Utah State University
BINGHAM ENTREPRENEURSHIP & ENERGY RESEARCH CENTER

ANNUAL REPORT

UINTAH BASIN AIR QUALITY RESEARCH PROJECT

NOVEMBER 2016

Submitted to:

Natural Resources, Agriculture, and Environment Interim Committee
Utah Legislature
Utah State Capitol Complex
House Building, Suite W210
Salt Lake City, Utah 84114

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DOCUMENT NUMBER: BRC_161116A
REVISION: ORIGINAL RELEASE
DATE: 16 NOVEMBER 2016

1. Executive Summary

During the wintertime inversion conditions that are common in basins and valleys throughout Utah, ozone in the Uintah Basin sometimes increases to levels that exceed standards set by the U.S. Environmental Protection Agency (EPA). Governor Gary Herbert recently recommended to EPA that portions of the Uintah Basin be declared in non-attainment of the ozone standard, and a final designation by EPA is scheduled for October 2017. Levels of particulate matter (i.e., $PM_{2.5}$), which are responsible for wintertime air pollution on the Wasatch Front, typically stay below EPA standards, and the Uintah Basin is not in danger of being declared in non-attainment for $PM_{2.5}$. The Uintah 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 (VOC), and the majority of NOx and VOC emissions in the Uintah Basin are due to 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 Uintah Basin is very different from those on the Wasatch Front, which leads to the formation of ozone, rather than $PM_{2.5}$.

This document reports on the Uintah Basin Air Quality Research Project and other air quality research activities performed by the USU Bingham Research Center during the past year. Section 6 presents a project management plan, including the project's mission, goals, organization, and performance measures. The mission of the project is to conduct scientific research that can be used by industry and government to develop effective solutions to the Uintah Basin's air quality problems at the lowest possible cost. The project's goals and organization are designed to achieve this mission. The project's performance measures include (1) data quality, (2) research reports and publications, and (3) use of the project's research output by stakeholders.

Sections 7, 8, 9, and 10 provide information about research projects undertaken over the past year. Section 7 details the results of ambient air measurements collected by USU and other entities during 2015-16. For most of winter 2015-16, frequent storms kept inversion episodes short, not allowing enough time for ozone to increase to levels exceeding EPA standards. During late January and early February, however, inversions lasted longer, and a number of exceedance days occurred. As has been observed in previous years, ozone formed first, lasted longest, and was observed at higher levels at the lowest elevations of the Uintah Basin. Also, ozone tended to be higher at monitoring stations that were closer to oil and gas development. As has occurred in most previous years, $PM_{2.5}$ increased during inversion episodes but stayed below EPA standards.

Section 8 presents a statistical model of the drivers of wintertime ozone and shows the importance of snow cover, inversion strength and length, solar radiation, and other parameters on ozone production. The model demonstrated a relatively small impact on ozone production from oil and gas production and drilling activity. The model was able to predict with 87% accuracy whether a particular day was an ozone exceedance day. It showed that attainment of the ozone standard is likely to occur during 46% of winter seasons.

Section 9 provides a summary of air quality model development work performed over the past year. We have investigated the feasibility of assimilating measurement and other data into meteorological models to improve their ability to accurately simulate inversion meteorology. We found that, while results from models that did not use data assimilation showed inversions that were too deep (i.e., extended too high above the surface), results from models that used data assimilation showed inversions that were too shallow (i.e., held too tightly to the surface). We also worked to incorporate global chemistry model results as background ozone (i.e., ozone from outside the modeled region) in our models. We used the GEOS-Chem global model and found that it underestimates surface ozone but provides more realistic ozone at altitude relative to commonly-used background conditions. Finally, we are working to incorporate the newly-developed Uintah-2014 oil and gas emissions inventory into our model framework and to investigate its ability to accurately simulate observed ozone and precursor concentrations in the atmosphere.

Section 10 provides short summaries of two emissions measurement studies completed during the past year. One study involved characterization of emissions of organic compounds from produced water ponds into the atmosphere, and the other involved characterization of emissions of organics from various soil surfaces, including well pad soils. Well pad soil emissions were due either to leakage of natural gas from subsurface infrastructure or re-emission from liquid hydrocarbon spills. Emissions from produced water ponds were found to be significant relative to other oil and gas-related sources, but emissions from soil surfaces were not.

In Section 11, we briefly summarize specific project performance measures from 2015-16. We note data coverage and data quality results. We highlight reports and publications completed. We also highlight examples of utilization of our research output by stakeholders. The most significant instance of utilization of our research output by others over the past year was our discovery of ozone-rich air from the stratosphere intruding to the surface and causing ozone exceedances during summer 2015, followed by our work with several regulatory agencies to ensure these exceedance days are declared exceptional events. Ozone exceedances due to causes outside of regulatory control (such as stratospheric intrusions) can be categorized as exceptional events by EPA, meaning that they are excluded from the regulatory record. After discovering these events, we notified the Ute Indian Tribe, the Utah Division of Air Quality, and EPA Region 8 and worked with EPA and others as they developed the exceptional event demonstration documents. The public comment period for this documentation has now closed, and we expect EPA to make a final decision about the exceptional event during 2017. If it is approved, it could lessen the severity of an ozone non-attainment designation for the Uintah Basin, resulting in much lower compliance costs.

Section 12 provides an overview of project objectives for the coming year. We will collect a variety of atmospheric measurements during winter 2016-17, focusing on locations and parameters that are not currently measured in regulatory monitoring networks, but are critical for understanding inversion meteorology and ozone chemistry. We will continue work to improve meteorological, chemical, and emissions-related aspects of air quality models. We will also assess emissions inventories and speciation profiles and determine what emissions measurements in coming years will provide the most useful information to improve existing emissions data.

Section 13 provides information about those who supported the work presented in this document, including the Utah Legislature, and Section 14 provides a list of references.

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5. Background and Introduction

Ozone has been measured continuously in ambient air in Utah's Uintah Basin since summer 2009 when air quality monitoring stations were established in Ouray and Red Wash. During winter 2009-10 ozone concentrations measured at Ouray and Red Wash 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 in during winter months in two places in the world: the Uintah Basin and the Upper Green River Basin in the area of Pinedale, Wyoming. Uintah and Duchesne Counties engaged the Bingham Research Center, part of the Utah State University Uintah Basin Campus in Vernal, to investigate the extent and causes of wintertime air pollution in the Basin in 2010, and the Bingham Center has been engaged in a wide variety of air quality research projects since that time. The results of many of these studies can be found in reports available at http://binghamresearch.usu.edu/reports.

In general, wintertime air quality in the Uintah 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 available sunlight to provide energy for the chemical reactions that form ozone. Ozone forms in the atmosphere from reactions involving oxides of nitrogen (NO_x) and volatile organic compounds (VOC), and the majority of NO_x and VOC emissions in the Uintah Basin due to oil and gas development. Inversion conditions trap these pollutants near ground level, increasing their concentrations and their ability to generate 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. 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 lowest elevation and secondarily in areas with the most oil and gas development. Longer episodes and episodes that occur late in the winter season tend to lead to higher ozone.

Utah's governor, Gary Herbert, recently recommended to EPA that portions of the Uintah Basin be declared out of attainment of the 70 ppb ozone standard, and a final designation by EPA is scheduled for October 2017. This will formalize a process already begun by the Utah Department of Environmental Quality, the Ute Indian Tribe, EPA, the oil and gas industry, and other stakeholders to eliminate the winter ozone problem by reducing NO_x and VOC emissions in the Uintah Basin. Efforts by the Bingham Center and many other entities have led to great improvement in understanding of the causes and impacts of the Uintah Basin's wintertime air quality problem, allowing industry and regulators to make more effective and more cost-effective decisions to decrease emissions. Much remains unknown or poorly known, 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 Uintah Basin air quality research conducted by Utah State University. Section 5 includes a project management plan for the Uintah Basin Air Quality Research Project. Sections 6 through 9 report on the status of Uintah Basin air quality during 2015-16 and provide the results of several specific air quality research projects completed during the past year. Section 10

provides a brief report on project performance measures for the past year. Section 11 provides project objectives for the coming year. Section 12 acknowledges funding and other support received, and Section 13 provides a list of references cited.

6. Project Management Plan

This project management plan was developed based on guidance given in *Best Practices for Good Management*, prepared by the Office of the Legislative Auditor General (http://www.le.state.ut.us/AUDIT/bp_2008.pdf).

6.1. Project Mission

The mission of the Uintah Basin Air Quality Research Project is to conduct scientific research that can be used by industry and government to develop effective solutions to the Uintah Basin's air quality problems at the lowest possible cost.

6.2. Project Goals

This project has several long-term goals, described below. Project objectives (i.e., specific plans to achieve the project goals) for the coming year are described in Section 12.

6.2.1. Ambient Air Measurements

In relation to measurements of the chemical and meteorological properties of ambient air, we will:

- Collect measurements that advance understanding of and increase our ability to resolve winter ozone problems in the Uintah Basin, and
- Collect measurements in accordance with established best practices and guidelines so that all collected data are adequately verified and defensible. This will include the establishment of and adherence to quality assurance criteria. These criteria will be at least as strict as those established by EPA, where applicable.

6.2.2. Air Quality Model Development

We will investigate existing and develop new parameterizations and tools for regulatory air quality models to improve the ability of models to adequately simulate the meteorological and chemical conditions of winter inversions in the Uintah Basin.

6.2.3. Emissions Characterization

We will conduct measurement campaigns and analyses to improve understanding of ozone-forming emissions into the Uintah Basin atmosphere. We will target emission sources that are poorly characterized and have the potential to be important for Uintah Basin ozone production. We will ensure that collected data meet pre-determined quality objectives.

6.2.4. Academic Integrity

Our Bingham Center air quality research team is housed within Utah State University's Regional Campus system and affiliated with the College of Science and Department of Chemistry. We will adhere to

academic standards of transparency and integrity. We will ensure that all activities related to this study are conducted with the goal of generating unbiased, reliable, and defensible information.

6.2.5. Stakeholder Engagement

We will ensure that (1) all the work completed for this project is relevant and useful to stakeholders in industry and government and (2) stakeholders are informed about project results. We will accomplish this through interaction with a stakeholder guidance committee, and by continuing and strengthening existing relationships with local, tribal, and state government officers, representatives from the oil and gas industry, and the public.

