instead incremental reactivities for specific, unique episodes that were different chemically from winter ozone episodes in Utah. Also, for some iterations of their modeling exercise, Carter and Seinfeld (2012) assumed very high concentrations of HONO, which was thought at the time to accurately represent reality (Rappenglück et al., 2014), but which we now know to be incorrect (Stoeckenius, 2015).

Figure 5-9 shows that alkenes are very important contributors to ozone production, particularly in the western and central Uinta Basin. On average, alkenes and alkynes constitute 55% of MIR-adjusted organic compound composition at western and central stations (C0 to C7) and 16% at eastern stations (M1 to C6). In contrast, Figure 5-8 shows that their actual composition, without consideration for MIR, was only 17% and 6% for western/central and eastern stations, respectively. Because alkenes are so reactive, they are especially important for ozone production, and reducing emissions from the sources of these compounds will likely be effective at reducing ozone.

![Figure 5-9. Average composition (percent by mass) of measured organic compounds at measurement stations multiplied by compound-specific incremental reactivities (Carter, 2009) and grouped by compound type. Stations in the figure are arranged from west to east. Only stations with at least three valid measurement days, excluding 17 April, are included in the figure.](image)

5.3.3. **Clues to the Source of Alkenes in the Western Uinta Basin**

The source of alkenes in the western and central Uinta Basin is not known with certainty, but it is expected that they are emitted from some kind of combustion source since no non-combustion sources are known to emit a high proportion of alkenes. In the following sections, we present here some evidence about what that source may be.

5.3.3.1. **Spatial Distribution**

We have shown previously that emissions from oil wells in the Uinta Basin tend to have higher heptane:toluene ratios than emissions from gas wells (Stoeckenius et al., 2014), and the
heptane:toluene ratio is an indicator of whether organics in ambient air were emitted from oil or gas production. Figure 5-10 shows the average heptane:toluene ratio for the stations shown in the previous figures. The western stations (C0 through C8) have relatively high heptane:toluene ratios, and the eastern stations (M1 through C6) have relatively low ratios, which is to be expected because oil development is predominant in the west, and gas development is predominant in the east. The heptane:toluene ratio at the C7 station is intermediate between the western and eastern stations, even though it is surrounded by gas wells. It is possible that, since winds blow predominantly from the west in the Basin, C7 is influenced more by emissions to the west of it than by emissions in its immediate vicinity.

Figure 5-10. Ratio of heptane to toluene (ppb:ppb) at measurement stations. Stations in the figure are arranged from west to east. Only stations with at least three valid measurement days, excluding 17 April, are included in the figure. Whiskers show standard deviation.

Figure 5-8 shows that Roosevelt was unique among measurements in the western basin in that its composition was relatively low in alkenes. Roosevelt is different from the other sites because it is urban, but it is also different because most or all of the oil wells in the Roosevelt area have electric motors, rather than natural gas-fueled engines, to power the pumps that draw oil from the ground. Most of the oil wells throughout the Basin, including those that are electrified, burn natural gas in heaters that keep separators, tanks, and other well pad equipment warm. Gas wells usually don’t have well pumps, so they don’t need engines or motors, but they do have heaters to keep equipment warm. Thus, while most wells around the Uinta Basin burn natural gas, only oil wells without electricity have natural gas-fueled engines. Compressor stations and some other oil and gas-related facilities also have natural gas-fueled engines. The map in Figure 5-11 shows that natural gas-fired engines are spatially associated with the stations that had a high percentage of alkenes in ambient air samples. Since natural gas-fueled heaters are ubiquitous at all oil and gas wells in the Uinta Basin, and since natural gas-fueled engines are only common in the areas of the Basin that tend to have elevated concentrations of alkenes in ambient air (with the exception of C7), we hypothesize that natural gas-fueled engines are an important source of alkenes. 98% of stationary engines in the Uinta Basin are natural gas-fueled (UDAQ, 2018).
5.3.3.2. Emission Ratios

Hesterberg et al. (2008) showed that, compared to uncontrolled diesel-fueled engines, uncontrolled natural gas-fueled engines have higher propylene:ethylene ratios (0.07 vs 0.28). 95% of natural gas engines in the Uinta Basin do not have emissions control equipment (UDAQ, 2018). In addition to having higher propylene:ethylene ratios, natural gas engines produce much more ethylene and propylene than diesel engines (17 times as much ethylene and 69 times as much propylene (Hesterberg et al., 2008)). Emissions from all engines typically contain acetylene in addition to ethylene and propylene. Ethylene:acetylene and propylene:acetylene ratios from vehicle emissions are usually in the range of 1-3 and 0.5-1.5, respectively (Lai and Peng, 2012; Poulsen and Wallace, 1994; Ryerson et al., 2003). Emissions profile information from EPA for natural gas engines shows an ethylene:acetylene ratio of 2.0 (EPA, 2018; Oliver and Peoples, 1985).

Figure 5-12 shows a plot of the relationship between ethylene and propylene in all measurements collected during this study. The two compounds were strongly correlated ($r^2 = 0.99$ for conventional Pearson correlation; $r^2 = 0.90$ for Spearman rank correlation), which indicates that they had a common source type. The slope of the relationship shown in Figure 5-12 is 0.65, higher than the 0.28 ratio measured by Hesterberg et al. (2008). Ethylene and propylene can be generated from the combustion of methane or from combustion of ethane and propane (Ranzi et al., 1993). The raw gas used in oilfield engines is richer in propane than the purified natural gas used by Hesterberg et al. (2008), and this additional propane could preferentially convert to propylene, explaining the difference between the two studies.
Ethylene and propylene exceeded 10 ppb in many measurements and comprised an average of 76% of all alkenes and alkynes. In contrast, only one acetylene measurement exceeded 5 ppb. Acetylene was not significantly correlated with ethylene and propylene, indicating that the compounds likely came from different sources. We hypothesize that in addition to a combustion source type that emits mostly ethylene and propylene, other, lower-emitting combustion sources exist that also emit these compounds, acetylene, and probably larger alkenes that were also observed in ambient air samples. Though ethylene and acetylene were not correlated, ethylene was 19.8 times more abundant than acetylene (average of all measurement stations in the study), a value much higher than would be expected for emissions from engines.

High ethylene and propylene concentrations and a large propylene:ethylene ratio indicate that the likely source of most of the alkenes observed in this study was combustion of natural gas. The lack of correlation of ethylene and propylene with acetylene implies that acetylene comes from a different source (or a mixture of sources). We could not find any studies of emissions from engines that burn raw gas, and it is possible that emissions from raw gas engines have lower acetylene than emissions from other engines. Lean-burning (Nine et al., 1997) and cooler engines (Russ et al., 1995) tend to produce emissions with a lower acetylene:ethylene ratio. 73% of natural gas-fueled engines in the 2014 Utah Air Agencies Emissions Inventory are categorized as lean burning (UDAQ, 2018). Catalytic converters scrub acetylene more efficiently than ethylene (Lai and Peng, 2012), which would also lower the acetylene:ethylene ratio, but, as mentioned above, the Utah Air Agencies inventory lists almost all natural gas engines in the Uinta Basin as “uncontrolled.”

Emission plumes from the Houston petrochemical industry are dominated by ethylene and propylene, with little acetylene (Jobson et al., 2004; Ryerson et al., 2003; Washenfelder et al., 2010; Wood et al., 2012), and could shed light on the similar emissions speciation observed in this study. The exact source of the emissions from Houston petrochemical facilities is not clear, however. Some of the petrochemical facilities in the Houston area produce ethylene as a chemical feedstock, and ethylene leaks from these facilities could be the dominant source of ethylene. Petrochemical facilities also use flares, and incomplete combustion from flares could be a source of ethylene and propylene. Flares or combustors at wells and other facilities in the Uinta Basin could be a source or the primary source of

---

**Figure 5-12. Ethylene versus propylene in all transect measurements. Both axes are shown in log scale.**
ethylene and propylene in the western and central Uinta Basin. However, flares typically emit acetylene in addition to ethylene and propylene. Emissions profile information from EPA for natural gas flares shows an ethylene:acetylene ratio of 0.5 (Allen and Torres, 2011; EPA, 2018), much lower than what was observed in our ambient air samples.

5.3.3.3. **Samples with Very High Alkene:Alkane Ratios**

Figure 5-13 shows a plot of total alkanes against total alkenes+acetylene for all samples collected. Most of the measurements exhibited a weak relationship between the two compound groups. A subset of samples, however, had especially high alkene:alkane ratios and formed a different trend. These samples are labeled in the figure by station name and date. The C1 station was consistently part of this group. C0R and C3 both had high alkene:alkane ratios on 15 March, and C9 and C7 had high alkene:alkane ratios on 27 February and 25 February, respectively. While the correlation between ethylene and propylene is consistent throughout the dataset (Figure 5-12), enhanced alkene:alkane ratios appear in only these few samples, implying that they may have unique, and possibly intermittent, sources.

![Figure 5-13. Total alkanes versus total alkenes+alkyne in all transect measurements. Measurements with an alkene+alkyne-to-alkane ratio greater than 0.41 are labeled with the site name and measurement date.](image)

5.3.3.4. **Summary**

Alkene concentrations in some parts of the Uinta Basin make up more than 10% of total organics. These highly reactive compounds are very important for winter ozone production. We are somewhat certain that the important sources of alkenes are raw natural gas combustion devices, but it is unclear which combustion devices are responsible. Our best guess is that the source is natural gas-fueled engines (which are mostly engines for pumps at oil wells), though very high ethylene:acetylene ratios in ambient air samples compared to the expected emissions composition leave some room for doubt. More work, and probably direct emissions measurements, will be needed to pinpoint the source(s) of these emissions.
5.4. Future Work

A second phase of this project has received funding from the Utah Division of Air Quality, with additional funds provided by the Utah Legislature. This continuation project is described in Section 17.16.
6. **Project Summary: Composition of Organic Compound Emissions from Oil and Gas Wells**

Authors: Trang Tran, Seth Lyman

6.1. **Introduction**

Regulatory agencies, industry, and academic researchers have worked for the past nine years to better understand organic compound emission rates and composition from oil and gas facilities and equipment in the Uinta Basin. These efforts have included top-down estimates of whole-basin emissions (Ahmadov et al., 2015; Foster et al., 2017; Karion et al., 2013), various facility-level and equipment-level emissions measurement campaigns (Lyman and Tran, 2015b; Lyman and Mansfield, 2018; Lyman et al., 2018b; Lyman et al., 2017b; Mansfield et al., 2018; Robertson et al., 2017; Tran et al., 2017; Warneke et al., 2014), intercomparisons of modeled and measured emissions (Ahmadov et al., 2015; Edwards et al., 2014; Mansfield, 2014; Matichuk et al., 2017; Tran et al., 2014) and emissions inventory efforts (Lyman et al., 2013; Stoeckenius, 2015; UDAQ, 2018). These efforts have filled in knowledge gaps and allowed industry and regulators to develop emissions reduction strategies that are based on sound scientific information.

We have participated in a new effort to improve estimates of the speciation of organic compound emissions from Uinta Basin oil and gas wells. This effort, led by the Utah Division of Air Quality (UDAQ) entailed:

*Work completed by Alliance Source Testing (AST):*
1. Collection and analysis of pressurized gas and liquid samples from separators at oil and gas wells, and data analysis and modeling to determine the hydrocarbon compositions of raw gas and flash gas (flash gas is the vapor emitted when liquid petroleum samples are depressurized and/or heated).

*Work completed by Utah State University:*
2. Collection of pressurized liquid samples from ten oil and gas wells, followed by laboratory analysis to determine the carbonyl compound composition of flash gas.
3. Use of composition data to develop speciation profiles that can be used in air quality modeling.
4. Direct, speciated organic compound emissions measurements from some of the same wells at which pressurized gas and liquid samples were collected.

A final report of this work will be released by UDAQ before the end of the year. When it is released, it will be available at [https://binghamresearch.usu.edu/reports](https://binghamresearch.usu.edu/reports). In this section, we provide a brief summary of and example figures from the study.

6.2. **Carbonyl Speciation in Flash Gas**

We collected fifteen pressurized liquid samples from separators at six oil and five gas wells (one sample from each well, as well as four additional quality control samples). The wells at which we collected these samples were a subset of the wells from which raw gas and pressurized liquid samples were
collected and analyzed by AST. We analyzed the pressurized liquid samples for flash gas content following PS Memo 17-01 from the Colorado Department of Public Health and Environment, *Flash Gas Liberation Analysis Method for Pressurized Liquid Hydrocarbon Samples* (CDPHE, 2017). We analyzed BPE-DNPH cartridges following the method described in Section 5.2.

Figure 6-1 shows the relationship between the gas-oil ratio determined from our laboratory measurements compared to the ratio calculated by AST, and Figure 6-2 shows the relative concentrations of different carbonyl compounds in flash gas from oil wells. A complete analysis of this work will be available in the final project report.

![Figure 6-1. Comparison of gas-oil ratios of flash gas measured from pressurized liquid samples we analyzed in our laboratory and gas-oil ratios modeled by AST in units of standard cubic feet per barrel. The linear regression equation and $r^2$ value of the relationship are shown.](image)

![Figure 6-2. Average carbonyl composition of gas flashed from oil samples.](image)
6.3. Development of Speciation Profiles

The overall goal of this study was to develop raw and flash gas organic compound speciation profiles for wells producing oil and gas from several geological formations, based on hydrocarbon and carbonyl composition measurements. These speciation profiles consist of the average weight percent of the compounds and compound groups analyzed by AST, and the average weight percent of 11 carbonyls and carbonyl groups we analyzed (when those data were available), averaged by formation. We created speciation profiles for different geological formations, well types (oil or gas), and gaseous emission sources (raw gas or flash gas). We will use the developed profiles to speciate total organic compound emissions from oil and gas production for photochemical modeling of Uinta Basin winter ozone.

Figure 6-3 shows flash gas emissions composition for several geological formations from which oil and gas wells in the Uinta Basin produce. We used maximum incremental activity information (Carter, 2009) for the individual compounds represented in the composition data to determine whether emissions from some well types (oil vs. gas) or formations were more reactive (i.e., more able to produce ozone) than others. Figure 6-4 shows the results of these calculations. It shows that flash gas from oil wells is more reactive than flash gas from gas wells.

![Figure 6-3. Formation-averaged hydrocarbon composition of flash gas. GR is the Green River formation, GRWA is Green River-Wasatch (multiple profiles exist), WA is Wasatch, MV is Mesa Verde, and WAMV is Wasatch-Mesa Verde (multiple profiles exist).](image-url)
Figure 6-4. Ozone that would be formed from emissions of 100 g of total organics from the flash gas speciation profiles indicated. The leftmost six bars are profiles for oil wells, and the rightmost two bars are profiles for gas wells. These values were calculated by multiplying the weight percentage of each compound or compound group in each profile by the maximum incremental reactivity for that compound or group (Carter, 2009).

We processed these organic compound speciation profiles with Speciation Tool 4.0 (SPTOOLv4.0) (Jimenez et al., 2016) to create SPECIATE organic compound profiles that can be utilized by the Sparse Matrix Operator Kernel Emissions Model (SMOKE) and are compatible with Carbon Bond 6 (CB6) chemistry in the Comprehensive Air Quality Model with extensions (CAMx). A full report of this work will be available in the final project report.

6.4. Direct Measurements of Emissions from Oil Wells

We visited 24 oil wells in Duchesne County to detect and directly quantify organic compound emissions. Each of the wells we visited was a well at which raw gas samples and pressurized liquid samples were collected and analyzed by AST. We used a FLIR GF320 optical gas imaging camera to detect emissions at each well. If the source was accessible and safe, we used a high flow emissions measurement system to quantify organic compound emissions from the source. We developed a high flow emissions measurement system, diagrammed in Figure 6-5, to measure emissions for 76 individual organic compounds from oil and gas sources.
Figure 6-5. Diagram of the high flow measurement system.

We used a Los Gatos Research Greenhouse Gas Analyzer to measure methane and carbon dioxide concentrations in sample gas and background air. In addition to methane and carbon dioxide, we determined the emission rate of a suite of C2-C10 hydrocarbons, light alcohols, and carbonyls. For C2-C10 hydrocarbons and alcohols, we collected 6-L silonite-coated stainless steel canister samples. For carbonyls, we collected DNPH cartridge samples. We analyzed these samples as described in Section 5.2.

Emissions measured from liquid storage tanks tended to be higher than those from other sources (Figure 6-6). Emissions from tanks were from leaking thief hatches 83% of the time, and the other tank emissions were from pressure relief valves. We detected emissions from a vent at the center of the tank top at some other overflow tanks. These vents were inaccessible with the high flow system, and we did not quantify them.

We measured emissions from nine sources on separator equipment, including connections, pneumatic devices, valves, and regulators. We collected four measurements from well heads, including connections, a valve, and an actuator. We also measured emissions from other connections and equipment at the wells visited. We did not measure every observed emission source. We tried to obtain measurements from a variety of sources at many wells. The maximum number of emissions we quantified at any well was three.
The composition of emissions measured directly from oil tanks was different from the flash gas composition modeled by AST (Figure 6-7). While biases in the methods could have caused this discrepancy, but some or all of the difference could also be due to the fact that the two methods measured different phenomena. AST modeled flash gas emissions, or the release of gases from a liquid when the pressure of the liquid decreases or the liquid is heated. Our direct emissions measurements, on the other hand, likely included a combination of flash gas emissions and “breathing” emissions, or evaporation from liquid while it resides in a tank. We were not able to discern whether our tank emissions measurements occurred during periods when separators moved pressurized liquids into tanks (i.e., when they flashed). Additional information about these direct emissions measurements, and additional comparisons with other datasets, will be provided in the final project report.
Figure 6-7. Emissions composition by carbon number for oil tank emissions measured with the high flow system, flash gas modeled by AST. Only compounds included in all methods were used to make this figure. For the AST data, only data from wells sampled with the high flow system are included.

6.5. Acknowledgments

This work was funded by the Utah Division of Air Quality, the Uintah Impact Mitigation Special Service District, and the Utah Legislature.
7. Organic Compound Fluxes at the Air-Snow Interface

Authors: Marc Mansfield, Huy Tran, Seth Lyman

7.1. Introduction

Fluxes of compounds between the snow and the air are well documented in polar regions, and it is well appreciated that they have an important impact on the chemistry of the polar atmosphere (Grannas et al., 2007; McNeill et al., 2012). Appreciation is also growing that the snowpack plays a role in urban, temperate regions (Ariya et al., 2018; Kos and Ariya, 2010). In polar regions, carbonyls like formaldehyde and acetaldehyde form photochemically in the snow (Grannas et al., 2007; Grannas et al., 2004), and it is likely that this also happens in snowpacks in temperate environments.

During winter 2019, we made flux chamber measurements of the movement of organic compounds in and out of the snow at the Horsepool monitoring station. We collected measurements over twelve periods (usually three hours) during the months of January, February, and March. Eight measurement periods occurred during daylight hours, and four occurred in the nighttime.

7.2. Measurement Methods

Our flux chamber system was very similar to the system described by Lyman et al. (2017b) and Lyman et al. (2018b). We pressed a 41 cm diameter stainless steel ring into the snow and attached a transparent polymer dome to the ring. A pump pulled air through this chamber at 10 L min⁻¹, through a heated Teflon line, and into our measurement trailer. Another heated Teflon line pulled air from just outside the chamber into the measurement trailer. We collected air samples in silonite-coated stainless steel canisters (analyzed for a suite of hydrocarbons and light alcohols) and with dinitrophenylhydrazine-coated cartridges (analyzed for carbonyls) from each of these lines. We analyzed these samples by the methods presented in Section 5.2. We calculated fluxes of individual organic compounds as the difference between concentrations inside and outside the flux chamber, multiplied by the flow rate and normalized by the area covered by the chamber. Details about these calculations are available in Lyman et al. (2018b).

Because the production of carbonyls in snowpack is thought to require sunlight, we modified the chamber to allow transmission of a broader spectrum of light. We cut away most of the polycarbonate dome, leaving only four ribs. We covered the dome with a PTFE film of ~0.1 mm thickness. In field tests, this film allowed the passage of 80% of ambient ultraviolet light.

7.3. Flux Chamber Drawbacks

Flux chambers are useful for measuring emissions from soils, bodies of water, and snowpacks. However, they present some drawbacks. Flux chambers perturb flux measurements in at least two ways: First, they shield against the wind, which can be problematic because moving air is more efficient at removing compounds from snow, soil, or water than stagnant air. Second, they act as greenhouses, artificially heating the area under the chamber. This can also be problematic, especially for snowpacks at temperatures near 0°C, in which a slight temperature change may be enough to abruptly alter the
physical state of the snowpack, stimulating significant changes in the liquid content of the snow. As we argue below, this seems to be occurring in our measurements.

7.4. Greenhouse Heating Under the Flux Chamber

The greenhouse warming effect is explored in Figure 7-1. Insolation measures the amount of solar energy reaching Earth’s surface per unit area per unit time. Points at 0 insolation represent nighttime measurements, while during wintertime daylight hours insolation varies between about 200 to 700 W m⁻², depending on cloud cover. We measured three temperatures during each flux run: T₁₀, the air temperature at 10 meters above ground, Tₜ₀, the near-surface air temperature just outside the flux chamber, and Tᵢᵣ, the air temperature inside the flux chamber. Figure 7-1 shows that during daytime, the temperature differences ΔTᵢᵣ = Tᵢᵣ - T₁₀ and ΔTₜ₀ = Tₜ₀ - T₁₀ are correlated with the insolation. When no flux chamber is present, we expect the snow surface to undergo radiative heating, which then heats the air by convection facilitated by eddy diffusivity. Tₜ₀ is the best proxy we have in our measurements for the surface air temperature in the absence of the chamber, and the temperature difference Tₜ₀ > T₁₀ is consistent with this upward heat flux. When the chamber is present, it disrupts eddy diffusivity, preventing the escape of heat from under the dome, and Tᵢᵣ > Tₜ₀. Although the flux chamber is ventilated, the ventilation appears inadequate to allow Tᵢᵣ ≅ Tₜ₀. In the nighttime, the surface cools radiatively, leading to Tₜ₀ < T₁₀, usually by about 3° or 4° C, while we see Tᵢᵣ ≅ Tₜ₀, at least to a resolution of about 1° C. We also expect nighttime heat transfer between the surface and air to be mediated by convective flow that is impeded by the chamber, but either this flow is inherently weaker than in daytime, or the chamber ventilation is adequate to achieve Tᵢᵣ ≅ Tₜ₀.