We have assembled a stakeholder guidance committee to help ensure the work accomplished for this project is relevant to industry and government stakeholders. The committee includes representatives from the following organizations that are integrally involved in Uintah Basin air quality issues:

- Utah Petroleum Association
- Western Energy Alliance
- Uintah County
- Duchesne County
- Ute Indian Tribe
- Utah Division of Air Quality
- TriCounty Health

During each summer, we will develop a preliminary plan of work for the following year (November through October). We will submit the plan to the committee members for review, and we will hold a meeting of the committee to obtain suggestions and comments relating to the work plan. Based on the committee's recommendations, we will revise and finalize the work plan. We will then submit the work plan as part of our annual report to the Utah Legislature's Natural Resources, Agriculture, and Environment Interim Committee. We will also provide the stakeholder committee with the annual report and all other research products from this project, and we will solicit their input on other matters related to the project as appropriate.

6.2.6. Student Involvement and Training

We will involve undergraduate and graduate students in all aspects of this project, including field data collection, data analysis, and reporting, and air quality model development, with the goal of providing training that helps prepare students to enter the workforce. We will involve students enrolled at the USU Uintah Basin Regional Campus and students from USU's Department of Chemistry and Biochemistry, with which the Bingham Center research team is affiliated.

6.2.7. Safety

In work at field sites, industrial sites, and in the laboratory, we will abide by USU safety guidelines and make every effort to make safety our highest priority.

6.2.8. Data Management, Quality, and Distribution

All data and other digital information we generate will be archived in at least two locations to protect data from being destroyed or altered. Where possible, one of those locations will be a cloud-based data storage server to eliminate the possibility of data loss in the event of fire or other localized destructive force.

For all laboratory and field data collection, we will keep electronic, password-protected, auto-archived logbooks that explain collection location, calibration, repair, and maintenance actions, and all other pertinent information to allow us to interpret and analyze the data.

All data we collect during this project will be public, and we will release raw or final datasets and all reports and publications generated to any party upon request. Some data we collect may be protected by nondisclosure agreements to safeguard the interests of private companies. In this case, we will release anonymized data upon request, and we will not release data that reveals the identity or proprietary information of private companies. Data requests may be made through our website at http://binghamresearch.usu.edu/data_request.

Data quality objectives for ambient air data collection are summarized in Table 6-1. We will review collected data weekly (for ambient air data) or daily (for emissions data) to determine whether they meet the objectives outlined in Table 6-1. If these objectives are not met, we will take action to correct the problem. Additional maintenance and repair not included in Table 6-1 will also be conducted according to best practices and instrument manufacturer specifications. All maintenance, repair and calibration procedures will be recorded in electronic logbooks. Data quality objectives for emissions measurements and other projects will be project-specific and are not included here.

Table 6-1. Summary of data quality objectives.

Measurement	Requirement	Frequency	Acceptance Criteria	Action if Criteria Not Met
Ozone	3-point calibration check	Weekly if automated, every two weeks if manual	+/- 5% of expected concentration or within 5 ppb of zero for zero calibrations	Recalibrate, or repair/replace instrument, correct or invalidate data if greater than +/- 7%.
	5-point calibration check	Beginning and end of measurement season	Same as above, and r^2 for regression curve >0.99	Recalibrate, or repair/replace instrument, correct or invalidate data
$PM_{2.5}$ filter sampling—field operations	Flow rate during sampling	Every sample, check after sampling	Average flow rate of 15.9-17.5 Lpm, CV <10%	Recalibrate, or repair/replace instrument, correct or invalidate data
	Leak and Flow Check	Every 2 months	Flow must be 16.2-17.2 Lpm (+/- 3%), and leak check must pass	Recalibrate flow meter. Invalidate data if greater than +/- 7%.

Measurement	Requirement	Frequency	Acceptance Criteria	Action if Criteria Not Met
	Temperature and Pressure check	Every 2 months	+/- 3°C +/- 10 mm Hg	Calibrate temperature and/or pressure sensors. Invalidate data if +/- 5°C or +/- 15 mm Hg.
$PM_{2.5}$ filter sampling—lab analysis	Balance check	Every day of use, at beginning and end of weighing	+/-5 µg—using 200 mg and 500 mg working standard weights	Check with primary standard weights, troubleshoot balance. Invalidate filter weighings if not bracketed by successful standard weighings
	Obtaining consistent filter weights	Each filter, during weighings before and after sampling	Condition for >/= 24 hr, then weigh once daily until 3 successive weights are all within +/- 15 µg	Allow more conditioning time, try weighing again, throw out filter, other troubleshooting as needed.
	Lab Blanks	One for each set of filters weighed	Average weight during initial weighing and final weighing must be within +/- 15 µg	Troubleshoot and solve problem
	Field Blanks	Once every 3 months	Average weight during initial weighing and final weighing must be within +/- 30 µg	Troubleshoot and solve source of contamination
	Compare working and primary gravimetric standards	Every 3 months	Both must agree within +/- 5 µg	Troubleshoot and solve problem
$PM_{2.5}$ and PM_{10} via Beta Attenuation Monitor	Clean sample inlet and virtual impactor	Beginning and end of measurement season		
	Flow Rate and Leak Check	Every 2 months	+/- 5%, must pass leak check	Recalibrate flow, invalidate data if greater than +/- 7%.
	Blank check and offset adjustment	Once per year		Adjust zero offset if needed

Measurement	Requirement	Frequency	Acceptance Criteria	Action if Criteria Not Met
	Ambient temperature and pressure check	Every 2 months	+/- 3°C +/- 10 mm Hg	Calibrate temperature and/or pressure sensors on BGI. Invalidate data if +/- 5°C or +/- 15 mm Hg.
NOx and/or NOy	3-point NO calibration check	Weekly	+/- 5% of expected concentration or within 3 ppb of zero for zero calibrations (for NO and NOx or NOy)	Recalibrate, or repair/replace instrument, correct or invalidate data if greater than +/- 7%.
	5-point NO calibration check	Beginning and end of measurement season	Same as above, and r^2 for regression curve >0.99 (for NO and NOx or NOy)	Recalibrate, or repair/replace instrument, correct or invalidate data
	NO_2 calibration check via gas phase titration	Weekly	+/- 5% of expected concentration (for NOx or NOy)	Recalibrate, or repair/replace instrument, correct or invalidate data if greater than +/- 7%.
	NOy calibration check via HNO_3 and organic nitrate permeation tubes	Once during each measurement season	+/- 20% of expected concentration (for NOx or NOy)	Recalibrate, or repair/replace instrument, correct or invalidate data if greater than +/- 25%.
Canister sampling for volatile organic compounds	Check canister pressure before use	Every deployment	Must be less than -22 “Hg.	Don’t use the can, inspect and repair can if necessary
	Check pressure upon receipt of can	Every canister	Must be within +/-2 PSI of that reported during field retrieval	If not the same, invalidate sample
	Calibration of GC-FID and GC-MS for each compound measured	Every analytical run	R^2 must be >0.99	Re-run samples

Measurement	Requirement	Frequency	Acceptance Criteria	Action if Criteria Not Met
	Canister cleaning check	Every fourth batch of cans cleaned	All compounds must be less than 5 ppb	Increase cleaning time or temperature
	Zero check	Every analytical run	All compounds must be less than 5 ppb	Re-run samples
	Duplicate sample	Every analytical run	Average difference for original and duplicate must be <15%	Re-run samples
	Laboratory spike	Every analytical run	Average difference from expected must be <15%	Re-run samples
Methane/total non-methane hydrocarbon real-time GCs	3-point calibration check with methane and propane	Weekly	+/- 5% of expected concentration or within 50 ppb of zero for zero calibrations	Recalibrate, or repair/replace instrument, correct or invalidate data if greater than +/- 10%.
	5-point NO calibration check with methane and propane	Beginning and end of measurement season	Same as above, and r^2 for regression curve >0.99	Recalibrate, or repair/replace instrument, correct or invalidate data
Wind speed and direction	Check against NIST-traceable standard in ambient air, and zero check for wind speed	Once per measurement season	Difference of <1 m s^{-1} for wind speed, difference of 20 degrees for wind direction	Recalibrate, or repair/replace instrument, correct or invalidate data
Temperature	Check against NIST-traceable standard in ambient air	Once per measurement season	Difference of <1 degree Celsius	Recalibrate, or repair/replace instrument, correct or invalidate data

Measurement	Requirement	Frequency	Acceptance Criteria	Action if Criteria Not Met
Humidity	Check against NIST-traceable standard in ambient air	Once per measurement season	Difference of <5% humidity	Recalibrate, or repair/replace instrument, correct or invalidate data
Barometric Pressure	Check against NIST-traceable standard in ambient air	Once per measurement season	Difference of <2 mbar	Recalibrate, or repair/replace instrument, correct or invalidate data
Solar radiation	Check against NIST-traceable standard in ambient air	Once per measurement season	Difference of <50 W m^{-2}	Recalibrate, or repair/replace instrument, correct or invalidate data

6.3. Performance Measures

6.3.1. Data Collection

A large portion of this project will involve data collection, and one basic measure of performance will be the quality and consistency of data collected. For ambient air data, we will strive for "uptime," or time when data are being collected and meet data quality objectives (see Table 6-1), of at least 90% of the total winter season (15 November through 15 March). For other data collected, we will strive for 100% of collected data to meet data quality objectives. We will review collected data annually and include a summary of data quality outcomes with each annual report to the Utah Legislature.

6.3.2. Publications

We will deliver a written report each November to the Natural Resources, Agriculture, and Environment Interim Committee of the Utah Legislature. This report will include information about accomplished tasks and research results for the previous year, the project management plan, project objectives for the coming year, and a report of performance measures. We will also work to publish research results in peer-reviewed scientific journals since peer-reviewed research results are more valid for use by regulators and industry to develop pollution reduction plans. The annual report to the Legislature will include a list of peer-reviewed papers our group has published relating to Uintah Basin air quality.

6.3.3. Utilization of Research Output by Stakeholders

The most important performance measure for this project will be the utilization of research output by stakeholders in government and industry to understand and mitigate air quality problems in the Uintah Basin. We will work to provide stakeholders in industry and local, tribal, and state government with research products, and we will attempt to track the use of these products by these entities. We will include an update of how our research has been used in our annual report to the Natural Resources, Agriculture, and Environment Interim Committee.

6.4. Project Organization and Personnel

This project is executed by scientists and technical staff at USU's Bingham Research Center, which is part of the Uintah Basin Regional Campus. Administrative staff at USU manage the project's financial and administrative aspects. Table 6-2 outlines the primary roles and responsibilities for project execution. The project will also involve students and provide opportunities for workforce training (see discussion above).

Table 6-2. Roles and responsibilities for the Uintah Basin Air Quality Research Project

Individual(s) Assigned	Responsibilities
Seth Lyman, PhD Bingham Research Center Director, Chemistry Department Research Faculty	• Project management and oversight • Quality assurance and data management • Field data collection and processing • Laboratory analyses • Reporting and publication
Marc Mansfield, PhD Senior Scientist, Chemistry Department Research Faculty	• Theoretical and statistical model development • Air quality model development • Data analysis • Reporting and publication
Huy Tran, PhD Senior Scientist	• Air quality model research and development • Emissions inventory research and development • Reporting and publication
Trang Tran, PhD Research Scientist	• Air quality model research and development • Emissions inventory research and development • Reporting
Colleen Jones, PhD Research Scientist	• Field data collection and processing • Laboratory analyses
Randy Anderson Air Quality Specialist	• Field data collection and processing • Electronics, communications, and data management • Web development
Trevor O'Neil Research Technician and Undergraduate Student	• Field data collection and processing • Laboratory analyses

7. Uintah Basin Air Quality and Meteorology During 2015-16

7.1. Introduction

This section provides an analysis of ozone, precursor, and meteorology data from air quality monitoring sites that operated around the Uintah Basin during winter 2015-16 and an analysis of all years of available ozone and particulate matter data. In this chapter, "winter 2015-16," "winter," "winter season," or other similar phrases refer to the period from 15 November through 15 March. Most measurements collected by USU were only during winter, with the exception of stations operated in cooperation with the Ute Indian Tribe (Table 6-1).

7.2. Methods

7.2.1. Ozone Measurements

During winter 2015-16, 18 air quality monitoring stations were operated in the Uintah Basin. Table 7-1 contains a list of all monitoring stations, including locations, elevations, and responsible operators. Data and methods used for stations operated by organizations other than USU were obtained from EPA's AQS database (https://ofmext.epa.gov/AQDMRS/aqdmrs.html), from http://airnowtech.org, or from the Utah Division of Air Quality (UDAQ). The AQS database contains finalized data, whereas airnowtech.org and data obtained from UDAQ were not yet finalized. We utilized 2B Technology Model 205 or 202 ozone monitors at most stations operated by USU, but an Ecotech Model 9810 ozone analyzer and a Thermo 49i were used at the Horsepool and Rabbit Mountain sites, respectively. 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 7-1. Air quality monitoring stations, winter 2015-16. All stations except Randlett and Wolf Flat measured ozone and basic meteorological parameters. Stations that measured VOC, NO_x, and/or $PM_{2.5}$ are indicated. NO_x* signifies NO_2 measured with a photolytic NO_2 (rather than molybdenum) converter. Ute is the Ute Indian Tribe. 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://ofmext.epa.gov/AQDMRS/aqdmrs.html). Airnow is the EPA real-time air quality database (http://www.airnowtech.org).

	Operator	Latitude	Longitude	Elev. (m)	VOC	NO_x, $PM_{2.5}$	Data Origin
Flat Rock	Ute/USU	39.547	-109.675	2274	N/A	$PM_{2.5}$	USU
Mtn. Home	Ute/USU	40.432	-110.382	2234	N/A	N/A	USU
Seven Sisters	USU	39.981	-109.345	1618	N/A	N/A	USU
Castle Peak	USU	40.051	-110.020	1605	N/A	NO_x	USU
Rabbit Mtn.	USU	39.869	-109.097	1879	N/A	N/A	USU
Dinosaur	NPS	40.437	-109.305	1463	N/A	N/A	AQS/Airnow
Red Wash	Ute Tribe	40.204	-109.352	1689	N/A	NO_x	AQS/Airnow
Vernal	UDAQ	40.453	-109.510	1606	N/A	NO_x, $PM_{2.5}$	AQS/Airnow
Whiterocks	Ute Tribe	40.484	-109.906	1893	N/A	NO_x	AQS/Airnow
Ouray	Ute Tribe	40.055	-109.688	1464	N/A	NO_x	AQS/Airnow
Roosevelt	UDAQ	40.294	-110.009	1587	VOC	NO_x*, $PM_{2.5}$	Airnow/USU
Myton	Ute/USU	40.217	-110.182	1610	N/A	NO_x, $PM_{2.5}$	Airnow/USU
Fruitland	UDAQ	40.209	-110.840	2021	N/A	NO_x	AQS/Airnow
Horsepool	USU	40.144	-109.467	1569	VOC	NO_x*, $PM_{2.5}$	USU
Ft. Duchesne	Ute/USU	40.282	-109.870	1559	N/A	$PM_{2.5}$	USU
Wolf Flat	Ute/USU	39.692	-109.793	1992	VOC	N/A	USU
Rangely	NPS/BLM	40.087	-108.762	1648	N/A	NO_x	AQS/Airnow
Randlett	Ute/USU	40.232	-109.845	1482	VOC	$PM_{2.5}$	USU

7.2.2. Ozone Precursor Measurements

We measured NO, true NO_2 (via a photolytic converter), and NO_y (sum of NO, NO_2, and other reactive nitrogen compounds) at Roosevelt and Horsepool with AQD/Teledyne-API and Ecotech systems, respectively. We calibrated the systems weekly with NO standards and for NO_2 via gas phase titration, and once during the campaign with nitric acid and n-butyl nitrate permeation tubes to calibrate for NO_y. At Castle Peak, we measured NO and true NO_2 with a Thermo 42C NO_x analyzer that incorporated a photolytic converter. Calibrations at Castle Peak were the same as at Roosevelt and Horsepool, except that NO_2 calibrations only occurred at the beginning and end of the winter season. All sites operated by other organizations measured NO and NO_2 via a molybdenum converter-based system, a method known to bias NO_2 and NO_x results high due to NO_y interference.

We measured 57 ozone-forming nonmethane hydrocarbons (NMHC; equivalent to VOC) in hourly samples at Roosevelt. NMHC were analyzed by sample concentration on activated carbon traps, followed by desorption into automated gas chromatography-flame ionization detection systems. Methane and total non-methane hydrocarbons were measured at Horsepool and Roosevelt with gas chromatograph-based instruments. We calibrated these systems every week with certified gas standards. EPA C2-C12 PAMS compounds (EPA, 2003) were measured by the automated system at Roosevelt.

7.2.3. Particulate Matter Measurements

We measured particulate matter with a diameter smaller than 2.5 micrometers ($PM_{2.5}$) at Horsepool with a BAM 1020 monitor. We measured $PM_{2.5}$ and PM_{10} at Myton with a Thermo TEOM DF-1450 monitor. We collected filter-based $PM_{2.5}$ samples at Fort Duchesne and Randlett using BGI PQ200 instruments and determined $PM_{2.5}$ gravimetrically in our laboratory. $PM_{2.5}$ at Fort Duchesne and Randlett was measured with 24-hour filter samples every 6th day. Instruments were operated according to manufacturer protocols, with leak checks, flow and mass calibrations, and cleanings performed at regular intervals. Particulate matter values from other sites were extracted from the EPA AQS database (https://ofmext.epa.gov/AQDMRS/aqdmrs.html).

7.2.4. Meteorological Measurements

We deployed solar radiation sensors at Horsepool (incoming and outgoing short wave and long wave with a Kipp and Zonen CNR-4 and UV-A and UV-B with a Kipp and Zonen UV radiometer) and at Roosevelt (incoming and outgoing shortwave with a Kipp and Zonen CNR-4). We operated a suite of comprehensive, research grade meteorological instruments at Horsepool and Roosevelt and more cost-effective instruments (Davis VantagePro) at other sites. We checked wind speed and direction, temperature, and humidity against a NIST-traceable standard once annually. We checked radiation measurements against calibration standards once every three years. We also obtained meteorological data from the EPA AQS database and mesowest.utah.edu.

7.3. Results and Discussion

7.3.1. Ozone

NO_x and VOC emissions into the atmosphere are relatively constant, but significant ozone production from NO_x and VOC only occurs in certain meteorological conditions. During Uintah Basin winters, ozone stays well below the EPA standard of 70 ppb except when adequate snow cover and temperature inversion conditions exist (a temperature inversion exists when the air temperature aloft is warmer than the temperature at the surface). Sunlight is the energy which 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 above, which promotes inversion formation and persistence. Inversions trap NO_x and VOC near their emission sources, allowing them to build up to concentrations that allow for rapid ozone production.

Much of the Uintah Basin was blanketed in snow from 14 December 2015 through 18 February 2016 (Figure 7-1). However, frequent storms during most of the winter kept the Basin atmosphere well mixed, so inversions were absent or short-lived, pollutant concentrations were not able to build up and ozone stayed lower than the EPA standard. By the end of January, however, more snow had accumulated and fewer storms broke up inversions, allowing ozone to increase to levels above the EPA standard during two inversion episodes. The second episode, which occurred during the first half of February, resulted in ozone concentrations well above the 70 ppb standard at many sites around the Uintah Basin (Figure 7-2).

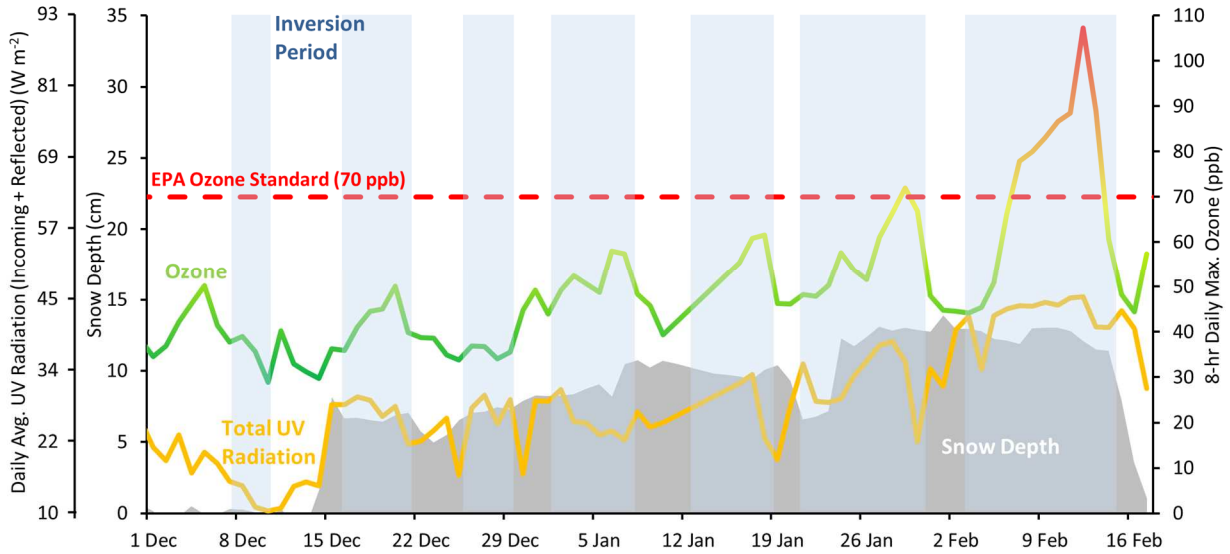

Figure 7-1. Horsepool ozone, snow depth, daytime average total UV radiation (incoming + reflected), and inversion periods (shown as light blue boxes) during winter 2015-16. The red dashed line shows the EPA ozone standard of 70 ppb.