![Figure 7-1](image)

**Figure 7-1.** Under conditions of strong insolation, a greenhouse effect leads to heating of the air under the dome of the flux chamber. Points at 0 insolation are nighttime data. All others are during daylight hours. ΔTᵢᵣ = Tᵢᵣ - T₁₀ and ΔTₜ₀ = Tₜ₀ - T₁₀, where T₁₀, Tₜ₀ and Tᵢᵣ are air temperatures at 10 meters, near the surface outside the flux chamber and inside the flux chamber, respectively.
Table 7-1 displays the temperature ranges of the chamber runs. Daytime chamber runs with $T_{in} > 0^\circ C$ are in the majority, while runs with $T_{out} < 0^\circ C$ are in the majority. As argued above, $T_{in}$ controls the process under the chamber, while $T_{out}$ is a better indicator of the physical state in the absence of the chamber. This probably means that during most of the chamber runs, greenhouse heating led to more rapid sublimation or melting than would have occurred without the chamber present.

Table 7-1. Temperature ranges in the chamber runs. $N$ indicates the number of runs in the categories indicated.

<table>
<thead>
<tr>
<th></th>
<th>Temperature range</th>
<th>$N$, $&lt; 0^\circ C$</th>
<th>$N$, $&gt; 0^\circ C$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Daytime runs</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$T_{in}$, °C</td>
<td>-0.4 to 9.9</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>$T_{out}$, °C</td>
<td>-5.2 to 2.4</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>$T_{10}$, °C</td>
<td>-10.2 to 2.9</td>
<td>7</td>
<td>1</td>
</tr>
<tr>
<td><strong>Nighttime runs</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$T_{in}$, °C</td>
<td>-14.9 to 0.4</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>$T_{out}$, °C</td>
<td>-15.2 to 0.4</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>$T_{10}$, °C</td>
<td>-11.9 to 0.6</td>
<td>4</td>
<td>0</td>
</tr>
</tbody>
</table>

7.5. Water Vapor Fluxes

Relative humidity was measured at 10 m during these flux chamber measurements, from which we calculated the 10 m absolute humidity. We also estimated the absolute humidity under the chamber by assuming that relative humidity was near 100% in the chamber because of close proximity to the snow surface. Then, based on the flow rate through the chamber, we estimated water vapor fluxes. These appear as a function of $T_{in}$ in Figure 7-2. In daylight hours, water vapor fluxes were correlated with temperature and were in the range of about +5 to +25 g m$^{-2}$ h$^{-1}$. Nighttime fluxes were much smaller and often negative. This indicates that sublimation and melting of the snowpack were occurring under the illuminated chamber. On the other hand, concurrent water vapor fluxes outside the chamber were probably much smaller, since $T_{out}$ was typically below $0^\circ C$. In all these measurements, daytime flux chamber results correspond to warm, melting and subliming snowpacks, and do not seem to represent conditions that would occur if the chamber were not present.
Figure 7-2. Fluxes of total non-methane hydrocarbons (TNMHC), alcohols (methanol and ethanol), and water vapor through the air-snow surface as measured by the flux chamber.
7.6. Hydrocarbon and Alcohol Fluxes

Figure 7-2 also displays fluxes of a number of hydrocarbon compounds, grouped together under the label of total non-methane hydrocarbons (TNMHC), and the combined fluxes of the alcohols methanol and ethanol. Daytime fluxes for both classes of compounds were almost always negative, while nighttime fluxes were almost always positive. This probably occurred because the greenhouse heating was increasing the liquid content of the snowpack, allowing it to dissolve more TNMHC and alcohols. By contrast, the temperature of the nighttime snowpack was below freezing, the liquid content was diminishing, and the snowpack was emitting TNMHC and alcohols.

7.7. Carbonyl Fluxes

Figure 7-3 displays fluxes of formaldehyde, acetaldehyde, and acetone. Unlike alcohols and TNMHC, for which we saw predominantly negative fluxes during the day and positive fluxes during the night, both day and nighttime fluxes fell in comparable ranges and were both positive or negative. (Fluxes for acetone were always negative.) It is possible that part of the difference was due to biases in the different analytical techniques used to measure carbonyls (HPLC vs. GC/MS), but the fact that daytime fluxes now seem to be elevated relative to nighttime ones may indicate photochemical generation of formaldehyde and acetaldehyde, which is known to occur in polar regions (Grannas et al., 2013; Grannas et al., 2002; Riedel et al., 2005). Because carbonyls have high ozone reactivity, this finding needs to be substantiated in further studies.
Figure 7-3. Fluxes of formaldehyde, acetaldehyde, and acetone through the air-snow interface as functions of temperature, as measured by the flux chamber.
7.8. Impacts of Organic Compounds from Snow on Ozone Chemistry

Based on snow flux measurements performed throughout winter 2019, we determined temperature dependences of the fluxes of formaldehyde, acetaldehyde, and acetone on surface temperature (as presented in Figure 7-3). Polynomial fitting equations for estimating fluxes of these compounds are as follows:

\[\text{Acetaldehyde} = -4 \times 10^{-5} \times T^2 - 4 \times 10^{-5} \times T + 0.0018\]
\[\text{Formaldehyde} = -2 \times 10^{-5} \times T^2 - 4 \times 10^{-4} \times T - 0.0008\]
\[\text{Acetone} = -3 \times 10^{-4} \times T^2 - 2.8 \times 10^{-3} \times T - 0.0012\]

where \(T\) is the temperature inside the chamber. Units for fluxes are mg m\(^{-2}\) hr\(^{-1}\).

To simulate air-snow fluxes in the Uinta Basin, we used the surface temperature and snow cover fraction that were simulated by the WRF model. Modeled snow cover determined the model gridded emissions as demonstrated below for formaldehyde:

\[\text{Gridded formaldehyde emissions} = (-2 \times 10^{-5} \times T^2 - 4 \times 10^{-4} \times T - 0.0008) \times \text{snow cover fraction} \times \text{area}\]

where \(\text{area}\) is the area of one grid cell, which equals to 1333 x 1333 m in our CAMx model configuration.

We set all negative fluxes to zero. We assumed that deposition of these compounds to the snow surface was handled adequately by the CAMx dry deposition module.

As shown in Figure 7-4, simulated emissions of formaldehyde, acetaldehyde, and acetone from snow were much lower than those from oil and gas activities in the Uinta Basin. Emissions from snow were higher at high than at low elevations, since much colder conditions were simulated by WRF for low elevations. Estimated emissions at Horsepool, where the measurements were collected, were often zero due to the persistent simulated low temperatures. Impacts of emissions of formaldehyde, acetaldehyde, and acetone from snow on simulated ozone production are discussed in Section 10.

Further improvements in characterizing emissions of these compounds from snow, both temporally and spatially, are needed. Our snow emissions simulations assume that fluxes of formaldehyde, acetaldehyde, and acetone depend only on surface temperature. If, as has been shown for the Arctic, fluxes of these compounds depend on sunlight as well, emissions may continue to increase at colder temperatures, rather than decrease, at least during daytime (daytime data in Figure 7-3 show increasing emissions of these compounds with decreasing temperature). A simulation that accounts for differences in temperature relationships between the daytime and nighttime flux data may result in higher emission rates of these compounds from snow.
Figure 7-4. Simulated emissions (mole hr⁻¹) of formaldehyde, acetaldehyde, and acetone from (left column) oil and gas and (right column) snow.
7.9. Summary

Daytime fluxes of hydrocarbons and alcohols were almost always negative, and nighttime ones were almost always positive. We have argued that the daytime behavior is an artifact of the greenhouse heating that usually produces temperatures above freezing. It is probably more representative of late-winter behavior when the snowpack is disappearing rapidly. At least for the measurements conducted this winter, temperatures outside the chamber were usually below freezing, meaning that the nighttime processes with positive fluxes might be more representative of behavior in the absence of the flux chamber.

Carbonyl fluxes did not follow the same pattern as the hydrocarbons and alcohols, which may mean that they were being produced photochemically in the snowpack, a process that has been well documented in polar regions (Grannas et al., 2004). If carbonyl production was occurring, it could have a meaningful impact on ozone formation in the Uinta Basin, since it would mean that organic compounds with relatively low ozone-forming potential were being converted into high-potential compounds. Such processes need to be substantiated in further studies, and air-snow processes such as these need to be incorporated into ozone models.

The net carbon budget must be balanced, so one could argue that the total carbon flux across the snow-air boundary must average to zero. On the other hand, other possible carbon sources and sinks probably exist. Organic compounds, either as aerosols or from the gas phase, may adsorb onto snowflakes as they grow and fall (Bartels-Rausch et al., 2014). (Some papers have argued that newly-fallen snow in polar regions is supersaturated with formaldehyde and HNO₃ (Dominé and Thibert, 1996; Houdier et al., 2002; Hutterli et al., 1999).) Any carbon that does not return to the atmosphere must wind up in liquid runoff or adsorb into the soil at the end of the season.
8. Meteorological Model Development - Investigating the Impacts of Observational Nudging With Sounding Data

Author: Trang Tran

8.1. Introduction

Meteorological models (our research team and regulatory agencies use the Weather Research and Forecasting (WRF) model) are an important component of photochemical modeling platforms. These models produce the meteorological fields that govern the formation and distribution of pollutants in photochemical simulations. It is critical that meteorological models produce correct meteorological conditions, especially for the study of winter ozone pollution in the Uinta Basin, because ozone production in the basin is directly dependent on a specific, local meteorological phenomenon—strong temperature inversions with snow cover. Unfortunately, mesoscale models like WRF still face many difficulties in simulating small-scale physical processes within inversion layers in the Uinta Basin. The most state-of-the-science modeling studies of winter ozone events in the Uinta Basin have shown that regular WRF physics configurations had problems fully representing some basic elements of inversion layer structure, including failing to capture the negative correlation between surface temperature and elevation, over-predicting warm clouds (i.e., clouds composed of liquid water droplets), under-predicting ice clouds (i.e., clouds composed of ice crystals), over-predicting planetary boundary layer height (i.e., the height of the inversion layer) and under-predicting inversion strengths. These are important meteorological conditions that need to be simulated more accurately to generate more reliable estimations of pollutant concentrations.

The motivation for the work described in this section is to improve WRF model simulations of inversion layer structure in the Uinta Basin using four-dimensional data assimilation, or “nudging.” Nudging involves using observational (i.e., meteorological measurements) or other datasets to “nudge” model results to match the dataset. Nudging can keep the model from over-predicting or under-predicting the parameters in the dataset. This approach has been shown to improve model performance in other locations around the world. Also, it is one of the most computationally efficient methods for improving model performance in areas with adequate observational data.

From our previous study (Tran et al., 2018), we found that nudging with observational data collected at surface stations (OUN) improved model performance in many aspects; however, it over-predicted warm clouds, which led to less sunlight reaching the Uinta Basin surface and, consequently, less ozone production. In this study, we examined whether adding sounding data (vertical temperature and relative humidity profiles measured with balloon-borne instruments) into the nudging process would help the model to resolve the cloud issue found in ONU. The study included two phases:

- **Phase One**: Investigating the impacts of nudging with sounding data on WRF performance in simulating surface meteorological quantities, vertical profiles, and cloud cover.
- **Phase Two**: Investigating the impacts of nudging with sounding data on photochemical model performance in simulating ozone concentrations in the Uinta Basin, and optimizing observational nudging configurations to achieve more accurate performance.
We used WRF model domain setups that were identical to those in Tran et al. (2018): a one-way triple-nested domain at grid-spacing resolutions of 12, 4, and 1.3 km (Figure 8-1) with 41 vertical layers extending from the surface to 14 km above ground. We selected an inversion event that occurred from 31 January through 4 February 2013 as the studied period.

Figure 8-1. WRF modeling domains. Black and red dots are locations of MADIS and AirNowTech meteorological monitoring stations, respectively. Purple diamonds are locations of USU monitoring stations. Blue diamonds are locations of the Roosevelt (Roo), Horsepool (Hp), Fantasy Canyon (FC) and Ouray (Ou) stations where sounding data were available. The red line indicates the Uinta Basin boundary used for our calculations of basin-wide cloudiness.

8.2. Summary of Phase One Experimental Results

In Phase One, we conducted two sensitivity tests with and without nudging with sounding data at Ouray using WRF model version 3.9:

- ONU: Simulations with surface observational nudging (i.e., nudging the model with meteorological measurement data collected at surface stations over the studied domain).
- G4: Simulations set up the same as ONU except that G4 included the addition of sounding data from the at Roosevelt and Ouray stations in the nudging process. We used vertical profiles from tethered balloon measurements collected at Horsepool and Fantasy Canyon for evaluation of the model output.

Phase One was completed in 2018 and is presented in detail in Section 5 of our 2018 Annual Report (Lyman et al., 2018a). Major conclusions included:

- Sounding nudging at Ouray improved WRF performance in simulating vertical profiles of temperature and relative humidity at the Horsepool at Fantasy Canyon sites. However, those
positive impacts were only noticeable up to around 200 m above the ground, the maximum height of the Ouray data used for nudging. This suggested that the higher sounding data goes, the better improvement for model performance could be made by sounding nudging.

- G4 predicted significantly less warm cloud species than ONU, especially during daytime hours when sounding data were available for nudging. Nudging with temperature and relative humidity vertical profiles did not improve model calculations of ice cloud species.
- As a result of less warm cloud formation in G4 compared to ONU, shortwave radiation at Horsepool predicted by G4 was higher than ONU and was closer to observed values over the entire studied period.

8.3. Phase Two Experimental Results

In Phase Two, our work was designed to understand:

- How sounding nudging in WRF affects simulated ozone concentrations in the Uinta Basin.
- Whether excluding surface station data at Ouray so that sounding nudging is applied starting at the lowest level of the model improves model performance in simulating surface-level relative humidity.
- Whether using Horsepool sounding data for nudging improves model performance in estimating temperature and relative humidity profiles at model heights above 300 m.
- The impacts of combining sounding nudging as in G4 with North American Mesoscale (NAM) 12-km analysis nudging for moisture at levels above where sounding data ends. NAM-12km analysis datasets are gridded, three-dimensional, nation-wide datasets produced by the National Centers for Environmental Prediction that are created from data assimilation of measurement and satellite data into WRF simulations.
- Why the Thompson micro-physics parameterization scheme used in our studies failed to capture ice-phase cloud species even when vertical temperature and relative humidity profiles were improved by sounding nudging.

Our photochemical sensitivity tests using meteorological inputs produced by ONU and G4 showed significantly higher simulated ozone concentrations in the Uinta Basin during daytime for G4 (i.e., when sounding nudging was applied). More details are shown in Section 8.3.1.

When we only used vertical data at Ouray (and not data from the Ouray surface station) for nudging in WRF simulations, the simulated vertical profiles of relative humidity were only marginally different in comparison with G4. However, we believe using just one data type for nudging at one site is a better practice generally. More details on this experiment are shown in Section 8.3.2.

When vertical temperature and humidity profiles at Horsepool were included in nudging, the WRF model yielded better performance in capturing temperature and humidity profiles at levels above 300 m. Therefore, for inversion episodes in Uinta Basin, we recommend that vertical profile measurements collected for nudging should be collected to a height of 2 km if possible since this is the maximum height at which low clouds exist. More details on this experiment are shown in Section 8.3.3.

Our tests on combining sounding nudging as in G4 with analysis dataset moisture nudging for levels above where sounding data ends showed inconsistent results. For example, this test for the study
episode 31 January through 4 February 2013 indicated a slight improvement in simulations of total-column cloud, but tests for several inversion episodes in winter 2011 did not improve simulations. We believe the accuracy of NAM-12km analysis data used for moisture nudging affects the results. Since NAM-12km analysis data were developed for large-scale meteorological phenomena, and since comprehensive evaluations of these datasets are not practical due to lack of observational data, we recommend not using these data for moisture nudging at high altitudes.

In all of our tests with different nudging configurations, the Thompson cloud microphysics parameterization in WRF failed to capture ice cloud formation. Our test with another parameterization (Lin et al. scheme), which has a comparably sophisticated mechanism in terms of resolving different cloud species, also failed to capture ice fog in the Uinta Basin (not shown in this report). We are still working on understanding this parameterization malfunction issue.

8.3.1. Impact of Sounding Nudging on Simulated Ozone in the Uinta Basin

In this analysis, we ran Comprehensive Air Quality Model with Extensions (CAMx) simulations using meteorological fields produced with and without sounding nudging WRF runs (e.g., G4 and ONU, respectively) to examine how the positive impacts of sounding nudging on meteorological quantities found in Phase One affected simulations of ozone concentrations in the Uinta Basin.

We carried out two CAMx simulation experiments with identical model configurations and emissions, except that one used meteorological inputs produced by ONU, and the other used G4 meteorology. We carried out these simulations over the period of 31 January through 4 February 2013. All differences in simulated ozone concentrations between the two experiments, therefore, only stem from whether or not sounding nudging was used in the WRF simulations.

We used the most updated CAMx version (v6.5) and its compatible supported processors, which incorporates important updates to the treatment of snow albedo and NOx chemistry that affect ozone chemistry in the Uinta Basin. We based oil and gas emissions on Ahmadov et al. (2015)’s top-down emission inventory and took domain-wide non-oil and gas emissions from the 2011 National Emissions Inventory (EPA, 2019), which we scaled to year 2013 based on production rates.

As discussed in the Phase One results, sounding nudging reduced overestimations of warm cloud in WRF and improved model estimations of shortwave radiation. As a consequence, CAMx simulations using meteorological fields produced by G4 with sounding nudging consistently predicted significantly higher ozone concentrations at Ouray and slightly higher ozone concentrations at Vernal over all five studied days (Figure 8-2), especially during hours when tethersonde data at Ouray were available for nudging (7:00 to 17:00 local time). The two experimental runs performed similarly at hours outside of these vertical nudging windows.
8.3.2. Impacts of Excluding Surface Data at Ouray from Nudging

We used both surface data (temperature and wind) and vertical data (temperature and moisture) for nudging in G4 simulations. Our Phase One analysis indicated that G4-simulated relative humidity at the model levels closest to the ground was still biased notably high compared to observations (Figure 8-3). Our hypothesis for the origin of these humidity biases was that the model nudging scheme placed greater importance on surface data compared to sounding data. Because surface nudging did not include moisture, the impacts of moisture nudging with vertical profiles on simulated humidity at lower levels could be mitigated by nudging with surface data, but only if our hypothesis was true. In this experiment, we excluded Ouray surface data from nudging (hereafter referred as G4_no_sOU) and compared the results against relative humidity vertical profiles from G4 to test our hypothesis.

G4_no_sOU resulted in slightly better performance in terms of surface-level humidity bias at Horsepool on 31 January through 2 February, but it did not help on 3 February (we did not evaluate 4 February because of missing observational data at Horsepool) (Figure 8-3, dashed lines). In contrast, excluding Ouray surface data from nudging did not result in significant improvement at Fantasy Canyon (Figure 8-3, solid lines). We conclude that removing Ouray surface data and only including Ouray vertical profiles for nudging did not resolve the relative humidity bias at lower altitudes at Horsepool and Fantasy Canyon.

This experiment also showed that vertical nudging at Ouray impacted the Horsepool site more than the Fantasy Canyon site in the near-surface model layers. This is because nudging impacts propagate from the nudging site (Ouray) to the surrounding area within a prescribed radius of influence (we used 50 km) through pressure coordinates (i.e., using atmospheric pressure as a proxy for height above sea level). Since Fantasy Canyon is located at a slightly lower elevation than Ouray (1454 m versus 1464 m above sea level), the propagation of nudging impacts through pressure coordinates from Ouray passed above the surface at Fantasy Canyon. Thus, when collecting data for vertical nudging, it is wise to locate the instrument at the lowest possible elevation so that nudging impacts will be beneficial to the largest modeled area.
Figure 8-3. Simulated and observed relative humidity vertical profiles at Horsepool (dashed lines) and Fantasy Canyon (solid lines). Y-axis indicates height above sea level (ASL). Observed data were collected by NOAA Tethersondes (black). Simulated data include ONU (orange - nudging with surface-level data only), G4 (blue - nudging with sounding at Ouray and surface-level data), and G4_no_sOU (red – same as G4 but surface temperature and wind at Ouray were excluded from nudging). RH is relative humidity.
8.3.3. **Impacts of Including Horsepool Sounding Data for Nudging**

In this experiment, we added tethersonde vertical profiles (temperature and moisture) collected at Horsepool into nudging (hereafter referred as G4_plus). We configured G4_plus exactly like G4, except that we used Horsepool sounding data for nudging. We used sounding data from Fantasy Canyon to evaluate model results.

Figure 8-4 indicates that including sounding nudging with data from Horsepool significantly reduced temperature biases at altitudes above 300 m (the height at which sounding data at Ouray ended for all studied days). These positive impacts are obvious not only at Horsepool but also at Fantasy Canyon, which is within the nudging radius of influence.