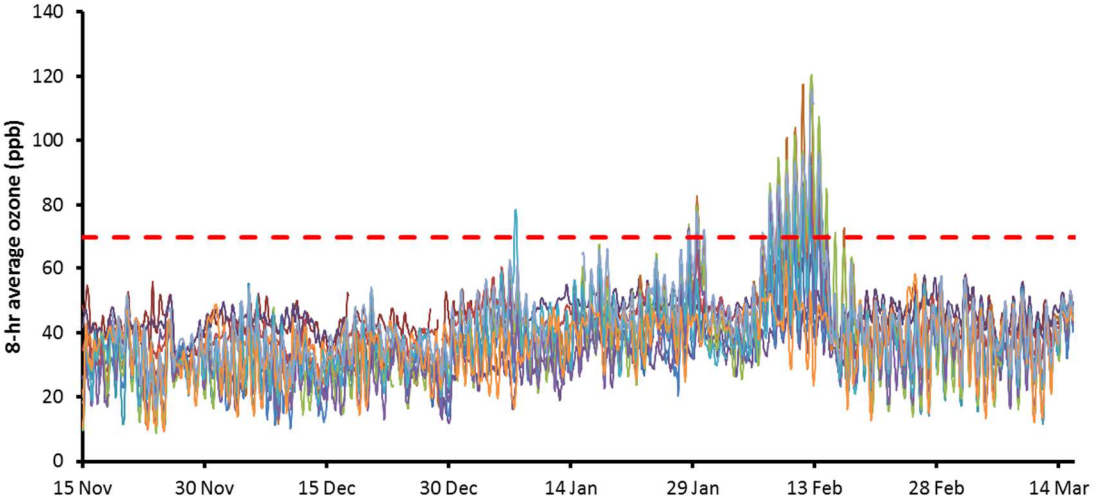

Figure 7-2. 8-hour average ozone from all sites listed in Table 7-1 during winter 2015-16.

Most of the reactions that lead to ozone formation require UV radiation to proceed. Figure 7-1 shows that total UV radiation (the sum of incoming and reflected UV-A and UV-B radiation) increased through the winter until a maximum in the first half of February. Total UV radiation depends on snow cover (since snow cover increases reflected radiation), but it also depends on the solar angle and day length. Thus, more energy is available to produce ozone later in the winter when the sun is closer and days are longer (as long as snow cover exists). Eventually, the sun is too warm and days are too long to maintain snow cover, and the snow melt ends the possibility of wintertime ozone. Figure 7-1 shows that the ozone exceedances experienced during winter 2015-16 occurred when snow depth, inversion length, and total UV radiation were all maximized. The winter ozone season ended on 18 February when most of the snow had melted from the Uintah Basin.

Table 7-2 provides information about ozone observed at all monitoring stations in the Uintah Basin during winter 2015-16. All but four stations reported at least one exceedance of the 70 ppb standard, and all but five experienced more than four exceedances. An exceedance occurs when the daily maximum 8-hour average ozone value at a station is greater than the EPA standard. The average of the fourth-highest daily maximum 8-hour average ozone value over three consecutive calendar years is used to determine compliance with the standard.

Table 7-2. 8-hour average ozone concentrations around the Uintah Basin, winter 2015-16.

	Mean	Maximum	Minimum	4th Highest Daily Maximum	Number of Exceedances
Flat Rock	44.2	58.2	30.0	54.6	0
Mtn. Home	46.7	72.4	32.6	64.3	1
Seven Sisters	39.3	117.5	11.0	100.9	9
Castle Peak	39.0	99.8	16.3	84.0	8
Rabbit Mtn.	32.9	52.9	11.8	48.2	0
Dinosaur N.M	37.0	83.6	9.5	75.3	5
Red Wash	39.9	96.0	18.6	83.5	7
Vernal	34.7	78.4	10.3	73.6	5
Whiterocks	43.4	86.1	25.3	81.3	7
Ouray	37.7	120.6	8.8	96.8	11
Roosevelt	35.2	96.0	10.8	84.8	10
Myton	38.7	95.1	16.6	85.5	8
Fruitland	36.4	62.4	9.3	53.1	0
Horsepool	44.1	115.8	16.4	93.6	11
Ft. Duchesne	31.9	96.8	6.8	90.4	9
Rangely	36.9	67.4	19.8	59.8	0

Figure 7-3 through Figure 7-6 show the spatial distribution of ozone around the Uintah Basin during the ozone episode that persisted from 5-14 February. Figure 7-3 shows conditions on 5 February at the end of a stormy period that resulted in low and uniform ozone across the Basin. By 8 February (Figure 7-4), ozone had increased above the 70 ppb standard at many locations around the Uintah Basin, and by 12 February (Figure 7-5) concentrations had reached a maximum. Figure 7-4 and Figure 7-5 show the highest ozone centered around the area between Ouray, Seven Sisters, and Horsepool, as has been observed in previous years. Lyman and Tran (2015) 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 Uintah Basin, and Ouray is nearby and is the site with lowest elevation.

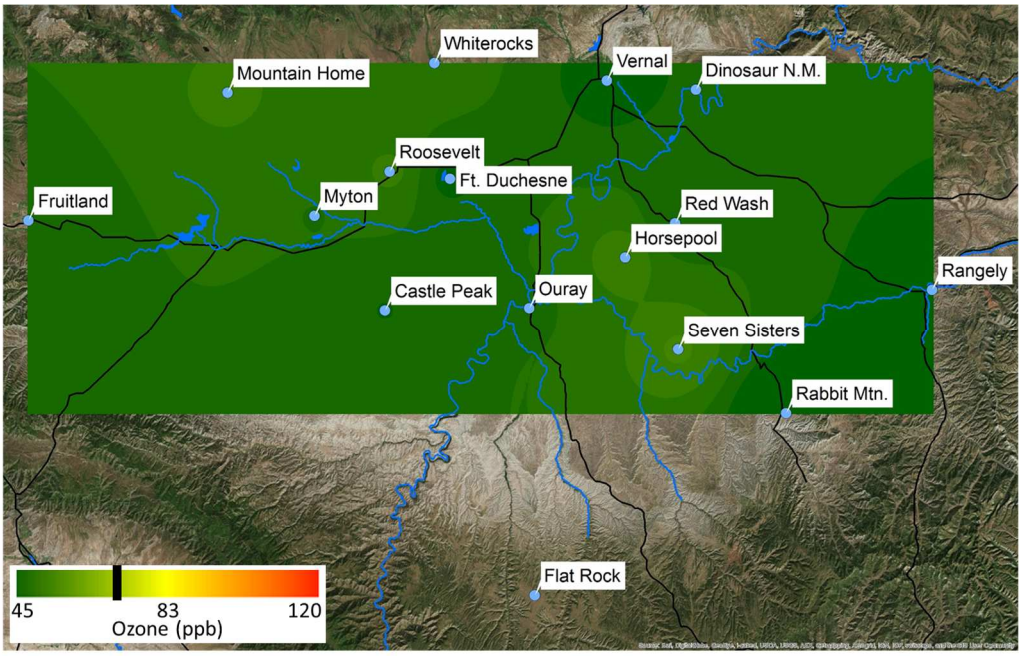

Figure 7-3. Daily maximum 8-hour average ozone on 5 February 2016. Color indicates ozone concentration and was interpolated using ArcGIS software. The black bar on the legend indicates 70 ppb.

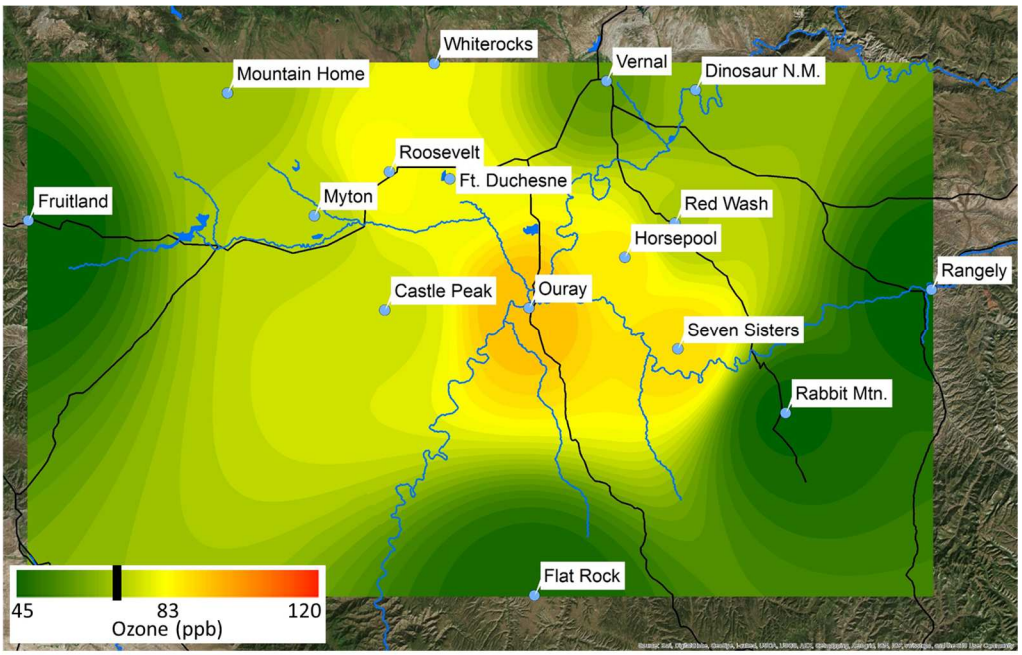

Figure 7-4. Daily maximum 8-hour average ozone on 8 February 2016. Color indicates ozone concentration and was interpolated using ArcGIS software. The black bar on the legend indicates 70 ppb.