Figure 8-5 shows a similar analysis but for relative humidity vertical profiles. Again, nudging with data that extend to higher altitudes improved model performance in simulating relative humidity, both at the nudging location (Horsepool) and within the radius of influence (i.e., at Fantasy Canyon). This positive impact was most obvious for 2 February between 1800 and 2200 m above sea level, where G4 and ONU predicted almost saturated conditions, but G4_plus was able to reproduce more realistic humidity values.

Nudging with vertical profile data at both Ouray and Horsepool (G4_plus) improved model performance for temperature and moisture over a larger extent of the vertical atmosphere. As a consequence, G4_plus reduced WRF overestimation of warm clouds to a greater extent than was possible with G4, especially during daytime hours when vertical profiles were available for nudging (Figure 8-6). CAMx simulations using meteorological fields from G4_plus also predicted higher ozone concentrations than CAMx runs using meteorological fields from G4 and ONU (Figure 8-7). All three CAMx runs with top-down emissions still underestimated ozone concentrations at both Ouray and Vernal. However, the WRF-CAMx model captured well the increasing trends in ozone concentrations accumulated over the studied episode at both Ouray and Vernal, indicating that WRF performed well in predicting the evolution of inversion conditions from day to day.

We conclude that nudging with more vertical profiles available at more stations into WRF simulations, including data that extended higher in the atmosphere, led to better model performance in predicting both meteorological quantities and ozone concentrations during inversion periods in the Uinta Basin.
Figure 8-4. Simulated and observed vertical temperature profiles at Horsepool (dashed lines) and Fantasy Canyon (solid lines). Y-axis indicates height above sea level (ASL). Observed data were collected by NOAA Tethersondes (black). Simulated data were derived from ONU (orange - nudging with surface-level data only), G4 (blue - nudging with sounding at Ouray and surface-level data), and G4_plus (red – same as G4, but with sounding at Horsepool added for nudging). T is temperature.
Figure 8-5. Simulated and observed relative humidity vertical profiles at Horsepool (dashed lines) and Fantasy Canyon (solid lines). Y-axis indicates height above sea level (ASL). Observed data were collected by NOAA Tethersondes (black). Simulated data were derived from ONU (orange – nudging with surface-level data only), G4 (blue – nudging with sounding at Ouray and surface-level data), and G4_plus (red – same as G4, but with sounding at Horsepool added for nudging). RH is relative humidity.
8.4. Conclusions

From these model sensitivity tests with different nudging setups (surface nudging only, surface nudging combined with sounding nudging at one site and sounding nudging at two sites) as discussed in this section and in Lyman et al. (2018a), we conclude that:

- Sounding nudging with temperature and relative humidity at Ouray improved WRF performance in simulating vertical profiles of temperature and relative humidity at the Horsepool at Fantasy Canyon sites to the maximum height of the Ouray data used for nudging. As a consequence, sounding nudging also improved model performance in simulating cloudiness, radiation, and ozone concentrations in the Uinta Basin. However, sounding nudging effects were limited to the hours when and to the heights where sounding data were available.
- Nudging with more vertical profiles available at more stations in WRF simulations, including data that extended higher in the atmosphere, led to better model performance in predicting both meteorological quantities and ozone concentrations during inversion periods in the Uinta Basin.

We recommend the following points be considered when collecting data for vertical nudging:

- Locate vertical sounding instrumentation at the lowest possible elevation in the Uinta Basin so nudging impacts will be beneficial to the largest modeled area.
• Extend data collection both vertically (to higher altitudes) and temporally (over more hours, including night), if possible.
• Besides temperature and vertical moisture profiles, consider collection of wind vertical profiles, which are not currently available for the Uinta Basin. If available, these data would be useful for further study to investigate whether vertical nudging of wind fields increases model accuracy in predicting mixing and advection processes within the basin.
9. Online Coupling of Meteorology and Chemistry in Photochemical Models

Author: Trang Tran

9.1. Introduction

Recent photochemical modeling studies of high winter ozone episodes in the Uinta Basin have been unsuccessful in simulating elevated ozone concentrations. Discrepancies in emissions inventories are believed to be the most important cause for the underestimation of ozone in models (Section 10), but inaccuracies in simulating inversion meteorology also lead to model underperformance (Section 8). The majority of earlier photochemical models applied to the Uinta Basin determined meteorological conditions separate from any possible influence of air chemistry on meteorology (Lyman et al., 2018a; Lyman and Tran, 2015b; Matichuk et al., 2017; Neemann et al., 2015). Only one modeling study, conducted by scientists at the National Oceanic and Atmospheric Administration, used techniques available in the WRF-Chem model to allow meteorological conditions and air chemistry to be influenced by each other (Ahmadov et al., 2015). This two-way feedback approach between meteorology and chemistry is often called online coupling. We conducted preliminary tests using similar model inputs to those of Ahmadov et al. (2015) but with the WRF-CAMx model in standard offline coupling mode (i.e., no two-way feedback), and these simulations led to lower ozone than was simulated by Ahmadov et al.

We have begun a study to compare the output from photochemical simulations using WRF-Chem and WRF-CAMx, with similar model configurations (e.g., same emission inventory, same chemical mechanism) for each model. Our hypothesis is that the meteorology-chemistry online coupling available in WRF-Chem, although requiring greater computational resources, will outperform the WRF-CAMx model without online coupling. The outcome of this study will help determine the best model platform for accurate simulation of winter ozone episodes in the Uinta Basin.

9.2. Experimental Design

We are currently planning and testing the best experimental designs to compare the two different model systems. Because WRF-Chem and WRF-CAMx are different model platforms, we cannot make every input to the models identical. However, we are selecting model versions, physics options, and chemical mechanisms that will allow us to use these models with as much similarity as possible. The ultimate goal of this study is to optimize WRF-CAMx simulations based on what we learn from WRF-Chem with online coupling. If WRF-Chem with online coupling performs better, we will use the comparisons to develop an offline coupling scheme for WRF-CAMx that optimizes coupling times and other aspects of meteorology-chemistry two-way feedback.

The two models are being configured with the following properties:

- WRF version 3.9
- The same meteorological nudging configurations
- The same top-down emissions inventory developed by Ahmadov et al. (2015)
- The same initial and boundary conditions.
• Similar chemical mechanisms (the carbon-bond mechanism developed by Yarwood et al. (2005) and (Yarwood et al., 2010))
• Similar physics options that resolve different cloud species (the Thompson scheme for WRF-CAMx and the Lin et al. scheme for WRF-Chem)

9.3. Study Progress

While the study is still underway, we present a brief update of progress thus far:
• We have finished WRF-CAMx runs with the emissions inventory from Ahmadov et al. (2015) for 31 January through 4 February 2013.
• We have converted inventory files to a format that can be utilized by WRF-Chem.
• We have created initial and boundary conditions for our 1.33 km domain (Figure 8-1) using simulated chemical fields from the Community Atmosphere Model with Chemistry (CAM-chem) with the mozbc processor. Initial ozone concentrations created by this tool varied from 40 to 47 ppb over the Uinta Basin. Using this initial condition helps to reduce initialization time for WRF-Chem simulations relative to using default initial and boundary conditions for ozone that assume a clean remote environment (i.e., 0 ppb).
• We have finished WRF-Chem simulations with the same emission inventory used by WRF-CAMx. As expected, WRF-Chem simulations were almost six times more computationally expensive than WRF-CAMx.
10. Improvements to Photochemical Models of Wintertime Ozone

Author: Huy Tran

In this section, we use the acronyms VOC and TOG. VOC stands for volatile organic compounds. The U.S. Environmental Protection Agency (EPA) defines the term to include all organic compounds that exist in the atmosphere except the relatively unreactive compounds methane and ethane. We follow that convention here. TOG stands for total organic gases, and it includes methane and ethane.

10.1. Emissions Inventory Improvements for Photochemical Modeling

10.1.1. Emissions of Organic Compounds from Pump Jack Engines and Turbines

While processing organic compound emissions from pump jack engines and turbines, as identified in the Utah Air Agencies Oil and Gas Emissions Inventory (UDAQ, 2018) for 2014 (referred to as UEI2014 hereafter), we recognized the following:

- Emissions of formaldehyde from engines in UEI2014 (and also in the recently released UEI2017) are calculated explicitly using heat throughput and manufacturer emission factors or emission factors from the U.S. Environmental Protection Agency AP-42 emission factor database (Table 10.1).
- Typically, formaldehyde emissions from engines in the Sparse Matrix Operator Kernel Emission (SMOKE) model (SMOKE is used to process emissions input and prepare emissions files that can be used by photochemical models) are determined by applying splitting factors determined by a VOC speciation profile (in this case, the profile ID is 1001). Formaldehyde emissions from engines, however, are very low when using this approach (Table 10.2).
- Formaldehyde emissions taken directly from UEI2014 are much higher than those derived by SMOKE and account for 30% of total organic compound emissions from engines on average (Table 10.1).
- We determined formaldehyde emissions from engines in two scenarios:
  - In the BASE case scenario, we took formaldehyde emissions from engines directly from UEI2014 (Table 10-1)
  - In the PROF scenario, we calculated formaldehyde emissions in SMOKE from VOC profile 1001 (Table 10.2). Formaldehyde emissions in BASE are about 500 tons yr⁻¹ higher than in PROF.
- Table 10-3 compares total formaldehyde emissions from all source categories (including oil and gas) over the Uinta Basin as obtained from several different approaches. In comparison to the top-down approach from Ahmadov et al. (2015) shown in the table, formaldehyde emissions are lower in both the PROF and BASE scenarios if the area of emissions in PROF and BASE is restricted to the same area encompassed by the original emissions estimations used by Ahmadov et al. (2015).
Table 10-1. Uinta Basin total emissions of VOC and formaldehyde from various categories of engines. Values are from UEI2014 (i.e., the BASE scenario).

<table>
<thead>
<tr>
<th>Engine Categories</th>
<th>Engine Types</th>
<th>VOC (tons yr⁻¹)</th>
<th>Formaldehyde (tons yr⁻¹)</th>
<th>Formaldehyde/VOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural Gas 4-Stroke Lean Burn-500+HP</td>
<td>4SLB</td>
<td>373.803</td>
<td>69.035</td>
<td>0.185</td>
</tr>
<tr>
<td>Natural Gas 4-Stroke Lean Burn-50-500HP</td>
<td>4SLB</td>
<td>7.838</td>
<td>1.722</td>
<td>0.220</td>
</tr>
<tr>
<td>Natural Gas 4-Stroke Rich Burn-0-50HP</td>
<td>4SRB</td>
<td>4.953</td>
<td>0.452</td>
<td>0.091</td>
</tr>
<tr>
<td>Natural Gas 4-Stroke Rich Burn-50-500HP</td>
<td>4SRB</td>
<td>14.195</td>
<td>1.276</td>
<td>0.090</td>
</tr>
<tr>
<td>Natural Gas 2-Stroke Lean Burn-0-50HP</td>
<td>Compressor</td>
<td>0.112</td>
<td>0.052</td>
<td>0.460</td>
</tr>
<tr>
<td>Natural Gas 2-Stroke Lean Burn-50-500HP</td>
<td>Compressor</td>
<td>15.568</td>
<td>4.609</td>
<td>0.296</td>
</tr>
<tr>
<td>Natural Gas 4-Stroke Lean Burn-500+HP</td>
<td>Compressor</td>
<td>209.021</td>
<td>73.712</td>
<td>0.353</td>
</tr>
<tr>
<td>Natural Gas 4-Stroke Lean Burn-50-500HP</td>
<td>Compressor</td>
<td>6.141</td>
<td>2.140</td>
<td>0.349</td>
</tr>
<tr>
<td>Natural Gas 4-Stroke Rich Burn-0-50HP</td>
<td>Compressor</td>
<td>0.049</td>
<td>0.034</td>
<td>0.693</td>
</tr>
<tr>
<td>Natural Gas 4-Stroke Rich Burn-50-500HP</td>
<td>Compressor</td>
<td>13.811</td>
<td>2.815</td>
<td>0.204</td>
</tr>
<tr>
<td>Natural Gas 4-Stroke Rich Burn-50-500HP</td>
<td>Compressor</td>
<td>50.767</td>
<td>5.150</td>
<td>0.101</td>
</tr>
<tr>
<td>Diesel Industrial Engine &lt;600 hp-500+HP</td>
<td>Generator</td>
<td>0.00353</td>
<td>0.00001</td>
<td>0.003</td>
</tr>
<tr>
<td>Diesel Industrial Engine &lt;600 hp-50-500HP</td>
<td>Generator</td>
<td>12.778</td>
<td>0.045</td>
<td>0.004</td>
</tr>
<tr>
<td>Natural Gas 4-Stroke Lean Burn-50-500HP</td>
<td>Generator</td>
<td>2.645</td>
<td>0.592</td>
<td>0.224</td>
</tr>
<tr>
<td>Natural Gas 4-Stroke Rich Burn-50-500HP</td>
<td>Generator</td>
<td>12.664</td>
<td>2.046</td>
<td>0.162</td>
</tr>
<tr>
<td>Natural Gas-Fired Turbine-0-50HP</td>
<td>Generator</td>
<td>0.031</td>
<td>0.001</td>
<td>0.039</td>
</tr>
<tr>
<td>Natural Gas-Fired Turbine-50-500HP</td>
<td>Generator</td>
<td>0.480</td>
<td>0.044</td>
<td>0.092</td>
</tr>
<tr>
<td>Natural Gas 4-Stroke Rich Burn-0-50HP</td>
<td>Pump</td>
<td>0.116</td>
<td>0.081</td>
<td>0.693</td>
</tr>
<tr>
<td>Natural Gas 4-Stroke Rich Burn-50-500HP</td>
<td>Pump</td>
<td>1.168</td>
<td>0.809</td>
<td>0.693</td>
</tr>
<tr>
<td>Natural Gas 2-Stroke Lean Burn-0-50HP</td>
<td>Pump Jack</td>
<td>61.063</td>
<td>35.496</td>
<td>0.581</td>
</tr>
<tr>
<td>Natural Gas 2-Stroke Lean Burn-50-500HP</td>
<td>Pump Jack</td>
<td>12.325</td>
<td>5.713</td>
<td>0.464</td>
</tr>
<tr>
<td>Natural Gas 4-Stroke Rich Burn-0-50HP</td>
<td>Pump Jack</td>
<td>18.445</td>
<td>12.776</td>
<td>0.693</td>
</tr>
<tr>
<td>Natural Gas 2-Stroke Lean Burn-0-50HP</td>
<td>Pumping Unit</td>
<td>360.168</td>
<td>101.328</td>
<td>0.281</td>
</tr>
<tr>
<td>Natural Gas 2-Stroke Lean Burn-50-500HP</td>
<td>Pumping Unit</td>
<td>437.371</td>
<td>193.385</td>
<td>0.442</td>
</tr>
<tr>
<td>Natural Gas 4-Stroke Lean Burn-0-50HP</td>
<td>Pumping Unit</td>
<td>2.063</td>
<td>0.474</td>
<td>0.230</td>
</tr>
<tr>
<td>Natural Gas 4-Stroke Rich Burn-0-50HP</td>
<td>Pumping Unit</td>
<td>6.805</td>
<td>3.479</td>
<td>0.511</td>
</tr>
<tr>
<td>Natural Gas 4-Stroke Rich Burn-50-500HP</td>
<td>Pumping Unit</td>
<td>33.777</td>
<td>9.991</td>
<td>0.296</td>
</tr>
<tr>
<td>Natural Gas-Fired Turbine-500+HP</td>
<td>Turbine</td>
<td>15.720</td>
<td>0.429</td>
<td>0.027</td>
</tr>
<tr>
<td>Total – BASE</td>
<td></td>
<td>1,674</td>
<td>528</td>
<td>0.315 (avg.)</td>
</tr>
<tr>
<td>Total – PROF</td>
<td></td>
<td>1,674</td>
<td>14</td>
<td>0.0081 (avg.)</td>
</tr>
</tbody>
</table>
Table 10-2. Speciation profile of TOG and NHAPTOGa applied for engines/turbines using SMOKE (i.e., the PROF scenario).

<table>
<thead>
<tr>
<th>Profile ID</th>
<th>Compound group</th>
<th>CB6 species(^b)</th>
<th>Split factor(^c)</th>
<th>Compound Group</th>
<th>CB6 species</th>
<th>Split factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1001</td>
<td>VOC/TOG</td>
<td></td>
<td></td>
<td>NONHAPVOC/ NONHAPTOG</td>
<td></td>
<td>11.8</td>
</tr>
<tr>
<td>1001</td>
<td>TOG</td>
<td>ALD2</td>
<td>0.000300</td>
<td>NONHAPTOG</td>
<td>ALDX</td>
<td>0.000101</td>
</tr>
<tr>
<td>1001</td>
<td>TOG</td>
<td>ALDX</td>
<td>0.000100</td>
<td>NONHAPTOG</td>
<td>ECH4</td>
<td>0.774300</td>
</tr>
<tr>
<td>1001</td>
<td>TOG</td>
<td>BENZ</td>
<td>0.001100</td>
<td>NONHAPTOG</td>
<td>ETH</td>
<td>0.006361</td>
</tr>
<tr>
<td>1001</td>
<td>TOG</td>
<td>ECH4</td>
<td>0.766900</td>
<td>NONHAPTOG</td>
<td>ETHA</td>
<td>0.141300</td>
</tr>
<tr>
<td>1001</td>
<td>TOG</td>
<td>ETH</td>
<td>0.006300</td>
<td>NONHAPTOG</td>
<td>ETHY</td>
<td>0.003231</td>
</tr>
<tr>
<td>1001</td>
<td>TOG</td>
<td>ETHA</td>
<td>0.140000</td>
<td>NONHAPTOG</td>
<td>IOLE</td>
<td>0.003151</td>
</tr>
<tr>
<td>1001</td>
<td>TOG</td>
<td>ETHY</td>
<td>0.003200</td>
<td>NONHAPTOG</td>
<td>OLE</td>
<td>0.012400</td>
</tr>
<tr>
<td>1001</td>
<td>TOG</td>
<td>FORM</td>
<td>0.008100</td>
<td>NONHAPTOG</td>
<td>PAR</td>
<td>0.028200</td>
</tr>
<tr>
<td>1001</td>
<td>TOG</td>
<td>IOLE</td>
<td>0.003121</td>
<td>NONHAPTOG</td>
<td>PRPA</td>
<td>0.029400</td>
</tr>
<tr>
<td>1001</td>
<td>TOG</td>
<td>OLE</td>
<td>0.012200</td>
<td>NONHAPTOG</td>
<td>TOL</td>
<td>0.000562</td>
</tr>
<tr>
<td>1001</td>
<td>TOG</td>
<td>PRPA</td>
<td>0.027900</td>
<td>NONHAPTOG</td>
<td>UNR</td>
<td>0.000059</td>
</tr>
<tr>
<td>1001</td>
<td>TOG</td>
<td>TOL</td>
<td>0.000555</td>
<td>NONHAPTOG</td>
<td>XYL</td>
<td>0.001026</td>
</tr>
<tr>
<td>1001</td>
<td>TOG</td>
<td>UNR</td>
<td>0.000059</td>
<td>NONHAPTOG</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1001</td>
<td>TOG</td>
<td>XYL</td>
<td>0.001014</td>
<td>NONHAPTOG</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^a\) Total Organic Gases, except hazardous air pollutants (HAPs), as defined by EPA.

\(^b\) Chemical species that are simulated in the Carbon Bond Mechanism version 6 (CB6). See Yarwood et al. (2005).

\(^c\) Factor to multiply by VOC or TOG estimates to derive emissions for the target model species.

Table 10-3. Comparisons of formaldehyde emissions over the Uinta Basin estimated using various approaches.

<table>
<thead>
<tr>
<th>Emissions estimation approach</th>
<th>Formaldehyde (mole hr(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top-Down Approach(^1)</td>
<td>2,193</td>
</tr>
<tr>
<td>BASE – Uinta Basin(^2)</td>
<td>1,393</td>
</tr>
<tr>
<td>BASE – Duchesne County</td>
<td>1,496</td>
</tr>
<tr>
<td>BASE – Uintah County</td>
<td>1,474</td>
</tr>
<tr>
<td>PROF – Uinta Basin(^2)</td>
<td>675</td>
</tr>
<tr>
<td>PROF – Duchesne County</td>
<td>796</td>
</tr>
<tr>
<td>PROF – Uintah County</td>
<td>971</td>
</tr>
</tbody>
</table>

\(^1\) Following Ahmadov et al. (2015)’s approach: Emissions of formaldehyde were derived from a formaldehyde/methane emission slope of 6.38 x 10\(^{-4}\) and an estimated methane emission over the Uinta Basin of 482,130 tons yr\(^{-1}\) (344 x 104 mole hr\(^{-1}\)).

\(^2\) Total formaldehyde emissions in BASE, but taken over the same grid-cells that were used in the Top-Down Approach.

Differences in formaldehyde emissions between BASE and PROF were most profound over the west side of the Uinta Basin, where oil production is concentrated (Figure 10-1). Photochemical model performance with the BASE and PROF scenarios is discussed in Section 10.2.
10.1.2. Other Emissions Modeling Improvements

Figure 10-2, Figure 10-3, and Table 10-4 present NO\textsubscript{x} and VOC emissions estimated from UEI2014 and processed by SMOKE from all area sources (i.e., emission sources that do not emit from a defined exhaust stack) and point sources with low stack heights in the BASE scenario. For comparison, we also present in these figures and table the corresponding NO\textsubscript{x} and VOC emissions estimated in our earlier modeling efforts (Lyman et al., 2018a), referred to as OLD hereafter.

In comparison to our earlier modeling work (BASE vs. OLD), we made the following improvements to the SMOKE emissions model:

- In BASE, we used the 2014 National Emissions Inventory (NEI2014; EPA (2019)) for emissions from sources other than oil and gas. In OLD, we used NEI2011.
- In BASE, we updated emissions from mobile sources with the MOVES20151201 model used in the NEI2014 Version 1 (NEI2014v1) for mobile sources.
- We applied speciation and temporal profiles from NEI2014v1 in BASE, whereas, in OLD, we used profiles that are based on NEI2011v6 and the Three-State Air Quality Modeling Study Emission Model (Adelman and Baek, 2015). The speciation profiles for oil and gas source categories in NEI2014v1 are updated from previous versions.
- We have included biogenic emissions in BASE, as determined by the biogenic emissions model BEIS3.61. In OLD, biogenic emissions were assumed to be zero during winter and thus were not included.
- In BASE, we temporalized emissions from the oil and gas sector in the Uinta Basin by the following method:
  - We associated each facility that had emissions in UEI2014 with its facility-specific API number;
We used the API number to retrieve monthly oil, gas, and water (depending on well type) production rates for each facility in 2011 from the Utah Division of Oil, Gas and Mining (DOGM) database (UDOGM, 2018) and used the data as a surrogate for allocating annual emissions from UEI2014 to each month; we then allocated monthly emissions to the daily and hourly scales assuming no daily and hourly variation.

In OLD, invariant annual temporal profiles were applied to oil and gas emissions (i.e., emissions from oil and gas were assumed to be constant throughout the year).

- We developed spatial surrogates for some oil and gas emissions categories in Utah from well location and production data obtained from DOGM for the modeled year. In both BASE and OLD, we treated oil and gas source categories in Duchesne and Uintah Counties as low-level point sources. This means that modeled emissions from these sources originated from specific points, rather than being distributed across a two-dimensional surface, and that emissions originated from ground level. For comparison, the majority of oil and gas emissions in other emissions models (including NEI2011v6 and NEI2014v1) area treated as area sources, with emissions allocated into the model grid cells by applying location- or production-based spatial surrogates. When treated as low-level point sources in BASE or OLD, oil and gas emissions are allocated into model grid cells based on the location of each specific facility. Thus, BASE and OLD have high accuracy in representing the spatial distribution of emissions from oil and gas wells.

As shown in Table 10-4, the majority of NOx and VOC emissions in the Uinta Basin are from oil and gas sources. Note that while the actual ratio of NO to NO2 in NOx emissions varies with the characteristics of each emission source, in the emissions model, NOx emissions are mostly attributed to NO (90%). We made a technical mistake in OLD that caused emissions of NOx and VOC from engines (e.g., compressors and pump jacks) to be higher than normal, which explains the higher NOx, VOC, and formaldehyde emissions in OLD compared to BASE (See Figure 10-2 and Figure 10-3). The impacts of the differences between BASE vs. OLD on ozone performance are discussed in Section 10.2.
Figure 10-2. NOx emissions from all source categories and from oil and gas production activities as calculated by the SMOKE emissions model in the BASE and OLD scenarios. Abbreviations of monitoring stations’ names are presented in Table 10-5.
Figure 10-3. VOC emissions (VOC excludes methane and ethane) from all source categories and from oil and gas production activities as calculated by the SMOKE emissions model in the BASE and OLD scenarios. Abbreviations of monitoring stations’ names are presented in Table 10-5.
Table 10-4. Summary of NO\textsubscript{x} and VOC emissions as estimated by the SMOKE emissions model for Duchesne and Uintah Counties (moles hr\textsuperscript{-1}). VOC does not include methane or ethane.

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Species</th>
<th>Duchesne All sources</th>
<th>Duchesne Oil-Gas</th>
<th>Uintah All sources</th>
<th>Uintah Oil-Gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>BASE</td>
<td>NO</td>
<td>12,135</td>
<td>10,234</td>
<td>14,300</td>
<td>11,641</td>
</tr>
<tr>
<td></td>
<td>NO\textsubscript{2}</td>
<td>1,231</td>
<td>1,064</td>
<td>1,452</td>
<td>1,190</td>
</tr>
<tr>
<td></td>
<td>(Formaldehyde – PROF)</td>
<td>(812)</td>
<td>(236)</td>
<td>(982)</td>
<td>(372)</td>
</tr>
<tr>
<td></td>
<td>Formaldehyde</td>
<td>1,496</td>
<td>937</td>
<td>1,474</td>
<td>876</td>
</tr>
<tr>
<td></td>
<td>Aldehydes\textsuperscript{a}</td>
<td>1,896</td>
<td>949</td>
<td>1,918</td>
<td>898</td>
</tr>
<tr>
<td></td>
<td>Benzene</td>
<td>316</td>
<td>284</td>
<td>1,102</td>
<td>1,061</td>
</tr>
<tr>
<td></td>
<td>Toluene</td>
<td>397</td>
<td>329</td>
<td>1,693</td>
<td>1,579</td>
</tr>
<tr>
<td></td>
<td>Xylenes</td>
<td>398</td>
<td>321</td>
<td>914</td>
<td>784</td>
</tr>
<tr>
<td></td>
<td>(VOC – PROF)</td>
<td>(74,913)</td>
<td>(62,662)</td>
<td>(193,663)</td>
<td>(179,753)</td>
</tr>
<tr>
<td></td>
<td>VOC</td>
<td>75,615</td>
<td>63,354</td>
<td>194,168</td>
<td>180,258</td>
</tr>
<tr>
<td>OLD</td>
<td>NO</td>
<td>13,403</td>
<td>10,664</td>
<td>17,941</td>
<td>13,331</td>
</tr>
<tr>
<td></td>
<td>NO\textsubscript{2}</td>
<td>1,422</td>
<td>1,886</td>
<td>1,185</td>
<td>1,481</td>
</tr>
<tr>
<td></td>
<td>Formaldehyde</td>
<td>1,759</td>
<td>1,152</td>
<td>2,428</td>
<td>1,745</td>
</tr>
<tr>
<td></td>
<td>Aldehydes\textsuperscript{a}</td>
<td>2,344</td>
<td>1,281</td>
<td>3,057</td>
<td>1,853</td>
</tr>
<tr>
<td></td>
<td>Benzene</td>
<td>254</td>
<td>227</td>
<td>467</td>
<td>425</td>
</tr>
<tr>
<td></td>
<td>Toluene</td>
<td>788</td>
<td>713</td>
<td>1,195</td>
<td>1,071</td>
</tr>
<tr>
<td></td>
<td>Xylenes</td>
<td>759</td>
<td>699</td>
<td>1,467</td>
<td>1,364</td>
</tr>
<tr>
<td></td>
<td>VOC</td>
<td>69,422</td>
<td>57,061</td>
<td>146,620</td>
<td>132,033</td>
</tr>
</tbody>
</table>

\textsuperscript{a}Aldehydes is the total of formaldehyde, acetaldehyde, propionaldehyde, and higher aldehydes.

10.2. Photochemical Model Performance and Sensitivities Studies

We performed simulations using the Comprehensive Air Quality Model with Extensions (CAMx) photochemical model version 6.5 with the CB6 chemical mechanism for a winter ozone episode that occurred from 31 January through 9 February 2013. We used WRF simulations with vertical nudging (G4 simulations, see Section 8) as meteorological inputs for CAMx. We used the BASE emissions scenario, as described in Section 10. We used the Model for Ozone And Related chemical Tracers (MOZART; https://www2.acom.ucar.edu/gcm/mozart) to provide boundary and initial conditions for the simulations.

In addition to the BASE emissions scenario, we also performed simulations for scenarios wherein NO\textsubscript{x} emissions in UEI2014 were reduced by half (the 0.5NO\textsubscript{x} scenario) and wherein NO\textsubscript{x} emissions from oil and gas were speciated into 70% NO and 30% NO\textsubscript{2} (the 7/3NO\textsubscript{x} scenario). We also considered an emissions scenario wherein we mistakenly increased emissions of ketones more than 10 times (the FALSE scenario). Details about these scenarios and CAMx’s performance in simulating ozone with them are discussed in the following sections. For comparison, we also present in these sections ozone performance from our earlier modeling work (the OLD scenario) that utilized the Community Multiscale Air Quality Model (CMAQ) version 5.2 and UEI2014 combined with NEI2011 for non-oil and gas emissions as described in Section 10 (also see Lyman et al. (2018a)). The OLD simulations utilized meteorological inputs from an earlier version of the G4 WRF simulation.
10.2.1. Ozone Performance Evaluation

While ozone performance was greatly improved in BASE compared to OLD, it was still underestimated basin-wide (Figures 10-4 and 10-5). Although no ozone exceedances (i.e., daily highest 8-hr average ozone concentrations greater than 70 ppb) were simulated at any monitoring stations, the BASE scenario properly simulated the temporal variation of ozone during the study episode. In comparison to OLD, ozone buildup and decline throughout the inversion episode were well reproduced in BASE. We attributed the improved ozone performance in BASE mainly due to the improved performance of the WRF G4 simulations that properly simulated meteorological conditions throughout the episode. Performance metrics for BASE are shown in Table 10-5.

In the FALSE scenario, we mistakenly estimated emissions of ketones as three times the emissions of paraffins, which resulted in ketone concentrations in FALSE as much as a thousand times higher than the amount estimated in BASE. In the CB6 mechanism, ketones undergo photolysis reactions that ultimately produce hydroperoxyl radical (HO$_2$). High ketones in FALSE resulted in much higher simulated ozone than in BASE and, interestingly, approximated observed ozone relatively well. In comparison to BASE, higher ozone in FALSE was most prominent over oil and gas fields, but also at the low-elevation center of the Basin, including at Ouray. We include the results from the FALSE scenario here even though the ketone emissions are incorrect because the reactivity of emitted organics in FALSE may provide a better representation of reality than the BASE scenario (see Section 10.2.3).
Figure 10-4. Comparisons of observed ozone (OBS) with ozone simulated by CAMx at several stations in the BASE, FALSE, and OLD scenarios. The national ambient air quality standard for ozone (NAAQS; 70 ppb) is also shown. The horizontal axis is time and is presented in MM/DD-HH (local time).
Figure 10-5. Spatial distribution of observed (colored circles) and simulated daily 8-hr maximum ozone by CAMx in the BASE scenario on 5 and 6 February 2013. Abbreviations of monitoring stations’ names are presented in Table 10-5.
and underestimate NO. Figure 10 photochemical and meteorological processes, rather than by temporal variation in emissions. Since the majority of NO\textsubscript{x} emissions are from oil and gas and have no diurnal cycle, temporal variation in simulated NO\textsubscript{x} concentrations is mainly driven by photochemical and meteorological processes, rather than by temporal variation in emissions.

The monitoring stations presented in Figure 10-6 are not located in where the highest NO\textsubscript{x} concentrations are simulated. CAMx typically estimates highest NO\textsubscript{x} over the area west of the Ouray station. Also, simulated NO typically peaks during daytime and NO\textsubscript{2} peaks during nighttime, and a less distinctive NO\textsubscript{x} diurnal cycle is observed. Since the majority of NO\textsubscript{x} emissions are from oil and gas and have no diurnal cycle, temporal variation in simulated NO\textsubscript{x} concentrations is mainly driven by photochemical and meteorological processes, rather than by temporal variation in emissions.

Figure 10-6 shows that, while NO\textsubscript{x} was underestimated overall, the model tended to overestimate NO\textsubscript{2}. We applied a standard speciation profile to the majority of NO\textsubscript{x} emissions from...
oil and gas production, and this profile leads to 90% of NOx being emitted as NO and about 10% as NO2. To evaluate the effect of NOx speciation on ozone, we performed the 7/3NOx simulation, in which we speciated NOx emissions from oil and gas sources into 70% NO and 30% NO2. As shown in Figure 10-7, simulated ozone in the 7/3NOx scenario was marginally higher than in BASE. The increased ozone was mainly due to the reduction of NO and is not sensitive to the increase in NO2. In contrast to the spatial distribution of simulated ozone in BASE, with the lowest ozone over oil and gas-producing areas (Figure 10-5), ozone in FALSE instead was highest over these areas (not shown). This behavior suggests that insufficient organic compounds exist in the BASE scenario to react with NOx, resulting in lower ozone. At present, we cannot come to a definite conclusion as to whether or not NOx emissions in UEI2014 are overestimated. However, there is clear evidence that the model underestimates the total reactivity of ozone-forming organic compounds.
Figure 10-6. Comparison of observed NO and NO\textsubscript{x} concentrations (OBS) with those simulated in the BASE scenario (SIM) at several monitoring stations. The horizontal axis is time and is presented in MM/DD-HH (local time).
10.2.3. VOC Performance Evaluation

While simulated total VOC were similar to observed values at the Horsepool station, hydrocarbon compounds with high ozone reactivity, including aldehydes, aromatics, and alcohols, were underestimated (Figure 10-8). The BASE emissions scenario with G4 meteorology simulated these compounds at significantly higher concentrations than was found by Matichuk et al. (2017).

The fact that mistakenly high ketone emissions in the FALSE scenario resulted in good model performance for ozone supports the hypothesis that UEI2014 does not necessarily underestimate total VOC, but that it does underestimate emissions of highly reactive organic compounds. For example, no oil and gas emission source in UEI2014 contains methanol emissions except the speciation profile that we developed for produced water ponds. Figure 10-8 shows that the BASE simulation cannot replicate the abundant amount of methanol measured in the atmosphere. Methanol is less reactive than many other organics (Carter, 2009), but it exists at relatively high concentrations in the Uinta Basin.
atmosphere. Better speciation profiles that accurately represent the emissions composition of oil and gas sources (see Section 6) will likely greatly improve future winter ozone simulations.

Additionally, oil and gas emission sources exhibit a complex spatial distribution over the Uinta Basin, and the Horsepool station is not located where emissions are concentrated. Therefore, observed data at the Horsepool monitoring station are inadequate to estimate the VOC composition across the entire basin. Organic compound measurements at additional locations are needed to better understand VOC chemistry in the basin. We have recently collected organic compound measurements from many distributed stations (Section 5), and we will continue this work in the coming winter (Section 17.16), providing valuable data for future model performance evaluations and improvements.
Figure 10-8. Comparison of observed (OBS) vs. simulated formaldehyde, acetaldehyde, benzene, toluene, xylenes, methanol, and VOC by CAMx in the BASE scenario at Horsepool monitoring station. Units are ppb. The horizontal axis is time and is presented in MM/DD-HH (local time).
10.3. Sensitivity Modeling Studies

As discussed in Section 10.2.3, produced water ponds are the only source of methanol emissions in the BASE emissions scenario. The only reaction undergone be methanol, in the CB6 mechanism is with hydroxyl radical (OH) to form formaldehyde and hydroperoxyl radical (HO₂). We ran the CAMx model with its reactive tracer (RTRAC) module to determine modeled concentrations of total and primary methanol, as well as primary and secondary formaldehyde. Primary compounds are those emitted directly from sources, while secondary compounds are those formed from chemical reactions in the atmosphere. We also performed CAMx simulations without emissions from produced water ponds (woPWP) and analyzed the differences in simulated ozone between the BASE and woPWP scenarios.

Figure 10-9 shows almost no difference between total and primary methanol in BASE, suggesting that there was very little transformation of methanol to formaldehyde in the model. Figure 10-9 also reveals that little formation of secondary formaldehyde occurs in general, and the majority of simulated formaldehyde is from primary emissions. Since the reaction of methanol+OH is relatively slow in comparison with other OH-related reactions, the availability of OH is the major limiting factor for this transformation.

Regardless, Figure 10-10 shows significant impacts of emissions from produced water ponds on simulated ozone. Produced water ponds’ contribution to ozone was greater than 5 ppb on average and, at several locations, greater than 10 ppb. The impact of produced water ponds on ozone varied with pond types and emission strengths. At several produced water facilities, such as near Gusher (GU), ponds’ impacts were most prominent in their immediate proximity, whereas impacts of other produced water facilities were strongest downwind. We speculate that the modeled contribution of produced water ponds to ozone production would be greater if the oil and gas emissions inventory accounted for more emissions of highly reactive compounds. Regardless, model results suggest that controlling produced water pond emissions would significantly reduce wintertime ozone in the Uinta Basin.
Figure 10-9. Comparison of simulated primary (directly emitted from sources) and secondary (formed via chemical reactions in the atmosphere) methanol and formaldehyde as obtained in the BASE (left column) and woPWP (right column) scenarios on 5 February 2013. Locations of produced water disposal ponds are indicated by open squares.
Simulations that include aldehyde emissions from the snow surface resulted in little or no increase in ozone compared to BASE (Figure 10-11). This is expected, given the low emissions of aldehydes from snow (see Section 5). Furthermore, emissions of aldehydes were mostly zero at low elevations where oil and gas emissions are concentrated because of lower temperatures in these areas, as discussed in Section 5.

10.4. Conclusions

With the improvements we implemented to the meteorological model (WRF) and the emissions inventory, we have achieved better ozone performance with a photochemical model (CAMx) than our
earlier modeling efforts. However, this model still greatly underestimates simulated ozone. After examining the CAMx model’s ability to simulate NO\textsubscript{x} and VOC, we conclude that the most important unresolved factor affecting the model’s underperformance for ozone is that VOC speciation profiles do not sufficiently account for emissions of highly reactive organic compounds.

10.5. Future Work

Section 16 provides details about our plans for this work for the coming year. We present a short summary here:

- We will attempt to further improve WRF model performance for better representation of advection of ozone and other pollutants.
- We will compare the new UEI2017 against UEI2014 for changes in the magnitude and spatial distribution of NO\textsubscript{x} and VOC emissions.
- We will process UEI2017 data and perform CAMx ozone simulations for a winter episode in 2017 and compare its performance with the BASE scenario for winter 2013 (see Section 10.2 for information about BASE performance).
- We will examine organic compound composition and spatial distribution from the distributed measurement stations that operated during winter 2018-2019 (Section 5) and will again operate in winter 2019-2020 (Section 17.16), and compare these measurements against model results.
11. Improving WRF/CAMx model Performance with Satellite Data Assimilation Techniques

Author: Huy Tran

Land surface characteristics determine many physical processes occurring in the planetary boundary layer (PBL) and play an important role in atmospheric models from large scale to regional and mesoscale. Transport of energy between the land surface and the atmospheric boundary layer, upward short-wave and long-wave radiation, and sensible and latent heat fluxes are often simulated by in meteorological models by a land surface model (LSM). For example, the state-of-art and widely-used Weather Research and Forecasting (WRF) model (Skamarock et al., 2008) includes several LSM options, including the unified Noah, Rapid Update Cycle, Pleim-Xiu, and others. We use WRF to generate meteorological inputs for air quality models, including the Community Model-3 Air Quality (CMAQ) model and the Comprehensive Air Quality Model with Extensions (CAMx). The performance of the WRF model is critical to the performance of these air quality models.

Among land surface parameters, the Leaf Area Index (LAI), vegetation fraction (VF), and fraction of absorbed photosynthetically active radiation (FPAR) are crucial parameters for determining energy fluxes at the ground surface and deposition rates of various atmospheric gases and particles. By default, WRF LSMS employ pre-defined vegetation and land use parameters from look-up tables or from out-of-date monthly average satellite vegetation parameters, which have limitations in capturing seasonal landscape changes (e.g., phenology and albedo) and disturbances (e.g., fires, storm damages, or urban development). For example, Ran et al. (2015) demonstrated that WRF simulations using the Pleim-Xiu LSM generally overestimated the vegetation fraction in comparison with satellite-derived data.

Applications of satellite data to improve LSM performance have been carried out with LAI, VF, and FPAR daily and annual data retrieved from the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite (Moore et al., 2010; Ran et al., 2015; Ran et al., 2016). Moore et al. (2010) demonstrated improvements in estimations of land surface temperature both temporally and spatially for a meteorological simulation over East Africa with the assimilation of MODIS dynamic LAI and VF data. Ran et al. (2015) incorporated LAI and FPAR inputs from MODIS into the WRF/CMAQ model to provide a better representation of the spatial and temporal variation of vegetation cover over the arid western U.S. They also incorporated MODIS albedo data into the WRF model to replace the calculated albedo performed by the Pleim-Xiu LSM. These treatments led to a reduction in error and bias in moisture but produced larger errors in temperature estimates. Simulated ozone increased because of reduced dry deposition velocity, which was caused by smaller LAI and VF values (Ran et al., 2015). Also, Ran et al. (2016) applied this MODIS data treatment for a year-long WRF/CMAQ simulation over the North American 12-km domain. They reported improvements in 2 m temperature and moisture estimates and an increase in ozone concentration due to reduced vegetation cover.

We are applying the approach presented in Ran et al. (2015) to ingest MODIS data into our current modeling platform (WRF/CAMx) for the Uinta Basin. More refined MODIS data products have become available after 2015, and we will thus use the improved versions of the MODIS datasets. Particularly, we will use the gap-filled and smoothed MODIS Collection 6 Level-4 LAI and FPAR dataset (MCD15A3H), which is available every 4 days at 500 m resolution for WRF simulations. For surface albedo, we will utilize the MODIS bidirectional reflectance distribution BRDF/Albedo Parameters Level-3 dataset.
(MCD43A1) and the corresponding BRDF/Albedo Quality Level-3 dataset (MCD43A2), both of which are available daily in 500 m resolution.