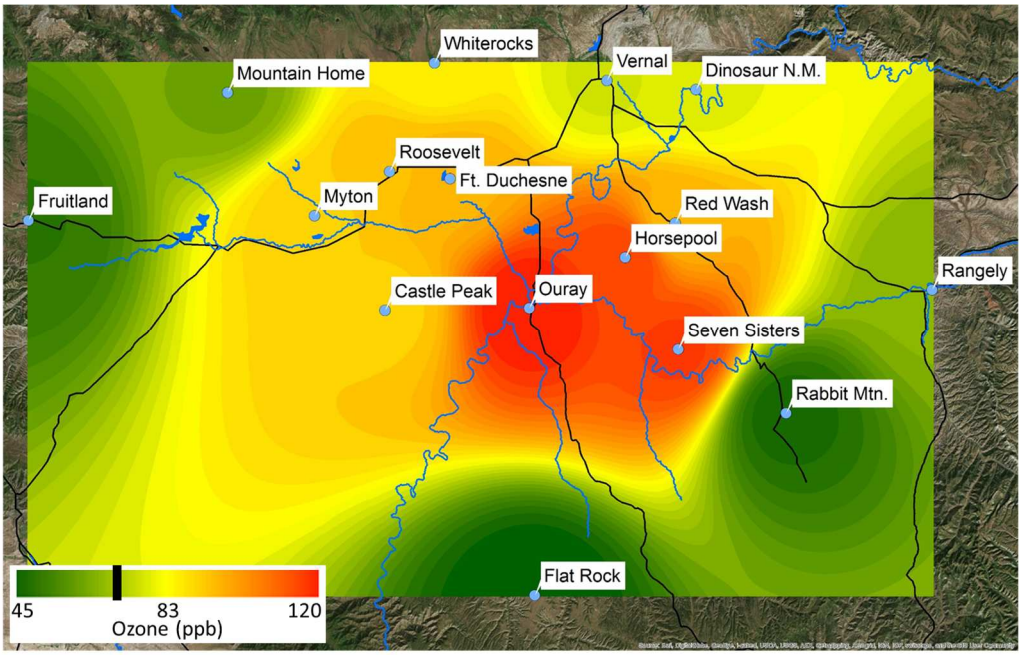

Figure 7-5. Daily maximum 8-hour average ozone on 12 February 2016. Color indicates ozone concentration and was interpolated using ArcGIS software. The black bar on the legend indicates 70 ppb.

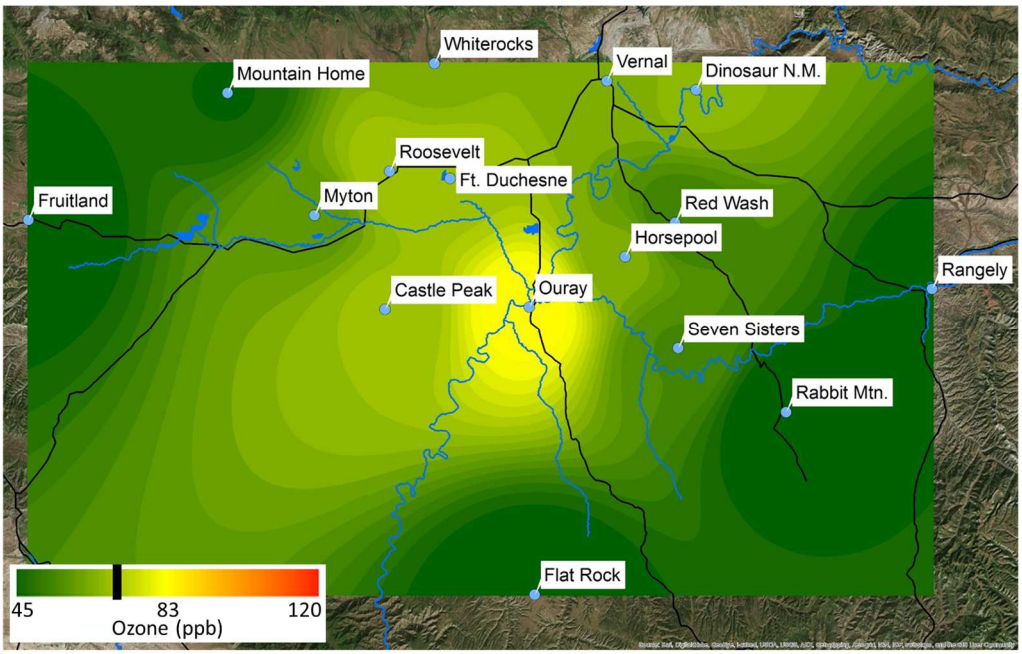

Figure 7-6. Daily maximum 8-hour average ozone on 14 February 2016. Color indicates ozone concentration and was interpolated using ArcGIS software. The black bar on the legend indicates 70 ppb.

By 14 February, a storm had flushed pollutants from the Uintah Basin atmosphere, leaving ozone at most locations below EPA standards (Figure 7-6). The exception was the Ouray station. Ouray is at low elevation very near the Green River, and storms that remove pollutants from most of the Uintah Basin atmosphere are often not able to break up inversion conditions completely at the lowest elevations

(Lyman and Tran, 2015). Thus, Ouray experienced more inversion days than any of the other monitoring stations (Table 7-2).

Figure 7-7 shows fourth-highest daily maximum ozone versus station elevation for all ozone monitoring stations. 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 the correlation between ozone and elevation shows that wintertime ozone is strongly dependent on meteorology. Exceptions to this rule were observed, however, and can be explained by proximity to oil and gas-related sources (Lyman and Tran, 2015). For example, Vernal and Seven Sisters are at approximately the same elevation, yet ozone at Seven Sisters was much higher than in Vernal, most likely because Vernal is relatively distant from oil and gas activity, while Seven Sisters is in an area of high-density oil and gas activity. Ouray and Dinosaur National Monument are also at similar elevation, and yet Ouray has much higher ozone, likely for the same reason. This shows that high wintertime ozone would not occur without inversions, but that oil and gas pollution sources are also required.

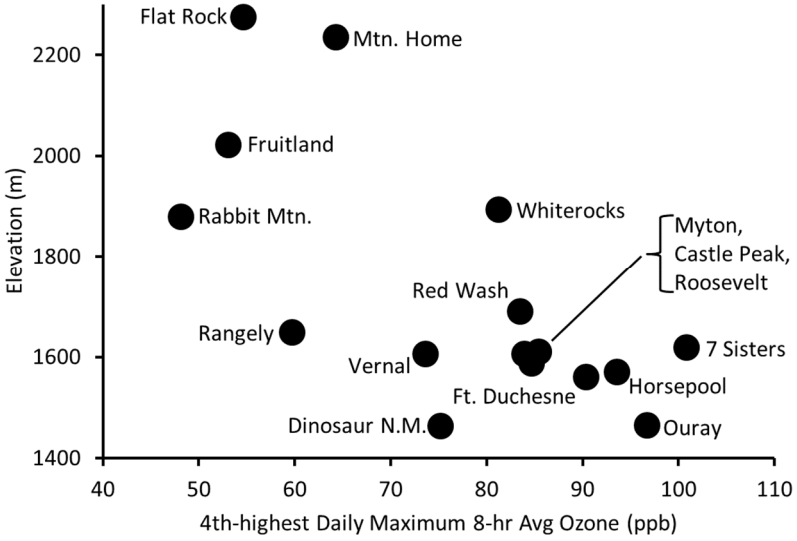

Figure 7-7. Fourth-highest daily maximum 8-hour average ozone versus station elevation for winter 2015-16.

Figure 7-8 shows a time series of ozone concentrations at several sites in the Uintah Basin from July 2009 through September 2016. The Ouray air quality monitoring station began operation in July 2009. During winter 2009-10, Ouray experienced multiple exceedances of the EPA ozone standard of 70 ppb. Subsequently, regulatory monitors in Roosevelt, Vernal, Fruitland, and Rangely were added. As Figure 7-8 shows, exceedances of the standard have been observed during five of the seven winters in the Uintah Basin for which continuous ozone monitoring data are available. UDAQ 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.

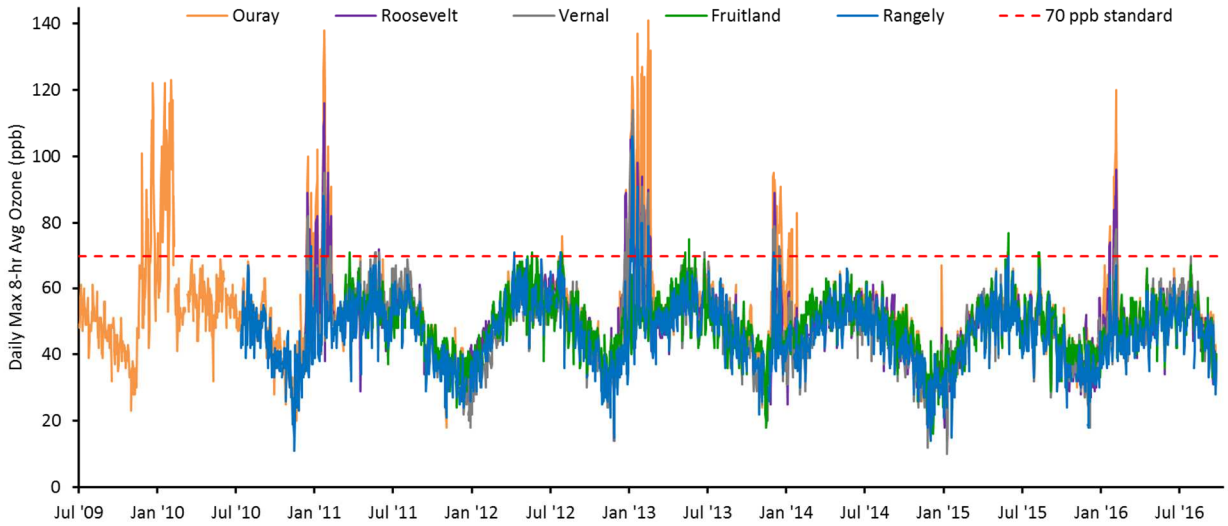

Figure 7-8. Time series of daily maximum 8-hour average ozone concentration at five sites in the Uintah Basin from July 2009 through September 2016. The red dashed line shows 70 ppb, the EPA standard for ozone.

Ozone statistics from the five sites shown in Figure 7-8 are summarized in **Table** 7-3 for each of the years that data are available. Data are organized by calendar year rather than by winter season since summertime exceedances have also occurred (albeit rarely) and since nonattainment designations are based on the average of the annual fourth highest daily maximum 8-hour average concentration averaged over three consecutive calendar years.