Figure 11-1 compares surface albedo processed from MODIS data versus data simulated by WRF for a case study on February 2019. The MODIS dataset showed significantly higher albedo in the Uinta Basin in comparison to WRF’s estimations, which were incorporated from the SNOw Data Assimilation System (SNOWDAS). WRF also failed to capture the heterogeneous distribution of albedo. In earlier WRF winter ozone modeling studies for the Basin, surface albedo values below a certain elevation were forced to match measurements collected at a limited number of locations (Neemann et al., 2015). This treatment led to albedo values closer to observations, but it failed to capture the heterogeneous distribution of albedo.

In standard WRF simulations, LAI, FPAR, and albedo are calculated by the WRF Preprocessing System (WPS) from a monthly-averaged MODIS 2001-2010 climatological dataset. We will modify WRF source codes to allow WRF to replace the WPS-calculated values with real-time MODIS data. This modified version of WRF will also write LAI, FPAR, and albedo data into the appropriate output format for use by CAMx’s dry deposition and photolysis modules.

![Figure 11-1. Comparison of surface albedo as processed from MODIS satellite data (left) and as estimated by the WRF model (right) on 21 February 2019.](image)

11.1. Acknowledgments

Work on this project is funded by the Utah Division of Air Quality, the Utah Legislature, and the Uintah Impact Mitigation Special Service District.
12. Regression Models of Uinta Basin Winter Ozone

Author: Marc Mansfield

12.1. Introduction

A regression model is a mathematical procedure for estimating a “response,” such as the daily ozone concentration, from a set of “predictors,” such as snow depth, solar zenith angle, inversion strength, etc. They have essentially two goals: first, to understand or uncover patterns in how the response depends on the predictors, and second, to make predictions about the response variable. An example of the first goal is to understand the relative importance of, say, snow depth and solar zenith angle in ozone formation. An example of the second goal is to ask for the odds, based on historical meteorological data, that any three-year period will be in attainment of the U.S. Environmental Protection Agency (EPA) standard for ozone.

Development of a regression model begins with selection of a “training set,” a dataset with observed values of the response associated with observed values of the predictors. The training set is then used to “train the model,” i.e., to tune mathematical parameters or functions in the model until the agreement between observed and predicted responses is optimized. Once the model is trained, we judge its behavior on a “testing set,” consisting of additional observational data not included in the training set.

We have been developing and refining regression models of the Uinta Basin ozone system since about 2014. As the response variable, we have always used the daily maximum 8-hr average ozone concentration at Ouray, primarily because Ouray has the longest history of winter ozone monitoring and because its ozone data have been used for non-attainment decisions. Table 12-1 describes the predictors that have been used in these models.

Model success depends on being able to select an appropriate set of predictors. For example, because of the paramount importance of snow depth, the models would be useless if we did not use it as a predictor, while inclusion of solar angle permits the models to finesse the difference between ozone events early and late in the season. The user should be cognizant of hidden impacts created by correlations between predictors. The solar angle is important because it directly captures the changing impact of solar radiation, but because it effectively measures the passage of time, it may indirectly capture other differences between early and late winter. Another caveat is that our models are based on daily data, which seems appropriate for typical winter days with stable meteorology, but they probably are less accurate on days when meteorological conditions are changing rapidly.
Table 12-1. Predictors used in our ozone regression models.

<table>
<thead>
<tr>
<th>METEOROLOGICAL PREDICTORS</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Daily snow depth (SD)</td>
<td>Averaged over multiple sites in the basin.</td>
</tr>
<tr>
<td>Solar zenith angle (SA)</td>
<td>Defined as the noon-time angle that the sun makes with the vertical. It varies from almost 64° in late December to about 42° in mid-March.</td>
</tr>
<tr>
<td>Pseudo-lapse rate (LR)</td>
<td>A measure of inversion strength based on daily maximum surface temperatures at sites throughout the basin.</td>
</tr>
<tr>
<td>Consecutive days since initiation of a multi-day inversion (CD)</td>
<td>The number of consecutive days before the present that the pseudo-lapse rate has been positive.</td>
</tr>
<tr>
<td>“Floor” temperature (FT)</td>
<td>Extrapolation of daily maximum surface temperatures to 1400 m elevation, the “floor” of the basin.</td>
</tr>
<tr>
<td>Daily maximum temperature at Vernal airport (TV)</td>
<td>The temperature at any one site is sometimes used as a proxy for inversion strength. Vernal is used because of availability of historical data.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>OIL AND GAS PRODUCTION PREDICTORS</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Monthly oil production statistics for Uintah and Duchesne Counties (OI)</td>
<td>Available since 1986 at the Utah Division of Oil, Gas and Mining website.</td>
</tr>
<tr>
<td>Monthly natural gas production statistics for Uintah and Duchesne Counties (GA)</td>
<td>Available since 1986 at the Utah Division of Oil, Gas and Mining website.</td>
</tr>
</tbody>
</table>

12.2. Sensitivity to Snow Depth

Our models struggle to properly represent sensitivity to snow depth. Physically, we expect to see a saturation effect, because as soon as the snowpack is deep enough to cover most surface irregularities, its depth no longer matters. Our earliest models employed so-called linear and quadratic regressions, but these are “strong extrapolators.” Sensing a dependence on snow depth, they predict very high ozone concentrations (around 400 to 500 ppb) at historically high snow depths. More recently, we have considered so-called random forest regressions (Breiman, 2001; CitizenNet, 2019). These do not extrapolate at all and, prior to 2019, gave acceptable snow-depth sensitivity, including the above-mentioned saturation effect. Winter 2019 was unique, with the deepest snowpack in over 10 years but with ozone concentrations somewhat smaller than the historical highs. We attribute the lower 2019 ozone to weaker inversions and weaker oil and gas activity. However, the random-forest algorithm attributed it to the snow depth variable and, instead of leveling off, it produced a downturn in the modeled snow depth sensitivity curves. Therefore, we are considering other regression algorithms that will allow us to program in the snow depth saturation effect, including generalized additive models (Hastie and Tibshirani, 1990, 1995). The expectation is that this will cause the regression to attribute the lower 2019 ozone concentrations to other predictors, including the inversion strength and oil and gas production.
12.3. Ozone Forecasting

We currently make qualitative ozone forecasts that allow oil and gas producers and the public at large to make plans to avoid high emissions or high exposure potential during winter ozone episodes (see Section 13). We aspire to produce quantitative ozone forecasts. If forecasted values of the predictors are available in advance, the regression model can be used in this way. The biggest challenge encountered so far as we have attempted this is that current meteorological forecasts are unable to accurately predict the lapse rate. We have been investigating whether the maximum daily temperature at any one site (e.g., the Vernal airport) is adequate as a predictor instead of the lapse rate since it is easier to forecast. Figure 12-1 compares results from two different random-forest regression models. The model on the left uses seven predictors (SD, SA, LR, CD, FT, OI, and GA) while the model on the right uses five (SD, SA, TV, OI, and GA), having replaced LR, CD, and FT with TV. The results display end-point biases that are common in random forest regressions: Observed ozone concentrations as high as 130 to 140 ppb are predicted to be about 90 ppb; concentrations as low as 20 ppb are predicted to be about 35 ppb. The end-point biases are major contributors to the standard errors, 11.2 and 12.8 ppb, respectively. In spite of the end-point biases the models are able to predict with about 90% accuracy (the “exceedance accuracy”) whether any given day was an ozone-exceedance day. Furthermore, the five-variable model has only slightly higher standard error. Based on these results, we will continue to investigate the feasibility of using the Vernal airport temperature in forecasts.

Figure 12-1. Random-forest model comparisons. The model on the left uses seven predictors (SD, SA, LR, CD, FT, OI, and GA), the one on the right, only five (SD, SA, TV, OI, and GA). The diagonal is the one-to-one line. Horizontal and vertical lines at 70 ppb are the EPA standard for ozone. They divide each figure into four quadrants, and the percentage of data points residing in each quadrant is shown. The “exceedance accuracy” is the fraction of data points for which the model successfully predicts whether a day is in exceedance or not, and is given by the sums of the percentages in the lower left and upper right quadrants. The standard error in each model is also shown. The median (bold traces) and 25th and 75th percentiles (light traces) taken over 500 independent models are shown.
Another option that we are considering is to use forecasting simulations to estimate a lapse rate, and to train regressions with this lapse rate rather than an observational one. Since the model is being trained on the same sort of data as is being used for the prediction, it stands a better chance of success.

12.4. Impact of Oil and Natural Gas Production Rates

Figure 12-2 shows annual oil and natural gas production in Duchesne and Uintah Counties since 1986. During the period with ozone measurements (2010 to the present), natural gas production peaked in 2012 to 2014 and has declined ever since. Oil production peaked in 2014, hit a low in 2016, and has since climbed again. While Section 4 argues that these fluctuations in fossil fuel activity have influenced concentrations of ozone precursors in the Uinta Basin, We seek here to discern whether they have also impacted ozone levels. Including production statistics (OI and GA) as predictors represents our attempt at answering this question. The question is still difficult to answer with certainty, since production statistics are confounded with other variables, such as the presence or absence of snow cover in any one season or the intensity of inversions. Furthermore, improvements in emission controls and modernization of equipment may have allowed the basin to produce the same amounts of oil or gas with fewer emissions, implying that production statistics alone may not be the best predictors.

Nevertheless, there is good reason to assume that the models are sensitive to oil and gas activity. We trained a model based on data from the “ozone era,” i.e., 2010 to the present, when ozone measurements have been available. Then we used historical meteorological data (from about 70 winters starting in 1950), coupled with modern oil and gas production data as predictors. In effect, we were asking how much ozone might have been expected during any of the 70 previous winters if there had been modern oil and gas production. Moreover, with a sample size of 70, we assume that the calculation encompasses all “typical” meteorological behavior and lets us talk about expectations for “typical” winters. An early application of this calculation led to the prediction that each winter season
has about 50% odds of producing four or more exceedances of the ozone standard and thereby triggering the non-attainment clock. Moreover, we concluded that the outcome of any one winter has no bearing on the next winter: Each winter is essentially a flip of a coin.

Table 12-2 summarizes the results for impacts from oil and gas production. We calculated the odds that three calendar years in succession would be classified as in ozone attainment or in any of the grades of non-attainment (marginal, moderate, etc.) if oil and gas production were assumed to be that of one specific test year. For example, based on the seven-predictor model, we estimate 31% odds for attainment when we assume that oil and gas production are always at 2010 values, and 65% odds for attainment when we assume 2018 values. These results indicate an impact from oil and gas production since no other variables change when we make the comparison, and they indicate that the economic downturn probably did improve the situation for ozone. However, because of the end-point bias seen in Figure 12-1, these calculations probably overestimate the attainment odds. They also neglect spring and summer ozone exceedances, which do occasionally occur.
Table 12-2. Natural gas and oil emissions have an impact on estimates of ozone attainment. Displayed are the percent odds that three typical successive years will produce ozone attainment, or any of the indicated grades of non-attainment, when it is assumed that oil and natural gas production are equal to those of the indicated test year.

Train with seven predictors (SA, LR, SD, CD, FT, GA, OI) in the ozone era, predict with historical SA, LR, SD, CD, FT combined with GA and OI from the test year.

<table>
<thead>
<tr>
<th>TEST YEAR</th>
<th>ATTAINMENT</th>
<th>MARGINAL</th>
<th>MODERATE</th>
<th>SERIOUS</th>
<th>SEVERE</th>
<th>EXTREME</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>31.3</td>
<td>29.8</td>
<td>28.6</td>
<td>10.3</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>2011</td>
<td>31.6</td>
<td>29.9</td>
<td>29.2</td>
<td>11.3</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>2012</td>
<td>30.3</td>
<td>25.6</td>
<td>31.0</td>
<td>13.1</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>2013</td>
<td>30.7</td>
<td>25.9</td>
<td>30.6</td>
<td>12.8</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>2014</td>
<td>47.4</td>
<td>34.2</td>
<td>16.8</td>
<td>1.6</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>2015</td>
<td>49.6</td>
<td>33.1</td>
<td>15.8</td>
<td>1.5</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>2016</td>
<td>42.4</td>
<td>30.4</td>
<td>21.9</td>
<td>5.2</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>2017</td>
<td>59.1</td>
<td>30.5</td>
<td>10.1</td>
<td>0.2</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>2018</td>
<td>65.4</td>
<td>27.4</td>
<td>7.1</td>
<td>0.1</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Train with five predictors (SA, TV, SD, GA, OI) in the ozone era, predict with historical SA, TV, SD combined with GA and OI from the test year.

<table>
<thead>
<tr>
<th>TEST YEAR</th>
<th>ATTAINMENT</th>
<th>MARGINAL</th>
<th>MODERATE</th>
<th>SERIOUS</th>
<th>SEVERE</th>
<th>EXTREME</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>34.1</td>
<td>35.9</td>
<td>23.8</td>
<td>6.2</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>2011</td>
<td>44.3</td>
<td>35.1</td>
<td>18.8</td>
<td>1.8</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>2012</td>
<td>36.7</td>
<td>36.3</td>
<td>23.3</td>
<td>3.7</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>2013</td>
<td>23.4</td>
<td>37.4</td>
<td>34.4</td>
<td>4.8</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>2014</td>
<td>59.4</td>
<td>34.9</td>
<td>5.6</td>
<td>0.1</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>2015</td>
<td>70.1</td>
<td>25.7</td>
<td>4.1</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>2016</td>
<td>54.4</td>
<td>31.9</td>
<td>13.0</td>
<td>0.7</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>2017</td>
<td>67.1</td>
<td>26.1</td>
<td>6.8</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>2018</td>
<td>80.0</td>
<td>17.8</td>
<td>2.2</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

12.5. Future Work

As mentioned above, future work will add generalized additive models (Hastie and Tibshirani, 1990, 1995) to the repertoire of regression models under consideration, with the goals of properly treating the snow-depth saturation effect, the end-point bias inherent in the random forest models, and better assessment of the impact of fluctuations in natural gas and oil production.

Work to develop an effective ozone forecasting model will also continue along two separate paths, first, using the Vernal Airport temperature data in place of the lapse rate, and second, using model calculations to train the models, to be followed with adoption of the preferred path.

More information about these plans is available in Section 17.15.
13. Ozone Alert Program

Authors: Seth Lyman, Huy Tran, Marc Mansfield

13.1. Introduction

At the request of oil and gas industry representatives, and with input from Utah DAQ, TriCounty Health, and several oil and gas companies, we created a program to alert oil and gas companies when high winter ozone was forecast. The program includes a web page, http://binghamresearch.usu.edu/OzoneAlert, to describe the program and a widget to allow individuals to sign up to receive alerts (Figure 13-1). The webpage lists the current air quality forecast and actions companies might consider taking if high ozone occurs. When individuals sign up at the web page, we collect their name, company name, and email. We send everyone on the list an email when (a) high ozone is forecast, (b) high ozone was forecast but did not materialize, and (c) a high ozone episode ends or is forecasted to end.

![Sign Up for Winter Ozone Alerts!]

The USU Bingham Research Center has partnered with the Utah Department of Environmental Quality (UDEQ) to provide email alerts when ozone exceeding EPA standards is forecast for the Uintah Basin. The purpose of these alerts is to provide the oil and gas industry with real-time information about air quality in the Basin so they can take action to reduce emissions of ozone-forming pollutants.

Sign up using the form below. When you sign up, we will send you emails:
1. Two days in advance of when air quality in exceedance of EPA standards is forecast,
2. When an inversion episode ends (or if one was forecast but did not materialize).

You will receive a subscription confirmation email after you submit this form.

Figure 13-1. Screenshot from the ozone alert program web page.

13.2. Development of an Ozone Forecast Model

Based on the findings of Mansfield (2018), we have developed a statistical tool in the form of a random forest algorithm to predict winter ozone concentrations (see Section 12). To improve our ability to forecast ozone in the Uinta Basin, we coupled this statistical tool with output from the High-Resolution Rapid Refresh (HRRR) 48-hr weather forecast data at a horizontal resolution of 3 km. Unfortunately, the
ozone forecast model did not successfully predict the high ozone episodes that occurred during winter 2018-19. We have identified discrepancies in forecast algorithms and are working on an improved version of the forecast model (Section 12).

13.3. Ozone Alert Emails

Since our ozone forecast model was unsuccessful in predicting high ozone episodes, we relied on our understanding of the relationship between meteorological conditions and ozone levels to conduct qualitative predictions of high ozone events. In general, we predict high ozone events when the following meteorological conditions existed in weather forecast:

- Sufficient snow cover to enhance shortwave radiation fluxes that are needed for ozone photochemistry and to sustain atmospheric inversions.
- A strong and persistent inversion layer that keeps ozone and its precursors accumulating within the surface layer. Because of the persistent inversion layer, ozone was often observed building up for several days preceding days that exceeded the EPA ozone standard. Strong inversion conditions, however, become less important late in the winter season when solar insolation increases.
- High barometric pressure, clear sky, and strong solar radiation.

We predicted the end of high ozone episodes when the weather forecast suggested low pressure or a frontal system would pass through the Uinta Basin. These conditions break up the atmospheric inversion layer and purge polluted air.

During winter 2018-19, we had 102 subscribers to our email-based ozone alert program, among which 32% were from industry (mostly oil and gas producers); 21% were from regulatory agencies (i.e., Utah DEQ, EPA, Ute Tribe, BLM, Tri-County Health); 21% were private citizens; 11% were from other agencies/organizations; 11% were academic researchers; 4% were working in media, and 2% were from environmental groups.

During winter 2018-19, we issued seven ozone alerts to our subscribers. An excerpt of an ozone alert email that was sent out on 25 January 2019 is shown here as an example:

```
ALERT: There is a reasonable likelihood that ozone in the Uinta Basin will exceed the EPA standard within the next several days. Conditions associated with ozone exceedances will remain until at least this weekend. Please take actions that will reduce ozone-forming emissions. For those in the oil and gas industry, a list of possible actions is provided at [http://binghamresearch.usu.edu/OzoneAlert](http://binghamresearch.usu.edu/OzoneAlert).

DISCUSSION:

Ozone built up over the weekend as expected. The maximum hour-average ozone at Ouray was 76 ppb yesterday (the EPA standard is 70 ppb), and 8-hour average ozone (the regulatory value) was 70.4 (it doesn’t “count” as an exceedance unless it is 71.0 or higher).

A front just passed us last night, but it was not strong enough to break up the inversion, as indicated by the fact that particulate matter is still high at several monitoring stations and ozone is already increasing this morning. It is possible that the inversion will still briefly break up and mix out today or tomorrow, but I don’t think so. Even if it does, the forecast is for high pressure over top of us for at least the remainder of the
```
The inversion was weak over this past weekend because we were between high pressure to the west and lower pressure to the east, but now the high pressure system is predicted to stagnate right on top of us for the whole week. This means the inversion will be stronger. Also, every week we move away from the winter solstice gives us more sunlight, allowing ozone more time each day to build up and more energy so it can form at an increased rate.

What this means is that, while we have been pushing up against the EPA standard over the past two weekends, this week we are very likely to blow past it. Also, the inversion until now has been shallow, affecting lower elevation sites only, and it has broken up and mixed out in Vernal each afternoon, but we can expect the inversion to build up and out to the edges of the Basin this week, probably leading to impaired air quality even in Vernal.

If you would like more information, please contact us. If you do not wish to receive these emails, please let me know.

You can view real-time air quality data for the entire Basin at any time here (our data feed for Myton, Dinosaur, and Rangely is still having trouble, so those data may not be updating in a timely way. We expect to have this problem fixed within the next couple of days).

The following is a list of the ozone alerts issued, along with information about prediction quality, during winter 2018-2019 (also see Figure 13-2):

- January 19 - 21 (Alert 1) and January 25 - 27 (Alert 2): We were not confident enough to send an alert until after ozone had started to build.
- January 29 – February 2 (Alert 3): We predicted the inversion breakup one day early.
- February 10 (Alert 4): We were not confident enough to send an ozone alert before the exceedance day. Instead, we sent alert on the day that ozone exceedance occurred. We also did not foresee the ozone exceedances that occurred on February 12-14.
- February 21 – March 3 (Alert 5): We predicted ozone would exceed the EPA standard during these days. This was the strongest ozone episode that occurred during this winter. On February 26, we sent out an email entitled “Continuing Episode Alert” that discussed the ongoing high ozone episode and alerted subscribers that we were not able to predict when the episode would end. On March 3 we sent an “End of Episode Alert” to inform subscribers that the high ozone episode was over.
- March 6 (Alert 6) and March 16 – 17 (Alert 7): We predicted that ozone was likely to exceed EPA standard on these days. In fact, ozone was building on these days but was not strong enough to exceed the standard.
13.4. Ozone Alert Survey

We sent an invitation to subscribers of our email-based ozone alert program to participate in a survey about their experience. The survey form is available at https://forms.gle/Y63myPxDuRvNijAR8. The objectives of the survey were to evaluate the effectiveness of the alert program and to understand how it can be improved. We received 30 survey responses, including responses from eight private citizens, three academics, ten representatives from government, two representatives of environmental advocacy organizations, seven industry representatives, and one journalist. 77% of the survey respondents live in the Uinta Basin. Many of the survey questions asked respondents to rate their level of agreement with a statement on a scale of one to five. Table 13-1 provides the results of these questions. The table shows that, in general, respondents found ozone alerts to be useful and indicated that they were not too long or technical. 28 respondents reported that they found the Ozone Alert system “helpful,” and the other two respondents reported that it was “somewhat” helpful.

Only 30% of respondents chose a four or a five in response to the statement, “Because of the alerts, I made efforts to limit activities that would add to the pollution,” and only one industry respondent chose a four or a five. Since the primary purpose of the Ozone Alert program is to provide industry with information that helps them reduce ozone-forming emissions, this result is concerning. Industry respondents, however, were somewhat likely to indicate that they or their companies implemented emission reduction practices (Table 13-1).
Table 13.1. Results of survey questions that asked respondents to rate their level of agreement with given statements. A response of one indicated complete disagreement, and a response of five indicated complete agreement. Responses are shown as means ± 95% confidence intervals.