EPA has indicated they will use calendar years 2014, 2015, and 2016 for this determination. Table 7-4 shows this value for the same monitoring stations shown in Figure 7-8 and **Table** 7-3. The 3-year average values shown in Table 4 assume that the highest ozone has already occurred in 2016. Ozone exceeding the EPA standard has been observed in December in previous years, and the values shown in Table 7-4 could change. Also, EPA is considering designating two ozone exceedance days that occurred at the Ouray station in June 2015 as "exceptional events," which would exclude them from the regulatory record, bringing the 3-year average for Ouray down from what is shown in Table 7-4. More information about the exceptional event designation is provided elsewhere in this report.

Table 7-3. Ozone summary statistics for five sites in the Uintah Basin over eight calendar years. All values were calculated from daily maximum 8-hour average concentrations. 2016 data are not yet finalized.

Year	Site	Mean	Median	Max	Min	4th High Daily Max	Exceedance Days (>70.9 ppb)
2009 (July-Dec)	Ouray	46	47	101	23	67	1
	Fruitland	--	--	--	--	--	--
	Vernal	--	--	--	--	--	--
	Roosevelt	--	--	--	--	--	--
	Rangely	--	--	--	--	--	--
2010	Ouray	56	54	123	20	117	45
	Fruitland	--	--	--	--	--	--
	Vernal	--	--	--	--	--	--
	Roosevelt	--	--	--	--	--	--
	Rangely	41	42	67	11	58	--
2011	Ouray	53	52	138	18	119	28
	Fruitland	48	50	71	24	65	1
	Vernal	55	55	95	33	84	12
	Roosevelt	55	54	116	29	103	21
	Rangely	48	50	88	21	73	4
2012	Ouray	48	50	76	18	67	1
	Fruitland	49	49	71	26	70	3
	Vernal	45	46	68	14	64	0
	Roosevelt	49	51	70	14	67	0
	Rangely	46	47	71	15	69	2
2013	Ouray	57	54	141	24	132	52
	Fruitland	49	50	75	18	69	2
	Vernal	52	52	114	20	102	32
	Roosevelt	56	54	110	25	104	35
	Rangely	50	50	106	22	91	13
2014	Ouray	48	50	91	17	79	8
	Fruitland	47	49	65	16	64	0
	Vernal	43	45	64	12	62	0
	Roosevelt	46	49	63	16	62	0
	Rangely	44	46	66	14	62	0
2015	Ouray	45	47	71	21	68	2
	Fruitland	46	46	77	23	69	3
	Vernal	43	43	67	10	64	0
	Roosevelt	42	42	66	14	60	0
	Rangely	43	45	70	15	66	0
2016 (Jan-Sep)	Ouray	52	51	120	31	96	11
	Fruitland	48	49	67	33	62	0
	Vernal	50	49	78	30	73	5
	Roosevelt	50	50	96	31	84	10
	Rangely	47	47	67	28	61	0

Table 7-4. Average of the 4th-highest 8-hour daily maximum ozone values during calendar years 2014, 2015, and 2016. Data through 2015 are final values taken from EPA's AQS database. 2016 data are not yet final and could change.

Station	3-year Average
Ouray	81
Fruitland	65
Vernal	66
Roosevelt	68
Rangely	63

7.3.2. Particulate Matter

As has been typical in previous years, periods with higher ozone tended to also have higher particulate matter ($PM_{2.5}$, or particulate matter with aerodynamic diameter smaller than 2.5 microns) concentrations during winter 2015-16. $PM_{2.5}$ was elevated during most of the winter (Figure 7-9), but the highest concentrations occurred during the same episode that led to ozone exceedances in the first half of February. No exceedances of the $PM_{2.5}$ standard were observed during winter 2015-16 (Figure 7-9).

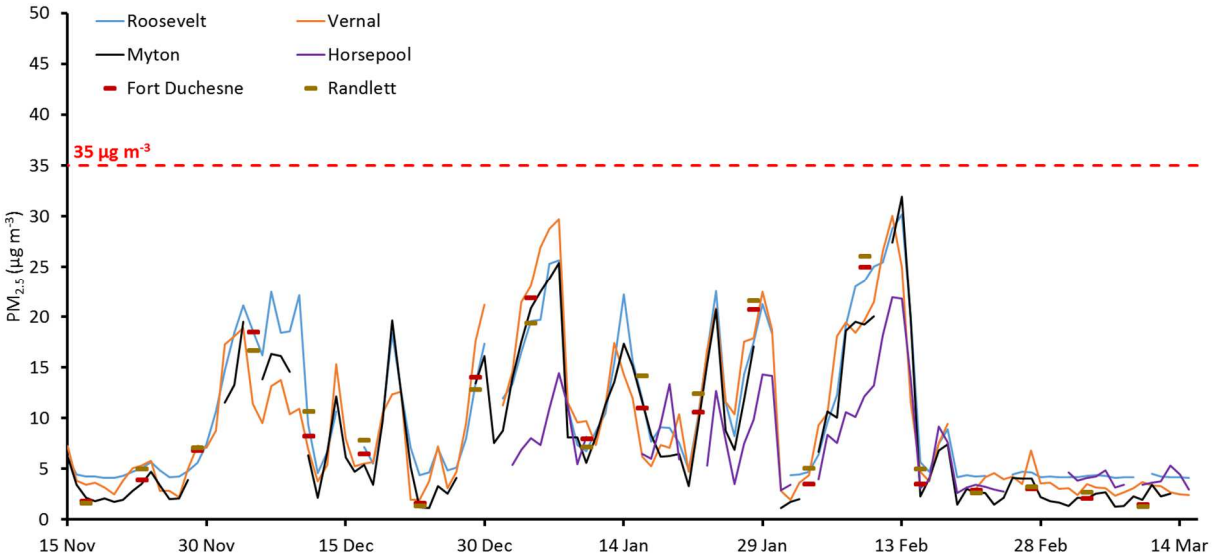

Figure 7-9. 24-hour average $PM_{2.5}$ from monitoring stations around the Uintah Basin during winter 2015-16. The red dashed line indicates the EPA $PM_{2.5}$ standard.

Figure 7-10 shows box and whisker plots of $PM_{2.5}$ at monitoring stations around the Uintah Basin. The highest $PM_{2.5}$ occurred in Roosevelt and Vernal, followed by Myton, Fort Duchesne, and Randlett. Horsepool, which has more oil and gas sources nearby, had lower $PM_{2.5}$. Unlike ozone, $PM_{2.5}$ in the Uintah Basin appears to be dependent on proximity to urban *and* oil and gas sources, and the highest $PM_{2.5}$ has consistently been observed in or near urban areas.

Rangely had much lower $PM_{2.5}$ than the other monitoring stations. Inversion conditions that affected most of the Uintah Basin appear not to have impacted Rangely. Ozone at Rangely was also low relative

to other monitoring stations (Table 7-2). Rabbit Mountain, near the Colorado border, has experienced high wintertime ozone in the past, but ozone stayed low at Rabbit Mountain this winter (Table 7-2). This may indicate that meteorological conditions on the eastern edge of the Basin were not conducive to ozone formation during winter 2015-16.

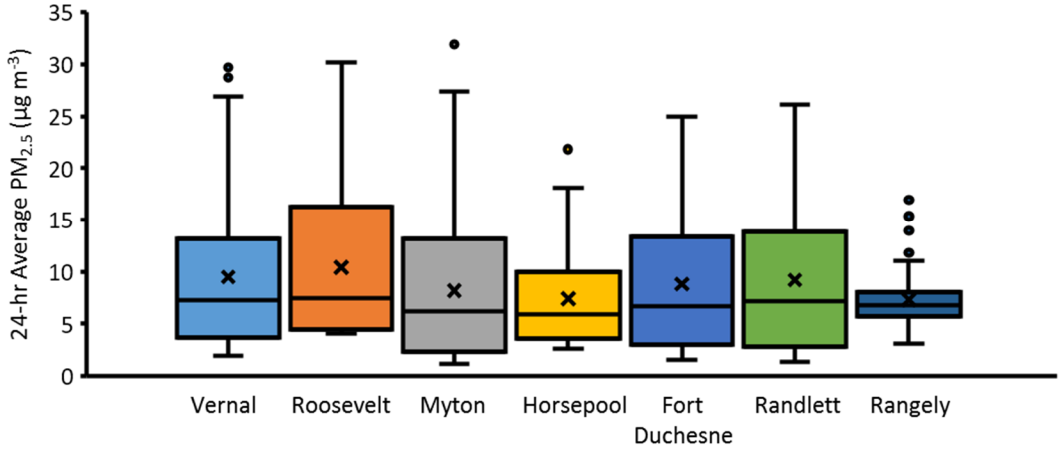

Figure 7-10. Box-and-whisker plot of $PM_{2.5}$ during winter 2015-16. X's indicate average values. Lines in the middle of boxes indicate medians. Tops and bottoms of boxes indicate the third and first quartiles. Top and bottom whiskers indicate maximum and minimum values. Circles indicate outliers.

Figure 7-11 shows a time series of all $PM_{2.5}$ measurements that have been collected in the Uintah Basin. Exceedances of the EPA $PM_{2.5}$ standard have occurred most often during winter. However, summertime $PM_{2.5}$ exceedances were observed in the Uintah Basin during summer 2012, and spikes in $PM_{2.5}$ have been observed during every summer. These summertime spikes in $PM_{2.5}$ concentrations have likely been caused by wildfire smoke.

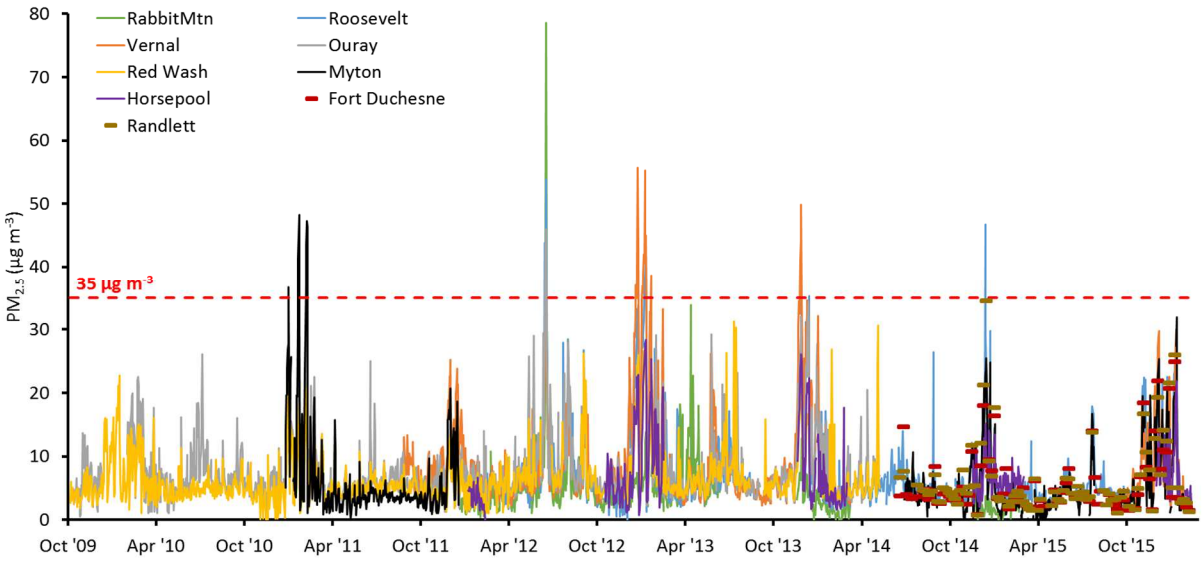

Figure 7-11. Time series of daily 24-hour average $PM_{2.5}$ concentrations at nine sites in the Uintah Basin, October 2009-March 2016. The red dashed line shows 35 µg m^{-3}, the EPA standard for $PM_{2.5}$.

Table 7-5 is a summary of $PM_{2.5}$ values at sites around the Uintah Basin from 2010 through March 2015. $PM_{2.5}$ values in Vernal and Roosevelt have exceeded EPA standards more than other sites, including Ouray, which has the highest ozone. To determine compliance with its 35 µg m^{-3} $PM_{2.5}$ standard, EPA uses the three-year average of annual 98th percentile values. The Uintah 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 7-5. $PM_{2.5}$ summary statistics for the Uintah Basin over seven calendar years. All values shown were calculated from daily 24-hour average concentrations.

Year	Site	Winter Mean	Winter Median	Winter Max	Winter Min	Annual # of Exceedance Days	Annual 98th Percentile Value
2010	Roosevelt	--	--	--	--	--	--
	Vernal	--	--	--	--	--	--
	Ouray	8.8	6.8	22.5	1.0	0	19.0
	Red Wash	7.2	5.8	22.7	0.0	0	16.0
	Myton	--	--	--	--	--	--
	Rabbit Mtn	--	--	--	--	--	--
	Horsepool	--	--	--	--	--	--
2011	Roosevelt	--	--	--	--	--	--
	Vernal	--	--	--	--	--	--
	Ouray	9.9	8.6	30.0	1.1	0	22.5
	Red Wash	7.8	6.6	23.7	1.0	0	17.8
	Myton	11.8	7.4	48.2	1.0	8	36.7
	Rabbit Mtn	--	--	--	--	--	--
	Horsepool	--	--	--	--	--	--
2012	Roosevelt	5.7	4.5	22.2	0.0	3	28.2
	Vernal	7.9	7.1	25.6	1.2	0	22.0
	Ouray	6.1	5.9	14.0	1.3	3	27.4
	Red Wash	4.9	4.8	10.6	1.0	0	16.0
	Myton	--	--	--	--	--	--
	Rabbit Mtn	2.7	2.6	10.7	0.4	4	20.3
	Horsepool	4.0	3.5	10.7	0.0	0	10.4
2013	Roosevelt	18.7	18.3	41.7	1.3	5	35.1
	Vernal	20.0	15.4	55.7	2.6	18	42.1
	Ouray	13.4	11.6	32.0	2.3	0	26.5
	Red Wash	10.9	8.0	26.7	3.0	0	26.0
	Myton	--	--	--	--	--	--
	Rabbit Mtn	5.0	4.7	13.9	1.4	0	18.0
	Horsepool	13.7	14.4	28.3	0.7	0	27.8
2014	Roosevelt	7.1	4.8	35.3	1.7	1	29.8
	Vernal	9.6	6.7	32.1	2.2	0	30.3
	Ouray	9.2	6.8	34.4	2.4	0	31.6
	Red Wash	6.0	4.2	26.8	3.2	0	15.1
	Myton	--	--	--	0.2	--	--
	Rabbit Mtn	2.0	1.9	5.0	0.0	0	5.1
	Horsepool	5.5	4.1	22.3	1.5	0	21.6

Table 7-5 Continued.

Year	Site	Winter Mean	Winter Median	Winter Max	Winter Min	Annual # of Exceedance Days	Annual 98th Percentile Value
2015	Roosevelt	8.7	5.3	46.7	2.7	1	21.2
	Vernal	--	--	--	--	--	--
	Ouray	--	--	--	--	--	--
	Red Wash	--	--	--	--	--	--
	Myton	6.7	3.9	25.5	0.1	0	19.8
	Rabbit Mtn	1.7	1.6	3.8	0.0	0	3.7
	Horsepool	7.0	6.1	15.2	3.0	0	14.4
	Ft Duchesne	7.6	6.7	18.5	1.7	0	18.0
	Randlett	9.4	7.0	34.6	1.4	0	21.3
2016 (thru Mar 31)	Roosevelt	11.0	8.2	30.2	4.1	0	28.8
	Vernal	10.5	7.6	30.0	1.9	0	29.7
	Ouray	--	--	--	--	--	--
	Red Wash	--	--	--	--	--	--
	Myton	8.9	6.6	31.9	1.1	0	27.4
	Rabbit Mtn	--	--	--	--	--	--
	Horsepool	7.4	5.7	21.9	2.7	0	21.8
	Ft Duchesne	9.5	5.8	25.0	1.5	0	25.0
	Randlett	10.1	6.1	26.1	1.3	0	26.1

7.3.3. Comparison of Roosevelt and Horsepool Station Data

The Horsepool and Roosevelt monitoring stations began operating in winter 2011-12 and were designed to contain a nearly identical suite of instrumentation. The areas surrounding the stations are very different from one another. The Horsepool station is on the northern edge of an area of dense oil and gas development, whereas the Roosevelt station is within a small city. Sparse oil and gas development exists within and near the city of Roosevelt. The two stations are at very similar elevations (Table 7-1).

Figure 7-12 and Figure 7-13 show NO_x and NO_z measured at Horsepool and Roosevelt. These stations measure NO_x with instruments that utilize photolytic NO_2 converters. Regulatory monitoring stations in the Uintah Basin utilize different methods to measure NO_x that suffer from a high bias during winter inversion episodes, making their NO_x data unreliable. NO_x is the sum of NO and NO_2, and together are important precursors to ozone production. NO_z is the sum of all reactive nitrogen compounds except NO_x (in other words, it is NO_y minus NO_x), and includes nitric and nitrous acids, organic nitrates, and particulate-bound nitrogen compounds. While NO_x is an ozone precursor, the compounds that comprise NO_z are mostly generated along with ozone as a result of photochemical reactions and can be thought of as byproducts and indicators of ozone production.

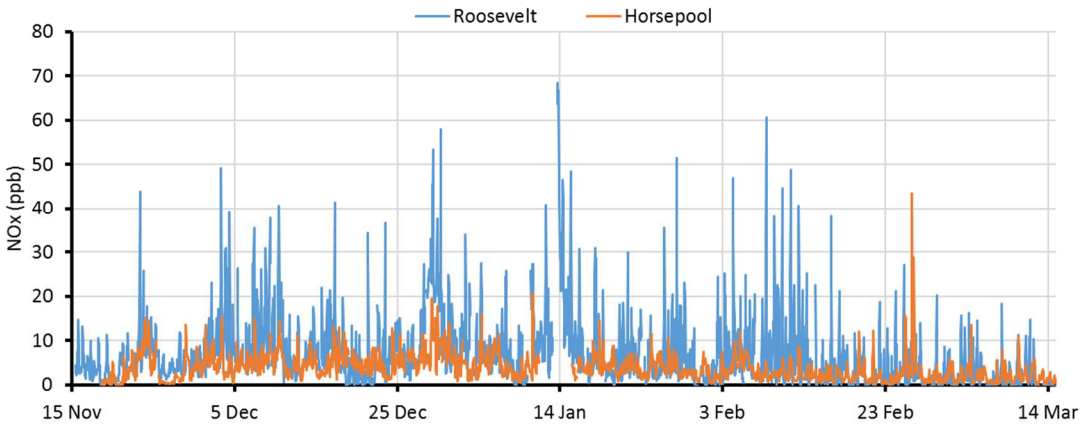

Figure 7-12. NO_x measured at Roosevelt and Horsepool during winter 2015-16.

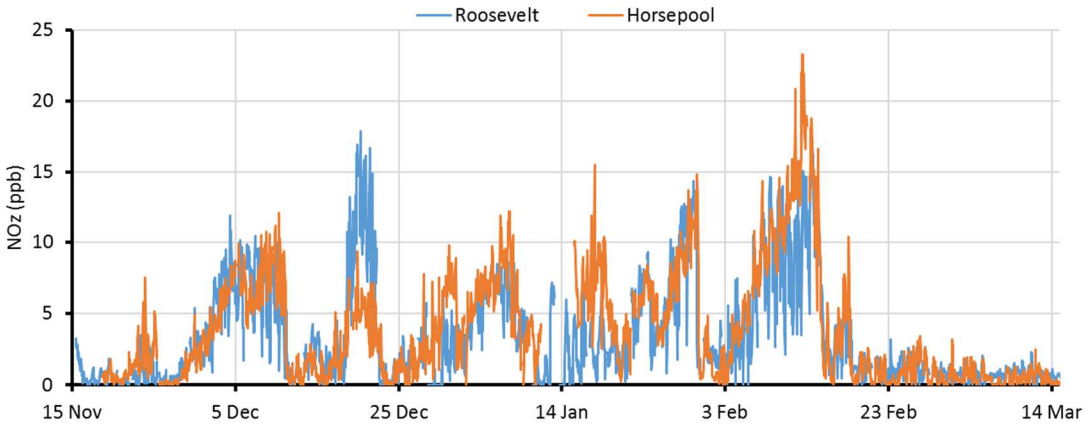

Figure 7-13. NO_z measured at Roosevelt and Horsepool during winter 2015-16.

During winter 2015-16, NO_x was almost always higher in Roosevelt than at Horsepool (Figure 7-12) and was 1.8 times higher on average. NO_x in Roosevelt is likely emitted from urban sources like cars and home heating, as well as from oil and gas sources. Since NO_x is an ozone precursor, one might predict that ozone in Roosevelt would be higher than at Horsepool, But ozone (Table 7-2, Figure 7-14) and NO_z (Figure 7-13) tended to be higher at Horsepool, especially during the inversion episode that occurred in the first half of February.