<table>
<thead>
<tr>
<th>Statement</th>
<th>Response</th>
<th>Industry Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>I paid close attention to the ozone alerts and acted on them as soon as I received them.</td>
<td>3.8 ± 0.4</td>
<td>3.2 ± 0.6</td>
</tr>
<tr>
<td>Ozone alert messages are too long or take too much of my time to read.</td>
<td>1.7 ± 0.4</td>
<td>2.0 ± 0.9</td>
</tr>
<tr>
<td>Ozone alert messages are too technical.</td>
<td>1.8 ± 0.4</td>
<td>2.2 ± 1.0</td>
</tr>
<tr>
<td>Ozone alert forecasts do not accurately predict high ozone days.</td>
<td>2.1 ± 0.4</td>
<td>2.0 ± 0.9</td>
</tr>
<tr>
<td>Because of the alerts, I made efforts to limit activities that would add to the pollution.</td>
<td>3.1 ± 0.5</td>
<td>2.4 ± 1.1</td>
</tr>
<tr>
<td>Because of the alerts, I made efforts to limit my exposure to ozone in the atmosphere.</td>
<td>3.0 ± 0.5</td>
<td>2.6 ± 1.1</td>
</tr>
<tr>
<td>The alerts provide a useful informational tool.</td>
<td>4.4 ± 0.3</td>
<td>3.8 ± 0.6</td>
</tr>
<tr>
<td>I would like to see informational or educational materials or presentations about ozone in the Uinta Basin.</td>
<td>4.2 ± 0.4</td>
<td>4.0 ± 1.5</td>
</tr>
<tr>
<td>I/we implemented ozone mitigation practices in response to USU's ozone alerts. (Examples include: Minimizing blowdowns, deferring or delaying liquids hauling or refueling, and minimizing truck idling during ozone alerts.)</td>
<td>2.6 ± 0.8</td>
<td>3.4 ± 1.1</td>
</tr>
<tr>
<td>I/we implemented continual winter practices prior to or during ozone season (Jan to Mar). (Examples include: IR camera or AVO surveys, leak detection and repair practices, inspection and maintenance of equipment.)</td>
<td>2.8 ± 0.9</td>
<td>3.6 ± 1.7</td>
</tr>
<tr>
<td>I/we perform staff training on minimizing VOC and NOx emissions and on how to use USU and UDAQ air monitoring apps.</td>
<td>2.4 ± 1.0</td>
<td>2.8 ± 2.0</td>
</tr>
</tbody>
</table>

13.5. Future Work

We will continue the Ozone Alert program during the 2019-20 winter. We will work to improve the program by (1) improving numerical ozone forecasts and (2) rolling out a web-based ozone forecast tool that is under development.

13.6. Acknowledgments

The ozone alert program is operated with funds from the Utah Legislature, the Uintah Impact Mitigation Special Service District, and the Utah Clean Air Partnership (UCAIR).

Authors: Workshop participants

14.1. Summary of the Workshop

A workshop was held at Utah State University in Logan, Utah, on 27 March 2019. Representatives from the oil and gas industry, air quality regulators, environmental advocacy organizations, and academic researchers attended. The objectives of the workshop were to:

1. Share technical information about three-dimensional photochemical models of wintertime air quality so those developing these models can avoid duplicated effort and have access to the latest model improvements and techniques, and
2. Connect researchers with regulators and industry to ensure that wintertime air quality models developed are relevant to all stakeholder needs.

This document describes the outcomes and recommendations of the workshop, as compiled from verbal and written comments by workshop attendees. The document doesn’t necessarily represent the views of all workshop participants. Instead, it attempts to provide a consensus view of what needs to be done to improve three-dimensional photochemical models of wintertime ozone.

14.2. Background

Extensive scientific work has been done to better understand winter ozone formation over the past decade. Winter ozone is a unique air quality issue that is at the intersection of research science and regulatory requirements. Ultimately, the primary impetus for these research efforts is to develop effective tools and strategies for air quality management and planning as required by the Clean Air Act. All comprehensive technical studies to-date have considered both known drivers for winter ozone: the ambient environmental conditions (e.g., snow cover, meteorology, deposition) and the presence of ozone precursors. It is important that a balanced and transparent approach continues in the Uinta Basin so that any future air quality management is based on the best science and therefore be most effective.

An important air quality management tool for the Uinta Basin may be the use of photochemical grid models. These models attempt to replicate the production of ozone during wintertime stagnation events. The conceptual model for winter ozone formation is well established and includes many meteorological and physical phenomena that have been difficult to replicate in meteorological and photochemical modeling. The contrast between years 2012 and 2013 in measured precursor and ozone concentrations demonstrates the importance of antecedent meteorological conditions for the production of winter ozone (Stoeckenius et al., 2014). This importance was reaffirmed in 2018 and 2019 based on the difference in winter ozone production between those years. The difference in winter ozone production between these years is attributed to a lack of snow cover (Lyman et al., 2018a). The driving meteorological phenomena include sunlight, snow cover, low mixing heights, vertical temperature inversions, and low speeds with variable directions. These conditions enhance photolysis, increase the strength of the inversion, have the “effect of reducing the vertical movement of the
precursors,” and limiting “the horizontal movement and dispersion of precursors” (Martin et al., 2011; Schnell et al., 2009). Modeling sensitivity tests for these, and other, physical phenomena have been well documented and continue, e.g., Ahmadov et al. (2015); Lyman and Tran (2015a); Matichuk et al. (2017); Neemann et al. (2015); Tran et al. (2018).

When generating emission inputs for photochemical models, the emissions are spatially allocated into the resolution of the modeled grid, e.g., 4 km. Also, the use of annual emission inventories will not capture the actual emissions that may have been occurring during the high ozone event. Both of these simplifications will introduce errors into the analysis. It is noted that several analyses have attempted to adjust the modeled precursor emission inventory with varying degrees of success (Ahmadov et al., 2015; Emery et al., 2015; Matichuk et al., 2017). Precursor emissions are heterogeneously spread across the Basin as captured by the aircraft transects during UBOS 2013 and documented elsewhere (Karion et al., 2013; Oltmans et al., 2014; Stoeckenius et al., 2014). Under the low wind speed, stable atmospheric conditions, precursor emissions were observed to “not advect far from their original source” (Stoeckenius et al., 2014). At the beginning of the high ozone period in early February 2013, the aircraft transects reveal isolated pockets of elevated ozone on 1 February 2013 with following days showing more areal coverage of higher ozone until the entire Basin is observed to have high ozone after several days. The observed ozone concentration gradients at the beginning of the episode indicate extreme, local-scale ozone production that can evolve into a basin-wide high ozone event if conditions persist.

In spite of these challenges, significant progress towards better understanding the winter ozone phenomenon has been made. Leveraging existing knowledge and openly integrating new information into the air quality management requirements for the Basin will lead to the most effective and workable solutions. As discussed in the Breakout group recommendations, there are several areas in which the emission inventory can be improved, including a higher temporal resolution, other inventory estimation approaches, and additional emission measurement campaigns. As also discussed during the Breakout groups, there are many environmental factors that still need to be addressed to ensure any model success is for the right reason. These factors include better coupling of meteorology and chemistry; mountain-valley flows and ventilation of the basin; a more refined or alternative approach to the treatment of turbulence in the surface layer; and snow-air exchanges of ozone precursors. It is imperative that further studies and evaluations continue on the meteorological and physical aspects of wintertime ozone formation so that a robust platform will be developed to guide the regulatory process.

14.3. Discussion About Regulatory and Industry Perspective on Model Needs

- It is important to have a unified model across regulatory jurisdictions, so decisions made from the model are also unified.
- A stakeholder process is needed to allow industry and regulators to be part of the model development process, including for model development work done by research groups.
  - Collaborative work done in the Upper Green River Basin is highlighted here.
- Emissions inventories have variability that may stymie successful implementation in regulatory models used for wintertime inversion episodes, including the inability to account for or spatially allocate large emission sources, and the lack of information about seasonal emissions.
- Previous modeling studies have shown that organics emissions are too low in inventories, and some studies have shown that NOx emissions are too high, but the apparent inventory problems
in models could instead be due to poor characterization of inversion height and/or poor
characterization of air exchange with the clean atmosphere outside of the inversion.
  ○ There is some disagreement about the level of confidence we should give to model-
derived assessments of the level of inventoried emissions.
• It is important that we have certainty that models get the right answer (i.e., the right amount of
  ozone) for the right reason. We need to be sure that we understand the system well enough
that we can have confidence in decisions made from the models.

14.4. Emissions Breakout Group Recommendations

14.4.1. What are we missing from current emissions inventories?

• Sources with anomalously high emissions, whether because of malfunction or emergencies
• Gathering pipeline emissions
• Current UDAQ emission inventories do not include methane emissions. Given the methane
  observations and interest in methane, better understanding these emissions could help
  emissions of other species (e.g., more reactive ozone precursors) as well
• Alcohols and carbonyls
  ○ In some cases, alcohols and carbonyls may be missing from the inventory or improperly
    allocated in speciation profiles. It is also possible that model chemistry does not
    produce enough carbonyls via photochemical reactions.
• Improvements to emission estimations from evaporation ponds--especially methods to
  represent temporal and facility-to-facility variability
• Well-specific composition data and better composition information from other sources.
• NOx emissions are apparently too high, while some evidence suggests organics emissions are too
  low.
• Lack of data for maintenance-related emissions (frequency and magnitude).

14.4.2. Solutions

• Seasonal / monthly emissions inventory – increase wintertime temporal resolution
• Perform additional statistical analysis on the inventory to examine trends
• Fund more research studies to attempt to understand emissions sources/volumes
• Explore alternative methods for estimating emissions beyond the inventory
  ○ Investigate the potential role of methanol as a precursor
• Compare 3-D photochemical model/inventory output against NOx and organics measurement
  data to determine areas or perhaps source types where inventory appears to be working more
  poorly.
• To reduce emissions, we could create better incentives for:
  ○ LDAR programs
  ○ Produced water recycling
  ○ Contractors/operators/employees reporting when they do maintenance and on what
  component

14.4.3. Hurdles

• Emissions (especially fugitives) are difficult to quantify in an inventory
Hurdles to emissions reductions:
- Solutions are often not economical for oil and gas operators
- Complicated air quality jurisdiction in the Uinta Basin
- A credit and banking system would need to be approached carefully and tailored for the area
  - California is a poor model
  - Property values may drastically change

14.5. Meteorology Breakout Group Recommendations

14.5.1. What is being or has recently been done to improve this aspect of modeling?
- Solutions have been implemented or are in the works for model problems with snow albedo, clouds, land cover, leaf area index, and surface-level and vertical data assimilation.
- Ozone deposition to snow is near zero and has been included in photochemical models

14.5.2. What hurdles or gaps remain that need to be addressed?
- WRF-Chem, which uses online coupling of meteorology and chemistry, appears to give reasonable performance in simulating winter O3 concentration in Uinta Basin in 2013 (Ahmadov et al., 2015). Efforts are underway to investigate if online coupling of meteorology and chemistry WRF-Chem (or WRF-CMAQ) would be a factor (compared to conventional offline-1hr coupling) to improve photochemical model performance in simulating ozone concentrations in Uinta Basin.
- Mountain-valley wind flow is well understood in general, but it may not be captured well in WRF. Measurement and modeling work is needed to investigate this.
- Air-snow exchange of ozone precursors is poorly understood and not adequately captured in models. Nitric acid deposition is probably overestimated. Some measurements are being made for organics (hydrocarbons, alcohols, and carbonyls), but the dataset is too small right now to be useful for model updates.
- Data assimilation works in a test case, but more measurement and modeling work are needed to ensure vertical mixing, inversion height, and loss and input of air at basin margins are accounted for in WRF outputs.
- WRF does not capture light winds well, and light wind conditions are dominant under inversion.
- It is important to consider which metrics need to be evaluated and how they should be evaluated when evaluating WRF performance. Standardization of evaluation techniques would be useful.
- The meteorological year for regulatory modeling is uncertain.

14.5.3. What options exist for addressing these hurdles?
- A multi-investigator measurement campaign, with good spatial coverage around the Basin, followed up by modeling work, would allow for model improvement in some of these areas. The campaign would focus on vertical conditions and conditions at the inversion margins. Addition of chemical measurements would help.
• BLM is working to install SODAR and radiometer measurements to continuously remotely sense vertical conditions of the atmosphere in the Basin. These measurements will be used to verify models and for data assimilation. U of U already has a ceilometer in the Basin.
• Model ensembles, including perhaps an “analog” ensemble, could provide accuracy with less computational cost.
• Large-eddy simulations, or something approximating it, could be useful in better simulating meteorology in complex terrain and a stable atmosphere. But it is also possible that better model resolution won’t improve model results.
  ○ One approach to address these complex, sub-grid scale processes during the onset of high ozone period would be using the 'plume in grid' approach or possibly a hybrid approach with AERMOD. CMAQ-APT can better resolve the fine-scale details of nearfield dispersion, transport, and chemistry. Based on a cursory review, it appears that has not been tested yet in Utah (or Wyoming) for winter ozone.

Author: Seth Lyman

This section contains information about our performance on overall goals for Uinta Basin air quality research, and performance for annual project objectives for the 2018-19 reporting period. Our management plan, which describes our group’s overall goals and objectives, is available here: https://usu.box.com/s/19t1dj3t1ztb49ix0aav7p8i5p18ewaf.

15.1. Research Output

The most basic outcome of our research is publications and presentations that describe our work and make it available to the public. Here we list the publications and presentations we have produced during the reporting period.

15.1.1. Publications


15.1.2. Presentations

Tran H., Tran T., Mansfield M., Lyman S., December 2018. Investigations of impacts of VOC emissions from produced water disposal facilities on winter ozone pollution in the Uinta Basin using modeling techniques. Presentation at the American Geophysical Union Fall Meeting, Washington, D.C.


O’Neil T., Lyman S., Elgiar T., September 2019. Routine, stable verification of atmospheric oxidized mercury measurements is possible. Presentation at the International Conference on Mercury as a Global Pollutant, Krakow, Poland.

Elgiar T., Lyman S., O’Neil T., Gustin M.S., Luippold A., Dunham-Cheatham S., September 2019. Ozone may not be an important oxidant of atmospheric mercury. Presentation at the International Conference on Mercury as a Global Pollutant, Krakow, Poland.


Lyman S., September 2019. Utah’s Uinta Basin: A unique natural laboratory for ozone and mercury chemistry. Seminar given at the School of the Environment, Nanjing University, Nanjing, China.

Lyman S., October 2019. Uinta Basin air quality research project: 2019 report. Given to the Natural Resources, Agriculture, and Environment Interim Committee of the Utah Legislature, Salt Lake City, Utah.


15.2. Funding

We have received $10,025,000 in research funding since 2011, including $8,325,000 in funding for research specific to the wintertime ozone issue. Figure 15-1 shows the funding we have received, organized by year and type of funding source.
Figure 15-1. Funding received by our research group since 2011, categorized by type of funding source. Each bar shows the amount of funding awarded in the year indicated, even though a portion of those funds may have been spent in subsequent years.

Figure 15-2 shows a breakdown of our team’s funding by source type. 34% of our funding has come from federal government sources, including the Bureau of Land Management, the U.S. Department of Energy, the U.S. Department of Defense, the National Science Foundation, and the U.S. Environmental Protection Agency. 35% has come from the state of Utah, including the Utah Legislature, the Utah Division of Air Quality, the Utah Science, Technology and Research Initiative, the Utah School and Institutional Trust Lands Administration, and TriCounty Health. 25% has come from the Uintah Impact Mitigation Special Service District (classified as local government in the figures in this section). 3% each has come from the Ute Indian Tribe and the State of Wyoming. 1% has come from private companies and foundations, and less than 0.1% has come from foreign entities.

Figure 15-2. All funding sources for our research team, from 2011 to the present.
83% of our funding has been for work specifically for projects related to wintertime ozone. Figure 15-3 shows a breakdown of funding sources for this portion of our research. Compared to our research funding as a whole, a greater portion of our winter ozone-specific research has come from the state of Utah (42%) and local government (30%), while less has come from federal government agencies (20%).

![Figure 15-3. Sources of funding for our research team for wintertime ozone projects, from 2011 to the present.](image)

### 15.3. Stakeholder Engagement

The mission of our research is to provide information that helps stakeholders (industry, regulators, and others) make better decisions about air quality. Thus, in addition to our research output, we strive to engage stakeholders in our research process and help them understand and utilize the information we produce. In this section, we report on our efforts to accomplish this goal during the reporting period.

#### 15.3.1. Stakeholder Guidance Committee

We engaged our stakeholder guidance committee to review and provide comments on our management plan ([https://usu.box.com/s/19t1dj3t1ztb49ix0aav7p8i5p18ewaf](https://usu.box.com/s/19t1dj3t1ztb49ix0aav7p8i5p18ewaf)), our research priorities (Section 16), and our research plan for the coming year (Section 16). We provided committee members with a draft plan, a draft of this 2019 annual report, and our management plan on 17 October and invited them to review these documents and provide comments. We held a meeting on 25 October to discuss the documents with the committee. We made changes to the research priorities list and the project objectives document in response to comments received from the committee. Members of the committee included representatives from:

- Utah Petroleum Association
- Local oil and gas companies
- Uintah Impact Mitigation Special Service District
- Duchesne County
- Utah Division of Air Quality
- TriCounty Health
- Bureau of Land Management
15.3.2. Winter Ozone Modeling Workshop

We hosted a workshop on 27 March 2019 to bring stakeholders together to discuss the most important priorities for improving computer simulations of wintertime ozone. A report of the outcomes of the workshop is available in Section 14.

15.3.3. Ozone Alert Program

Section 13 provides information about our ozone alert program, which alerts industry and others when high ozone is expected so they can reduce emissions when it matters most.

15.3.4. Uinta Basin Ozone Working Group

In 2018 we worked with individuals from government, industry, and environmental advocacy organizations to organize the Uinta Basin ozone working group. The purpose of this group is to determine and promote actions that will reduce wintertime ozone in the Uinta Basin. The group’s website is here: https://basinozonegroup.org/. We have given presentations to the group about the science of wintertime ozone, we actively participate in all working group meetings, and Marc Mansfield serves on the group’s steering committee.

15.3.5. Other Stakeholder Engagement Activities

Below we list additional actions undertaken to learn from and provide information to government entities, industry, and the public. This list does not include formal presentations given or reports produced since those are already listed in Section 15.1.

- [ubair.usu.edu](http://ubair.usu.edu), our real-time air quality data website, had 442 unique users who visited the website in 2,021 sessions over the last 12 months. This is 8% more users than the previous 12-month period. Visits to the website increased when air quality worsened during winter months, as shown in Figure 15-4.
• **binghamresearch.usu.edu**, our team’s main website, had 2,178 unique users who visited the site in 3,312 sessions during the past 12 months. This is 35% more users than the previous 12-month period. Users accessed our homepage, information about our research team, our reports page, our ozone alert page, our page about the winter modeling workshop, and our data access page.

• We have given periodic reports to the Uintah Impact Mitigation Special Service District board about our ongoing activities.

• We provided our annual report and specific project reports to members of our stakeholder committee and others in government and industry upon request.

• At their request, we provided research summaries and datasets to officials in industry and government.

• In April 2019, we participated in a field trip by middle school students to the USU Vernal campus. We taught students about air quality and helped them try out our emissions measurement equipment. In June, we participated in the USU summer science camp, teaching students about ozone and particulate matter and helping them build a particulate matter sensor with an Arduino microcomputer. In September Seth Lyman gave a presentation about air quality to students at Uintah Middle School.

### 15.4. Stakeholder Survey

We created a survey to solicit information from stakeholders about how our research products are used and how we can improve the effectiveness of our team’s operations. The survey is available at [https://forms.gle/ENTYC2uW6BgNwosB9](https://forms.gle/ENTYC2uW6BgNwosB9). We sent the survey to 81 people who work in all levels of government, the energy industry, and environmental advocacy organizations.

We received eight responses to the survey. The survey respondents identified as the following:

- Appointed official in county government
- Regulatory or land management agency representative in federal government (2)
- Outdoor recreation economy consultant
We asked respondents to answer the open-ended question, “How have you and the organization you represent used information generated by USU’s Uinta Basin air quality research team? Please be specific.” Four respondents indicated that they use the data we generate, including our real-time data website (http://ubair.usu.edu), to make decisions that impact public health or to reduce emissions. Four respondents indicated that they use our research output in decision-making within their organization, including regulatory decision-making. One respondent indicated they use our research products to educate the public and students about air quality.

We asked respondents to rate their level of agreement with three statements about our research. Table 15-1 shows the questions asked and the responses received.

**Table 15-1. Results of survey questions that asked respondents to rate their level of agreement with given statements.** A response of one indicated complete disagreement, and a response of ten indicated complete agreement. Responses are shown as means ± 95% confidence intervals.

| Statement                                                                 | Response  
|---------------------------------------------------------------------------|----------
| USU’s Uinta Basin air quality research helps the local public understand and respond to air quality issues. | 8.8 ± 1.2 |
| USU’s Uinta Basin air quality research helps industry respond more effectively to air quality issues. | 8.5 ± 2.0 |
| USU’s Uinta Basin air quality research helps government agencies make better decisions. | 9.1 ± 1.5 |

We asked respondents what specific actions we could take to improve our research program. We received the following responses.

- Keep improving the ozone forecasting model and implement the plans for 2019-20.
- Collaborate with other organizations to ensure use of the most current and accurate emissions inventories and speciation profiles.
- Propose effective best practices to industry to achieve air quality improvement.
- Air quality is a complex topic. Much of USU's research is technical, and USU could do more to make the technical aspect understandable to industry and the public. That's a difficult task, but could allow everyone to better understand how their actions impact air quality and make individual changes.
- Continued improvements in air modeling.
- Higher budget

We asked respondents what specific actions we could undertake to ensure our research products are used by stakeholders. We received the following responses.

- Can you partner with TriCounty Health to ensure that the public knows (via all forms of news and social media) of forecast exceedance events and, most importantly, what voluntary actions individuals can take to reduce emissions and ozone levels?
- Offer seminars to elected officials at all levels of government.
• Outreach to industry is already pretty good. There could be some usefulness in providing industry a means for quantifying the impact of their emissions reduction measures. I've seen similar tools for carpooling and using alternate forms of transportation.
• For the public, you could have an Air Quality 101 page on your website.
• Provide us research document links we can place on our websites.
• I don't think that it should be tied to the research team, but I think having a policy expert who is well versed in the research but also well versed in policy that could help form positive policy and change strategies would be ideal. However, I think that this person would need to have some distance from the team so that the team can continue to operate with an unbiased approach to understanding the truth.
• Dedicated communications staff person.

We are already working to accomplish many of the suggestions made by respondents to the stakeholder survey, and we have incorporated these suggestions into our research plan for the next year, which is available in Section 16.

15.5. Student Involvement and Training

A generous endowment from Anadarko Petroleum Corporation has provided funds for students to participate in Uinta Basin air quality research. We used these funds to hire Makenzie Holmes in spring 2018 and Tyler Elgiar in January 2019 (http://binghamresearch.usu.edu/studentfellowship).

Makenzie is an undergraduate biology student at our campus. She analyzes samples for concentrations of organic compounds in our laboratory and has participated in several field projects. She has attended several research conferences and is working with Seth Lyman on a publication about her research. Makenzie participated in analysis of data collected from portable monitoring stations last winter, and she is a co-author of Section 5 of this report. Tyler is an undergraduate wildlife student. He performs maintenance and repairs at our field sites and has participated in building and testing new research instrumentation. Tyler is working with Seth Lyman and Marc Mansfield on a peer-reviewed publication.

15.6. Data Management, Quality, and Dissemination

15.6.1. Data Management

As described in our management plan, all measurement data we have generated during the reporting period has been stored on a cloud-based data storage server, with regular backups to local, removable hard drives. We have collected field and laboratory notes using a secure, cloud-based electronic note-taking software that complies with 21 CFR part 11 of the Federal Code. We stored all instrument maintenance, calibration, and repair information within this management structure. We used established standard operating procedures for our work. These are publicly available here: http://binghamresearch.usu.edu/team_pages/std_operating_proced.
15.6.2. Data Quality

Table 15-2 shows a summary of data quality results for ambient air measurements we collected during the reporting period. The maximum uptime possible for most measurements shown in the table is about 95% due to maintenance and calibration periods.

Table 15-2. Data quality summary for ozone, NOx, carbon monoxide (CO), and organic compound data collected during 2018-19. Results are shown as average ± 95% confidence intervals for all locations at which the indicated measurements were collected, where applicable (applicable if n > 3). For a list of measurements collected and sites of collection, see Table 2-1. Percent uptime indicates the percent of the measurement period for which valid measurements were obtained. NMHC indicates non-methane hydrocarbons. N/A means not applicable.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Zero calib. (ppb)</th>
<th>Span calib. (% recov.)</th>
<th>Percent uptime</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ozone</td>
<td>0.6 ± 0.3</td>
<td>101 ± 1</td>
<td>87 ± 24</td>
</tr>
<tr>
<td>NO</td>
<td>-0.2 ± 0.1</td>
<td>98 ± 3</td>
<td>95 ± 3</td>
</tr>
<tr>
<td>NO\textsubscript{x} (NO calib.)</td>
<td>0.2 ± 0.3</td>
<td>101 ± 2</td>
<td>95 ± 3</td>
</tr>
<tr>
<td>NO\textsubscript{y} (NO calib.)</td>
<td>0.2 ± 0.1</td>
<td>97 ± 2</td>
<td>94</td>
</tr>
<tr>
<td>NO\textsubscript{x} (GPT calib.)</td>
<td>N/A</td>
<td>94 ± 4</td>
<td>95 ± 3</td>
</tr>
<tr>
<td>NO\textsubscript{y} (GPT calib.)</td>
<td>N/A</td>
<td>97 ± 7</td>
<td>94</td>
</tr>
<tr>
<td>CO</td>
<td>16 ± 6</td>
<td>99 ± 2</td>
<td>96</td>
</tr>
<tr>
<td>Methane</td>
<td>233 ± 124</td>
<td>103 ± 1</td>
<td>79</td>
</tr>
<tr>
<td>Total NMHC</td>
<td>61 ± 29</td>
<td>101 ± 1</td>
<td>79</td>
</tr>
<tr>
<td>Speciated NMHC</td>
<td>0.06 ± 0.01</td>
<td>94 ± 0</td>
<td>81</td>
</tr>
<tr>
<td>PM\textsubscript{2.5} (BAM)</td>
<td>N/A</td>
<td>N/A</td>
<td>92</td>
</tr>
</tbody>
</table>

15.6.3. Data Dissemination

We have uploaded the winter 2018-19 ozone dataset (Section 2) and a 2011-2019 air chemistry and meteorology dataset for the Roosevelt, Castle Peak, and Horsepool monitoring stations to the data access page of our website, [http://binghamresearch.usu.edu/data_access](http://binghamresearch.usu.edu/data_access). We have also added a link to example videos and an anonymized dataset from our recent publication about an optical gas imaging survey of oil and gas wells conducted in 2018.

15.7. Outcomes from Annual Project Objectives

We established project objectives for the current reporting period in Section 14 of our previous annual report, which is available here: [https://usu.box.com/s/rigadr7yt7ipir4gzj75vfaazoe8u8mt](https://usu.box.com/s/rigadr7yt7ipir4gzj75vfaazoe8u8mt). In Table 15-3, we report on any discrepancies between planned work and actual outcomes for each of the project objectives outlined in the previous annual report.
Table 15-3. Outcomes of annual project objectives for the current reporting period.

<table>
<thead>
<tr>
<th>OBJECTIVE</th>
<th>OUTCOMES</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Stakeholder and Community Engagement</strong></td>
<td></td>
</tr>
<tr>
<td>Operate ubair.usu.edu website to display map-based, real-time air quality information to the public</td>
<td>We completed this objective for the reporting period (see information about performance in Section 15.3.5). We have re-established this objective for the coming year.</td>
</tr>
<tr>
<td>Operate the Ozone Alert program</td>
<td>We completed this objective (see information about performance in Section 13). We will continue operation of this program in the coming year.</td>
</tr>
<tr>
<td>Organize a winter air quality modeling workshop</td>
<td>We completed this objective (see information about outcomes in Section 14).</td>
</tr>
<tr>
<td><strong>Ambient Air Monitoring</strong></td>
<td></td>
</tr>
<tr>
<td>Operate air quality monitoring stations</td>
<td>We completed this objective (see information in Section 2 and Section 15.6). We will continue operation of these stations in the coming year.</td>
</tr>
<tr>
<td>Continue evaluation of long-term trends in ambient air chemistry</td>
<td>We completed this objective. See Section 4 of this report for information about our findings. We will continue updating this analysis each year.</td>
</tr>
<tr>
<td>Measure non-methane hydrocarbon and carbonyl fluxes at the air-snow interface</td>
<td>We completed this objective. See Section 7 of this report for information about our findings.</td>
</tr>
<tr>
<td>Deploy drone with meteorological instrumentation to characterize vertical structure of winter inversion episodes</td>
<td>We did not complete this objective. We purchased the drone, but it malfunctioned soon after we received it and had to be sent back to the manufacturer for repairs. We did not receive it from the manufacturer until after the winter season. We will carry out this objective during the coming winter.</td>
</tr>
<tr>
<td><strong>Air Quality Model Development</strong></td>
<td></td>
</tr>
<tr>
<td>Develop a quantitative method to forecast winter ozone</td>
<td>We did not succeed in developing a quantitative method to forecast winter ozone. Our method, which used output from the HRRR model as input for a statistical prediction of ozone concentration, was not successful because the HRRR model did not accurately simulate the winter inversion conditions that existed in the Uinta Basin during winter 2019. See information about this in Section 12. Our qualitative forecasts were reasonably successful during winter 2019 (see Section 13). We will continue this work in the coming year.</td>
</tr>
<tr>
<td>Continue investigation of data assimilation impacts on meteorological model performance</td>
<td>We have achieved this objective (see Section 8). We will submit a manuscript about this work for peer-reviewed publication soon.</td>
</tr>
<tr>
<td>OBJECTIVE</td>
<td>OUTCOMES</td>
</tr>
<tr>
<td>----------------------------------------------------</td>
<td>---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Investigate the impacts of online coupling of meteorology and chemistry in photochemical simulations of winter ozone.</td>
<td>We have not completed this objective. Section 9 provides information about our progress.</td>
</tr>
<tr>
<td>Investigate techniques to assimilate chemical and land cover data into photochemical models</td>
<td>We have not completed this objective. We have received funding from the Utah Division of Air Quality to continue this work over the coming year. Our progress so far is described in Section 11.</td>
</tr>
</tbody>
</table>

**Emissions Characterization**

<table>
<thead>
<tr>
<th>Emissions composition measurements</th>
<th>We completed most elements of this objective. A final report of this work will be released soon by the Utah Division of Air Quality. A summary of the report can be found in Section 6. We did not complete a model performance evaluation of the new composition information. This is planned for the coming year.</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-density measurements of organic compounds in oil and gas-producing areas</td>
<td>We completed this objective. The results are described in Section 5. We received funding from the Utah Division of Air Quality to continue this work in the coming year.</td>
</tr>
</tbody>
</table>
16. Priorities for Uinta Basin Winter Ozone Research

Authors: Seth Lyman, Huy Tran, Trang Tran, Marc Mansfield

The following is a working list of what we feel are the most important gaps in scientific understanding of the Uinta Basin wintertime ozone phenomenon. The purpose of this list is to guide current and future air quality research in the Uinta Basin. Our project objectives for the coming year (see next section) are designed to address these questions.

16.1. Air Chemistry

- How are ozone, NO\textsubscript{x}, and organic compound concentrations in the wintertime atmosphere changing spatially and over time due to changes in (1) industry operations and (2) the regulatory landscape?
- How does the snowpack physically and/or chemically process volatile organic compounds?

16.2. Air Quality Modeling

- How can we produce meteorological simulations that accurately represent surface-level and vertical conditions during wintertime inversion episodes?
- What model parameterizations and techniques best reproduce actual physical and chemical conditions during winter inversion episodes?
- How can we quantify non-local (summer and winter) influences to Uinta Basin air quality?

16.3. Emissions

- What specific oil and gas production processes and/or equipment types are responsible for discrepancies between inventoried and actual (i.e., directly measured) organic compound emissions from the oil and gas industry? Possible discrepancies include:
  a. Heavy-tailed distribution in the actual magnitude of emissions (i.e., a few very large sources that make up a significant portion of total emissions from all sources), compared with a normal distribution in inventoried emissions;
  b. Intermittent emissions not accounted for in inventories; and
  c. Sources that are either excluded from or not adequately accounted for in inventories.
- What is the composition of organic compounds (including alcohols and carbonyls) emitted from specific areas, industry processes, and/or equipment types?

16.4. Stakeholder Engagement

- How can we make sure all of our research output is useful to and utilized by regulators in their air quality modeling and decision-making activities.
- How can we work with industry and others to (1) facilitate emissions reductions and (2) improve our understanding of oil and gas processes that lead to emissions?
- How can we ensure that the work we carry out is useful to and utilized by regulators, industry, and others?
17. Research Plan for 2019-20

Authors: Seth Lyman, Trang Tran, Marc Mansfield, Huy Tran

This section provides information about our annual project objectives. It deals with specific activities we are currently undertaking or plan to undertake during the next year. Information about our general operations and goals are available in our management plan, which can be found here: https://usu.box.com/s/19t1dj3t1ztb49ix0aav7p8i5p18ewaf.

17.1. Real-time Data Website

We will continue to operate our real-time data website at ubair.usu.edu. The site provides data about air quality and meteorological conditions around the Uinta Basin and is used by industry, government, and the public to assess current air quality conditions.

- **Plan:** Trevor O’Neil and Seth Lyman will maintain, repair, and update the website as needed. We will show the website on our public display computer at the USU Bingham Building in Vernal. We will promote the site at events we attend with stakeholders and the public.
- **Responsible person:** Seth Lyman
- **How we will measure performance:** Number of unique users each year
- **Which priority this relates to:** Stakeholder Engagement (Section 16.4)

17.2. Ozone Alert Program

We will continue to operate our ozone alert program (http://binghamresearch.usu.edu/OzoneAlert). The purpose of the program is to alert oil and gas operators and others when high ozone is forecast so they can take action to reduce ozone-forming emissions. The primary form of communication for the alerts is email, but we also provide updates on Twitter, and we are developing a web app for the program.

We have discussed with stakeholders the value of receiving information from industry about specific actions taken in response to this program. We (USU) feel that we would need support and cooperation from a government agency to develop an adequate system to collect this information and encourage companies to participate. We will engage in discussions with agencies over the coming year to determine whether something like this will be possible for the future.

- **Plan:** Seth Lyman and Huy Tran will work together to determine when ozone alerts should be issued. Seth will send alert emails. Huy will develop and maintain the web app.
- **Responsible persons:** Seth Lyman and Huy Tran
- **How we will measure performance:** Number of unique users (including industry users), subscriber survey at the end of the season
- **Which priority this relates to:** Stakeholder Engagement (Section 16.4)
17.3. Uinta Basin Ozone Working Group

The Uinta Basin Ozone Working Group is a collaborative forum to facilitate attainment of the ozone standard in the Uinta Basin (https://basinozonegroup.org/). The group includes representation from government, industry, researchers, and environmental advocates. We will continue to participate in the ozone working group and do all we can to facilitate its success.

- **Plan:** Marc Mansfield will participate as a member of the group’s steering committee, and Seth Lyman, Huy Tran, and Trang Tran will participate in group meetings and provide information for the group as needed.
- **Responsible person:** Marc Mansfield
- **How we will measure performance:** Meeting attendance.
- **Which priority this relates to:** Stakeholder Engagement (Section 16.4)

17.4. Interact More Frequently With Stakeholders

Several stakeholders in industry and government have suggested that we provide more frequent opportunities to interact with our team regarding our research plans and progress. Stakeholders agreed that workshops or conferences that allow all stakeholders to come together to discuss the issue are important, though the timing, frequency, and location of such a meeting are still undetermined. Also, based on feedback from stakeholders, we will create and distributed short quarterly newsletters to update stakeholders on our progress and to solicit feedback. We will determine the best way to accomplish this and execute that plan in the coming year. At the end of the year, we will assess the effectiveness of the effort and make changes as needed.

- **Plan:** Seth Lyman will continue to communicate with stakeholders about the best way to organize a workshop. Seth will work with others in our research group to create and distribute the quarterly newsletters.
- **Responsible person:** Seth Lyman
- **How we will measure performance:** A satisfaction survey at the end of the reporting period.
- **Which priority this relates to:** Stakeholder Engagement (Section 16.4)

17.5. Make Fact Sheets to Summarize Study Results for Lay Readers

Stakeholders have requested that we produce fact sheets to summarize some of our work. We will

- **Plan:** Seth Lyman will work with others in our research group to create and distribute the fact sheets. He will also create a webpage that will be a repository for the fact sheets.
- **Responsible person:** Seth Lyman
- **How we will measure performance:** Number of visits to and downloads from the fact sheet webpage.
- **Which priority this relates to:** Stakeholder Engagement (Section 16.4)
17.6. Operate Ambient Air Monitoring Stations

We will operate meteorology and air quality monitoring equipment at the following stations during winter 2019-20 (15 November through 15 March):

- Horsepool
- Roosevelt
- Castle Peak
- Seven Sisters
- Willow Creek
- Fruitland

These stations are not official regulatory monitors but are instead operated for research purposes. They have two main purposes. The first is to measure chemical conditions around the Uinta Basin that are not captured at regulatory stations. Regulatory NO$_x$ instruments suffer from a high bias during winter inversion episodes and thus do not provide accurate NO$_x$ measurements (See Section 4 of Lyman et al. (2018a)), whereas we measure NO$_x$ via an unbiased technique at Horsepool, Roosevelt, and Castle Peak. Our measurements of speciated organic compounds at Horsepool and Roosevelt are the only ongoing organics measurements in the Uinta Basin. We also measure NO$_y$, CO, particulate matter smaller than 2.5 μm (PM$_{2.5}$), snow depth, solar radiation and albedo at various wavelengths, and, with new funding from the Utah Division of Air Quality (UDAQ), we will begin daily measurements of carbonyls at Horsepool and Castle Peak this winter.

The other purpose of our monitoring stations is to provide information about the spatial distribution of ozone in the Uinta Basin region. Many regulatory monitoring stations operate in the Uinta Basin, but they are not evenly distributed around the Basin. We operate ozone monitoring stations to provide a more spatially representative dataset to use in comparison with results from our photochemical modeling work (Figure 18-1).

![Figure 17-1. Air quality monitoring stations that will operate in the Uinta Basin during winter 2019-20.](image-url)
Some of our stations have operated since 2010, and the entire dataset, including data from regulatory stations and stations we operate, constitutes an essential long-term record of meteorology and air quality in the Uinta Basin.

- **Plan:** Seth Lyman, Trevor O'Neil, and student Tyler Elgjar will operate, maintain, and repair the monitoring stations. Seth, Trevor, and student Makenzie Holmes will analyze organic compound samples in the laboratory. Operations will begin in October 2019, with the goal of having all stations fully functional by 15 November 2019.
- **Responsible person:** Seth Lyman
- **How we will measure performance:** Data quality, data uptime, datasets available to the public, use of data in reports and publications.
- **Which priority this relates to:** Air Chemistry (Section 16.1)

### 17.7. Continue Investigation of Carbonyl Fluxes at the Air-snow Interface

It is well established that in polar regions, physical and chemical processes in the snowpack have a significant impact on the chemistry of the atmosphere. Snowpacks play two roles, (1) reservoirs and exchange media and (2) photochemical reactors. Compounds from the atmosphere can adsorb onto snow crystals either from the gas phase or from aerosols, and either when the crystals first form in the atmosphere or after the snow has accumulated on the ground. Re-release of these compounds, either to the atmosphere, the soil, or the hydrosphere, often follows a diel or a seasonal cycle. Photolysis of hydrogen peroxide, nitrate, nitrite, and organics in snow lead to OH and other radicals, which lead to the generation and release to the atmosphere of reactive species such as formaldehyde, reactive nitrogen, and halogen atoms. The reactions are usually assumed to occur in the quasi-liquid layer at the surface of ice crystals or in other liquid-like domains.

We have measured fluxes of organic compounds at the air-snow interface over the past several years. Our most recent work is described in Section 7 of our draft 2019 annual report. The field measurements described there show that carbonyl compounds, which are very active in winter ozone production, are emitted from the snow under some conditions. For this study, we will (1) build on those findings through laboratory studies designed to determine whether Uinta Basin snow acts merely as a reservoir for carbonyl compounds, or whether carbonyls are produced in the snowpack from other, less reactive compounds; and (2) conduct air quality modeling to determine the importance of compounds emitted from the snow in wintertime ozone chemistry.

#### 17.7.1. Laboratory Work

We will place snow in a PTFE bag in a customized chest freezer, and we will fill the bag with purified, organic compound-free air (Figure 18-2). We have already obtained 35 L of relatively pristine snow for this purpose from the Uinta Mountains. The chest freezer will be at -10°C. We will add organic compounds to the bag from certified compressed gas standards in a mixture that approximates their composition and concentrations in the Uinta Basin atmosphere. We will measure the composition of the air immediately after adding organic compounds, and again after several hours. Since others have shown that solar radiation impacts snow chemistry (see discussion above), we will install mirrors on the freezer’s inside walls, and for some tests, we will operate the apparatus outdoors with an ultraviolet-transparent glass cover on the freezer. The PTFE bags we will use transmit 80% of ultraviolet light.
We will collect whole-air samples in silonite-coated stainless steel canisters and analyze them for volatile hydrocarbons and alcohols by cold-trap preconcentration followed by gas chromatography and mass spectrometric detection. We will collect carbonyls onto two dinitrophenylhydrazine (DNPH)-coated cartridges in series with a PTFE-lined pump. We will elute DNPH-carbonyls from the cartridges and analyze the eluent via high-performance liquid chromatography and diode array detection.

We will conduct the following tests with this apparatus to determine whether the organic compound composition of the air within the bag is altered over time in the presence of snow, with and without sunlight:

- Three tests with sunlight
- Three tests in dark
- Three tests in the light with ambient levels of carbonyls added at the beginning (for other tests, only hydrocarbons and alcohols will be added)
- Three tests without snow (two in sunlight, one in dark)

These laboratory tests will allow us to determine whether hydrocarbons and/or alcohols are oxidized to become carbonyls in the presence of (1) snow and (2) sunlight. If hydrocarbons and/or alcohols are being converted to carbonyls, this means snowpack is a source of carbonyls that needs to be included in photochemical models. If snow is merely a short-term reservoir for carbonyls, its influence on wintertime ozone production is likely less important.

**17.7.2. Incorporation into Computer Models**

We will code measurement information about snow fluxes of carbonyls, and perhaps other organics, into our most recent version of the WRF-SMOKE-CAMx photochemical model to determine how important these emissions are to wintertime ozone production. We will compare ozone and carbonyl concentrations in model output against concentrations measured around the Uinta Basin. This work will be a continuation of Section 7 of our draft annual report.
17.7.3. Additional Details

- **Plan:** Seth Lyman, Trevor O’Neil, and student researchers will build the freezer apparatus and conduct the laboratory tests in spring-summer 2020. Marc Mansfield and Seth Lyman will analyze collected data. Huy Tran will carry out computer modeling.
- **Responsible persons:** Seth Lyman and Huy Tran
- **How we will measure performance:** Successful completion of the laboratory tests, with data that meet quality objectives, and successful completion of model analyses.
- **Which priority this relates to:** Air Chemistry (Section 16.1)

17.8. Drone Deployments to Characterize Vertical Structure of Inversion Episodes

We will use a quadcopter drone that carries temperature, relative humidity, barometric pressure, and ozone sensors to collect measurements from the ground surface to above the top of the inverted layer. We will compute wind speed and direction from yaw, pitch, and roll angles and the GPS vector that are recorded by the drone during flight. We constructed and tested this system during winter 2018-19, but the drone malfunctioned and had to be returned to the manufacturer for repairs. The repairs have been completed, so we will carry out deployments this winter. We will carry out these flights periodically throughout the winter season, especially during atmospheric inversions with high ozone. This will include comparisons of data from the drone against data collected at air quality monitoring stations.

- **Plan:** Huy Tran and student Tyler Elgiar will conduct the drone deployments.
- **Responsible person:** Huy Tran
- **How we will measure performance:** Number of successful drone flights, use of drone data for model data assimilation and validation.
- **Which priority this relates to:** Air Chemistry (Section 16.1) and Air Quality Modeling (Section 16.2)

17.9. Cooperation with BLM in Their Measurements of Vertical Inversion Structure

The Bureau of Land Management (BLM) intends to deploy a radiometer profiler, a SODAR, a meteorological measurement tower, and other instrumentation in the Uinta Basin during winter 2019-20 and 2020-21. We will assist BLM in this work as requested, archive the collected data, and, as time and funding allows, we will use the collected data for model data assimilation and validation.

- **Plan:** Trang Tran will coordinate this effort with BLM. Seth Lyman and Huy Tran will assist as needed.
- **Responsible person:** Trang Tran
- **How we will measure performance:** Successful coordination with BLM and archival of collected data will constitute success.
- **Which priority this relates to:** Air Quality Modeling (Section 16.2)
17.10. Online Coupling of Meteorology and Chemistry in Photochemical Simulations of Winter Ozone

Recent photochemical modeling studies of winter ozone episodes in the Uinta Basin have been unsuccessful in capturing elevated ozone concentrations. Discrepancies in emission inventories are considered to be the primary cause for the underestimation of ozone in models, but inaccuracies in simulating inversion meteorology is also an important reason for model underperformance. The majority of earlier photochemical models have simulated meteorology and chemistry in offline coupling fashion without considering feedbacks from chemical conditions to meteorology, and so far, only one modeling study conducted by NOAA simulates online coupling of meteorology and chemistry using WRF-Chem (two-way feedback). Our preliminary tests using similar model inputs to the NOAA study but with WRF-CAMx in standard offline coupling mode failed to reproduce elevated ozone concentrations as simulated in the NOAA study.

We will conduct photochemical simulations using WRF-Chem and WRF-CAMx with similar model configurations (e.g., same emission inventory and chemical mechanism) and compare ozone performance for the two models. We expect that meteorology-chemistry coupling in WRF-Chem, although being more computationally costly, outperforms the performance of WRF-CAMx in decoupled mode. The outcomes of this study will serve as a basis for future selection of the best model platform for accurate simulation of high winter ozone episodes in the Uinta Basin. This will be a continuation of work begun in 2018-19, which is described in Section 9 of our draft 2019 annual report.

We will also compare carbon-bond computational chemical mechanism in WRF-Chem with some other more comprehensive gas-phase chemistry mechanisms, e.g., the Model for OZone And Related chemical Tracers (MOZART) or Regional Atmospheric Chemistry Mechanism (RACM) in WRF-Chem to test winter ozone sensitivity to different chemical mechanisms in photochemical models.

- **Plan:** Trang Tran will carry out these model comparison studies.
- **Responsible person:** Trang Tran
- **How we will measure performance:** Successful completion of the planned modeling exercises. Trang will also deliver an oral presentation on this research topic at the American Geophysical Union (AGU) in December 2019 and plans to submit a publication to a peer-reviewed journal.
- **Which priority this relates to:** Air Quality Modeling (Section 16.2)

17.11. Sensitivity Tests of Different Organic Compound Emissions Composition Scenarios

Emissions inventories (databases of emission sources) report organic compound emissions from oil and gas sources as tons per year of lumped total organics. However, photochemical simulations of ozone concentrations require emission information of specific compounds, for example, methane, formaldehyde, benzene, butane, etc., because these compounds have very different reactivities (i.e., very different abilities to produce ozone). Accurate information about total organic compound emissions, therefore, is only half of what is needed for an accurate and useful emissions inventory. The other half of what is required is accurate organic compound speciation profiles (a speciation profile
contains information about the percentages of different individual compounds or compound groups in total organic compound emissions).

We are nearing completion of a study conducted with and funded primarily by Utah DAQ to determine the composition of emissions from some oil and gas sources in the Uinta Basin. A final report of that work will be released later this year (see Section 6 of our draft 2019 annual report for a summary). This study has provided the most comprehensive speciation profile database that has ever been available for the Uinta Basin. It includes a comparison of two different sampling and measurement approaches. One approach was the direct measurement of organic compound composition from actual emission plumes using a custom measurement system our team developed. The other approach involved collecting raw gas and pressurized liquid samples from water-oil-gas separators at oil and gas wells, analyzing these samples in the laboratory, and determining emissions composition from the laboratory analysis. This approach is common practice for developing speciation profiles for models. Modelers commonly apply raw gas composition data determined by this method to a variety of emission sources, including well completions, blowdowns, pneumatic controllers, pneumatic pumps, fugitive leaks, and others. Emissions from liquid storage tanks are calculated in this method from the composition of pressurized liquid samples.

Our analysis of these two different measurement approaches has shown that speciation profiles from direct measurements of actual emission plumes are more reactive (i.e., they contain higher percentages of more reactive compounds) than profiles developed from samples collected at separators. In particular, use of separator samples appears to underestimate emissions of highly reactive compounds such as toluene, ethylbenzene, and xylenes.

We will conduct photochemical simulations that utilize organic compound speciation profiles determined from direct emission measurements and samples collected at separators (total organic compound emissions will be consistent across the simulations). We will test whether direct measurement-based profiles create more modeled wintertime ozone. We will also determine which profiles lead to better agreement between simulated and actual organic compound composition in the atmosphere.

- **Plan:** Trang Tran will conduct the photochemical simulations. Seth Lyman will assist Trang in preparing data and analyzing results.
- **Responsible person:** Trang Tran
- **How we will measure performance:** Successful completion of the planned modeling exercises. Trang and Seth will also present the results of this work at the Utah Air Quality: Science for Solutions conference in March 2020, and they plan to submit the results of this and related work for peer-reviewed publication.
- **Which priority this relates to:** Air Quality Modeling (Section 16.2)

**17.12. Processing of 2017 Utah Air Agencies Emissions Inventory for Photochemical Modeling**

Utah DAQ has released the Utah Air Agencies oil and gas emission inventory for base year 2017 (UEI2017) as a component of the EPA’s 2017 National Emissions Inventory (NEI2017). We have received from Utah DAQ a UEI2017 version that is suitable for modeling applications. At a recent meeting on 7
October 2019 between USU, Utah DAQ, EPA, and representatives from industry, there was discussion of choosing the year 2017 as the base year for Utah DAQ’s and EPA’s regulatory ozone modeling, which will be part of their implementation plans to address ozone nonattainment in the Uinta Basin. A more recent year than 2017 could be considered for meteorology in these regulatory models, though no decision has been made. Regardless, the UEI2017 and NEI2017 will serve as the base emissions inventory for future regulatory ozone modeling in the Uinta Basin.

We have had success with using the UEI2014 in performing photochemical model simulations of winter 2013 ozone episodes in the Basin and have developed software to process the UEI2014 for the SMOKE emissions model. As the UEI2017 is in the same format as the UEI2014, adopting what we have developed for the UEI2017 should significantly reduce effort in processing the data. We are actively working with modelers at Utah DAQ to define an ozone model configuration that could be used for USU’s research and UDAQ’s regulatory purposes. Working on a unified model configuration will facilitate data sharing between agencies without the need for data conversion.

After the UEI2017 is processed in the SMOKE emission model, we will use the SMOKE output to perform ozone simulations for a winter 2017 ozone episode using the WRF/CAMx photochemical model. The organic compound speciation profiles used will be determined by the work to be completed in Section 18.11. We will investigate the model’s performance and identify necessary improvements to the model. We will share our findings from this activity to all stakeholders.

- **Plan:** Huy Tran will process the UEI2017 data with the SMOKE emission model and perform CAMx simulations for a winter 2017 ozone episode. Trang Tran will execute the WRF model to provide inputs for the CAMx model. Trang Tran and Huy Tran will evaluate WRF and CAMx model performance.
- **Responsible persons:** Huy Tran and Trang Tran
- **How we will measure performance:** Successful processing of the UEI2017 in SMOKE and successful testing of the output in the WRF/CAMx photochemical model for a 2017 winter ozone episode. We will share these findings with regulatory agencies and present the results at the Utah Air Quality: Science for Solutions conference in 2021.
- **Which priority this relates to:** Air Quality Modeling (Section 16.2) and Emissions (Section 16.3)

### 17.13. Comparison of the 2017 Utah Air Agencies Inventory against Top-down Estimations of Basin-Wide Emissions

In comparison to the UEI2014, the UEI2017 has significantly lower emissions of NOx and organic compounds in the Uinta Basin. Specifically, organic compound emissions in the UEI2017 are more than 50% lower, and NOx emissions are 15% lower, than the UEI2014. While evidence exists that ozone-forming emissions decreased from 2014 to 2017 (see Sections 4 and 12 of our draft 2019 annual report), winter 2018-19 still had 16 days that exceeded the EPA ozone standard, indicating that NOx and organic compound emissions are still adequate to produce elevated ozone when meteorological conditions are right. Some stakeholders have expressed concern that the UEI2017 may not accurately represent the actual emissions from oil and gas production in the Uinta Basin. From that concern raises the need to ground-truth the UEI2017.
A top-down approach to estimating NO\textsubscript{x} and organic compound emissions was applied by Ahmadov et al. (2015) for winter 2013. In this approach, relationships of NO\textsubscript{x} and organic compound emissions with methane were determined from an observational dataset at the Horsepool monitoring station, and their emissions were scaled for the entire Basin from an aircraft-based estimate of methane emissions for oil and gas production in Uintah County (Karion et al., 2013). The top-down emissions estimate from Ahmadov et al. (2015) contained organic compound emissions that were 1.8 times higher and NO\textsubscript{x} emissions that were 0.25 times lower than the NEI2011.

We will apply a similar top-down approach to Ahmadov et al. (2015) to estimate NO\textsubscript{x} and organic compound emissions in the Uinta Basin during winters 2014 to 2019. Throughout these winters, NO\textsubscript{x}, organic compounds, and methane were measured at the Horsepool and Roosevelt monitoring stations. We will analyze relationships among ozone-forming compounds at these stations. Recent methane emissions estimates for the Uinta Basin are available (Foster et al., 2017; Foster et al., 2019), and we will use these estimates, along with methane data at Horsepool and Roosevelt, to estimate basin-wide emissions of NO\textsubscript{x} and speciated organics. Also, we will use measurements from portable organic compound sampling stations that were deployed around the Uinta Basin in winter 2018-19, and will again be deployed in the coming winter (see Section 18.15), to better understand the relationships of ozone-forming compounds with methane.

- **Plan:** Huy Tran will process measured data for NO\textsubscript{x}, organic compounds, and methane relationships, estimate Basin-wide NO\textsubscript{x} and organic compound emissions using the top-down approach throughout winters 2014 – 2020 and compare these estimates with the UEI2014 and the UEI2017.
- **Responsible person:** Huy Tran
- **How we will measure performance:** Successful completion of the Basin-wide emissions estimates and comparisons. We will also present the results of this work at the Utah Air Quality: Science for Solutions conference in March 2021.
- **Which priority this relates to:** Emissions (Section 16.3)

**17.14. Development of a Box Model for Investigation of Emissions and Chemistry**

The goal of our modeling is to develop a state-of-the-art photochemical grid model of the Uinta Basin. Such models divide the atmosphere over the region of interest into a grid of three-dimensional cubes. These computations are very complex: Essentially, they must start with a meteorological model, already a very complex problem, of how the air moves across the exterior boundaries of the model and then how it moves from cube to cube inside the model. Next, they superimpose emissions from thousands of ground sources in each cube onto the meteorological model. Finally, they compute the chemical and transport processes that occur in each cube. These models require several hours of computation time on large, multi-processor supercomputers for every simulated day.

However, there is another class of models, “box models,” that eliminate most of the complex calculations of the photochemical grid models and focus only on the chemistry. Imagine running the chemical reactions that produce ozone inside an enclosed chamber in the laboratory rather than trying to measure them in the field. Essentially, box models simulate this laboratory process. Since they omit most of the complexities of the photochemical grid models, they execute much more quickly and do not require supercomputers. They provide a rapid technique for testing hypotheses about photochemistry
without running a full-blown grid model. They are called box models because they are equivalent to grid models with only one cube, or box. They are not meant to replace three-dimensional models. The implementation plans that regulators will prepare in response to the Uinta Basin non-attainment designation will be based on three-dimensional photochemical grid modeling.

We will develop a box model for Uinta Basin winter ozone. The photochemical grid model CAMx, which we already use routinely, has a little-known option that allows it to run in box-model mode. Ramboll, the firm that developed and maintains CAMx, has already offered to train us in its use. We will use the box model to (1) test whether ozone in different areas of the Uinta Basin is more sensitive to reductions in NO\textsubscript{x}, versus organic compounds, (2) improve our understanding of how chemical and physical processes in the snowpack impact wintertime ozone (see also Section 18.7), and (3) test the impact of highly reactive compounds like ethylene and propylene on ozone production (see Section 5 in our draft 2019 annual report for information about why ethylene and propylene are important).

- Plan: Marc Mansfield will develop and execute CAMx as a one-dimensional box model.
- Responsible person: Marc Mansfield
- How we will measure performance: Development of a working box model, use of the box model as described above
- Which priority this relates to: Air Chemistry (Section 16.1) and Air Quality Modeling (Section 16.2)

17.15. Continued Development of Tools to Predict Wintertime Ozone

Our attempts to quantitatively forecast wintertime ozone have not met with consistent success (see Section 12). We will determine whether generalized additive models (Hastie and Tibshirani, 1990, 1995) can overcome some of the shortcomings of our current random forest statistical model. Specifically, we will explore whether generalized additive models can adequately represent the snow-depth saturation effect, improve the end-point bias inherent in the random forest models, and better assess the impact of fluctuations in natural gas and oil production.

As described in Section 12, we will also continue work to develop an effective ozone forecasting model along two separate paths. First, we will use the Vernal Airport temperature data in place of the lapse rate, and second, we will use model calculations to train the models. After initial experimentation, we will adopt and optimize the preferred path.

- Plan: Marc Mansfield will carry out these analyses.
- Responsible person: Marc Mansfield
- How we will measure performance: Improvement in our understanding of how to best predict wintertime ozone
- Which priority this relates to: Air Chemistry (Section 16.1) and Air Quality Modeling (Section 16.2)
17.16. Organic Compound Measurements from Portable Collection Stations

Emissions inventories developed for oil and gas exploration activities in the Uinta Basin, including the UEI2014 and UEI2017, contain significant uncertainties for organic compounds in both the total amount of emissions and emissions composition. For this project, we will conduct a synthesis analysis study combining measurements, receptor model analysis, and photochemical simulations to resolve the deficiencies in organic compound emission estimates in existing emission inventories and to develop spatial and source-type emission factors of organic compounds for 3D-photochemical simulations. This is a continuation of a pilot study conducted during winter 2018-19, which is described in our draft final report in Section 5. The work we described here has been funded primarily by Utah DAQ, but funds from the Utah Legislature will also be used to complete the project tasks.

This study will include three main tasks: (1) distributed sampling and analysis of organic compounds, (2) receptor modeling, and (3) photochemical model simulations.

1. **Distributed sampling and analysis:** We will deploy 17 portable sampling stations to collect samples that will be analyzed in the laboratory for concentrations of 76 hydrocarbons, alcohols, and carbonyls. We will deploy the stations in different configurations around the Uinta Basin. We will also collect daily speciated measurements of the same compounds at the Horsepool and Castle Peak monitoring stations. Some of the portable stations will be equipped with low-cost sensors to continuously measure methane and total organics.

2. **Receptor modeling:** We will carry out a wind analysis to identify potential sources within the immediate vicinity of sampling stations. We will also conduct back-trajectory analysis to understand wind transport patterns over longer distances. We will use the wind analyses with positive matrix factorization to identify emission sources. Positive matrix factorization uses a statistical method called factor analysis, along with organic compound composition information from various source types, to determine which sources impacted a given air sample.

3. **Photochemical modeling:** We will conduct photochemical model simulations and sensitivity tests to determine how well existing and modified emissions inventories are able to reproduce observed organic compound concentrations. These analyses will help identify areas where emissions inventories can be improved.

For more information about this study, please read the funded study proposal here: [https://usu.box.com/s/snl53q7z4te72e7p45aeyv88ty6cuuqgr](https://usu.box.com/s/snl53q7z4te72e7p45aeyv88ty6cuuqgr).

- **Plan:** Trang Tran will lead this effort. Huy Tran and Trevor O’Neil will lead the effort to build the portable measurement stations. The entire group will work together for field deployments. Student Makenzie Holmes, Trang Tran, Seth Lyman, and Trevor O’Neil will analyze samples in the laboratory. Huy Tran will carry out receptor modeling. Trang Tran and Huy Tran will carry out photochemical modeling.
- **Responsible person:** Trang Tran
- **How we will measure performance:** Data collected that meet quality assurance criteria, successful completion of analysis and modeling exercises, and a final report and papers describing study results.
- **Which priority this relates to:** Air Chemistry (Section 16.1) and Air Quality Modeling (Section 16.2)
17.17. Improving WRF/CAMx model Performance with Satellite Data Assimilation Techniques

Previous studies have demonstrated that accurate characterization of surface characteristics, such as snow albedo and vegetation cover, plays a vital role in photochemical model performance. Meanwhile, the typical approach in meteorological (WRF) and photochemical (CAMx) models is to apply long-term averaged datasets of such surface characteristics. These averaged datasets are usually outdated and do not represent the actual conditions of the modeled episode. We have successfully processed data from the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite to derive high-resolution land surface characteristics for the Uinta Basin. We will modify WRF and CAMx model source code to incorporate the MODIS data and examine its impacts on simulated meteorology and ozone.

This project is a continuation of work completed over the past year (see Section 11 of our draft 2019 annual report). The majority of the funding for this continuation has been provided by Utah DAQ. The funded proposal is available here: https://usu.box.com/s/0r5c89j8r6ak3ieo6dg1da6u9y0tzy.

Plan: Huy Tran will process MODIS data and modify WRF and CAMx model source codes to incorporate the new data. Trang Tran will perform WRF simulation with and without MODIS data incorporation and examine its performance. Huy Tran will perform CAMx model simulations with WRF model inputs and examine CAMx’s performance in estimating ozone.

Responsible person: Huy Tran and Trang Tran.

How we will measure performance: Presenting the results of this activity at the AGU 2019 conference, in the UBOS 2020 annual report, and at the Utah Air Quality Science for Solutions conference in March 2020.

Which priority this relates to: Air Quality Modeling (Section 16.2)

17.18. Other Funded Activities for 2019-20

In addition to the work listed above, we will be working on the following separately-funded projects during the 2019-20 project period:

- We are working with the Wyoming Department of Environmental Quality to improve existing models that predict emissions of organic compounds from produced water ponds using information about water chemistry and meteorology. We anticipate releasing a final model and report by the end of 2019.
- We are developing a three-dimensional photochemical model platform for the Bureau of Land Management (BLM) to assess air quality impacts from oil and gas development. This effort is part of BLM’s Air Resource Management Strategy (ARMS). The model platform and final report are due in April 2020.
- Anadarko Petroleum Corporation (now Occidental) provided USU with an endowment to fund students to work with us on Uinta Basin air quality research. Two students are currently supported by this endowment. More information is available here: https://binghamresearch.usu.edu/studentfellowship.
18. Acknowledgments

The primary purpose of this document is to report on activities we have carried out with financial support from the Utah Legislature and the Uintah Impact Mitigation Special Service District. We are grateful to these two entities for their ongoing support of our work. Additional funding for Uinta Basin air quality research we have carried out over the past year, including work mentioned in this report, has been provided by the Utah Division of Air Quality, and the Utah Clean Air Partnership (UCAIR). We administer an endowment from Anadarko Petroleum Corporation that provides opportunities for students to participate in air quality research. Student recipients of those funds participated in the work presented here. Site access, electricity, and/or equipment at some of our monitoring stations is provided by the Utah Division of Air Quality, Enefit American Oil, Encana, Middle Fork Energy, and the Bureau of Land Management. Many energy companies have provided data and access to oil and gas facilities for our work.
19. References


Lyman, S., Tran, T., 2015a. Inversion structure and winter ozone distribution in the Uintah Basin, Utah, USA. Atmos. Environ. 123, 156-165.