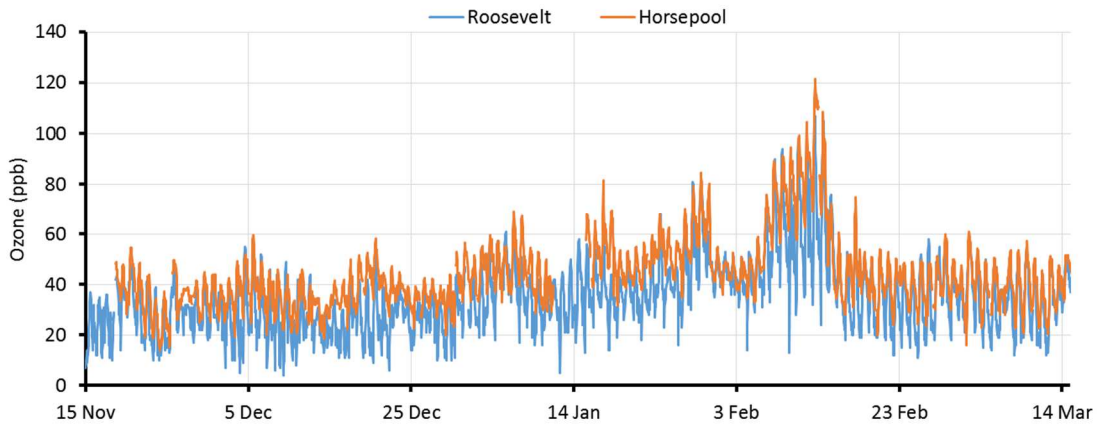

Figure 7-14. Ozone measured at Roosevelt and Horsepool during winter 2015-16.

In contrast with NO_x, methane and total non-methane hydrocarbons (TNMHC; equivalent to VOC) were consistently higher at Horsepool than in Roosevelt (Figure 7-15 and Figure 7-16). Thus, organic compounds appear to be more important than NO_x in determining the amount of ozone production in this comparison of two sites. While this is not a definitive analysis, it provides additional evidence to that which already exists indicating reductions in VOC emissions will have a greater impact on ozone than reductions in NO_x emissions.

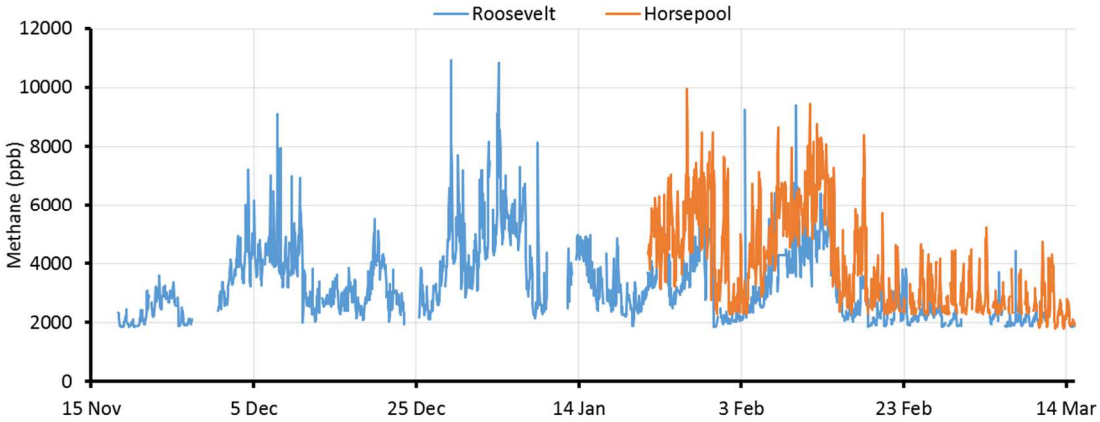

Figure 7-15. Methane measured at Roosevelt and Horsepool during winter 2015-16.

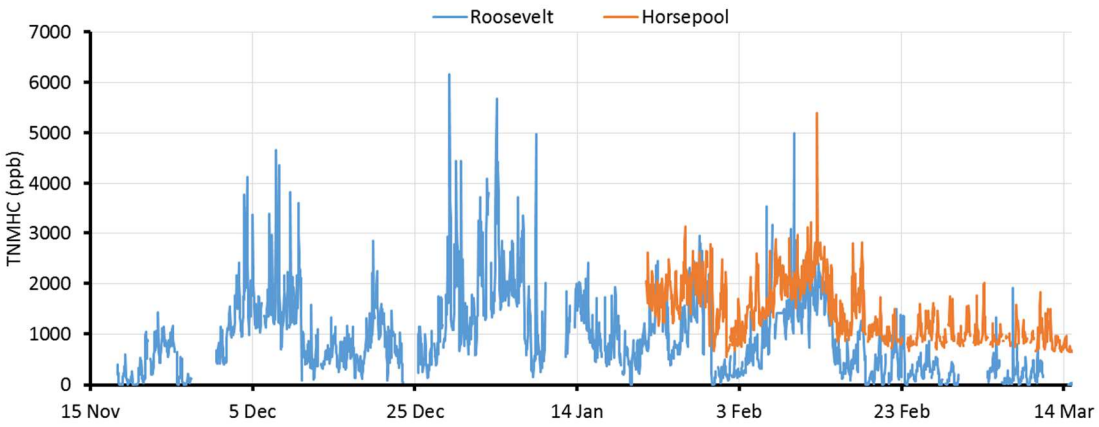

Figure 7-16. Total non-methane hydrocarbons (TNMHC; equivalent to VOC) measured at Roosevelt and Horsepool during winter 2015-16.

7.3.4. Ozone During Non-winter Seasons

The Uintah Basin is well-known for high ozone during winter seasons. However, ozone concentrations also occasionally approach or exceed the 70 ppb EPA standard during early spring and summer seasons (Figure 7-8). Four highest daily maximum 8-hour average ozone values in 2015 at almost all monitoring stations in the Basin occurred in June and August, rather than during winter months. Similarly, all ozone exceedance days in 2012 occurred during summer seasons. Summertime ozone exceedances increase the likelihood of violations of the EPA ozone standard, which is determined as the three-year average of the annual fourth highest daily maximum 8-hour concentration. While local emissions from oil and gas production are considered to be the major contributor of high ozone in winter, and impacts from long-range or stratosphere-to-troposphere ozone transport during the winter are low, evidence indicates that high ozone during non-winter seasons is not due primarily to local anthropogenic emissions.

We used various observed and modeled datasets to identify an ozone exceptional event on 8-9 June 2015, when ozone exceeded the 70 ppb standard, which was caused by a stratospheric intrusion. On these days, ozone levels above 70 ppb occurred at almost all monitoring stations in the Basin (Figure 7-17). This is in contrast to wintertime inversion episodes, during which high ozone levels typically occur only at low-elevation monitoring stations and in areas of high oil/gas concentration (see discussion above). We presented our findings to the Ute Indian Tribe and the Utah Division of Air Quality and participated with these entities and EPA in preparing a formal demonstration document for the exceptional event. The document was released for public review on 1 September 2016 (https://www.epa.gov/air-quality-analysis/public-notice-exceptional-events-uinta-basin-utah).

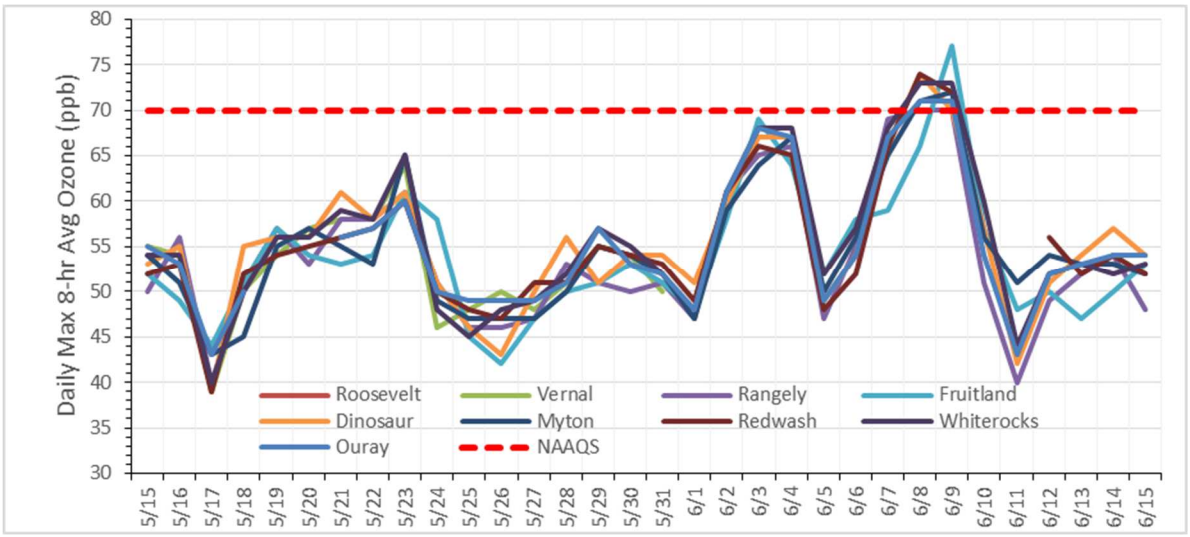

Figure 7-17. Time series of the daily maximum 8-hour average ozone concentration at air quality monitoring sites during 15 May to 15 June 2015. NAAQS indicates the National Ambient Air Quality Standard for ozone of 70 ppb.

We found that naturally-induced surface ozone events are not uncommon in the Basin during spring and summer seasons, although very few exceed the ozone standard. For example, using observational data and modeling techniques, we have determined that high ozone levels occurring on 12 May 2015 and 3-4 June 2015 (66, 67-68 ppb at Ouray, respectively) were caused by stratospheric ozone intrusion. On 20 August 2015, high ozone (69 ppb at Ouray) was likely caused by wildfires occurring at this time.

There were no ozone exceedances in spring and summer 2016 (Figure 7-18). As simulated by the MOZART-4 Chemical Forecast model (https://www2.acom.ucar.edu/acresp/forecasts), stratospheric ozone intrusions occurred frequently during summer, especially in May and June, but they were not as significant as those which occurred during June 2015 and were poorly correlated with surface ozone (Figure 7-19). Nevertheless, Figure 7-19 suggests that stratospheric ozone is one of the main contributors to surface ozone in the Uintah Basin during spring and summer.

In summer 2016, ozone was highest on 2 August 2016 (Figure 7-18; 69 ppb at Redwash and Dinosaur Monument, 65 ppb at Ouray). There are indicators that this high ozone day was caused by wildfires: both observed CO at Rabbit Mountain and $PM_{2.5}$ at several monitoring sites were higher on this day than other days; while the MOZART-4 model predicted a minimal stratospheric ozone contribution. Note that August seems to be the most common time for wildfire-driven ozone events.

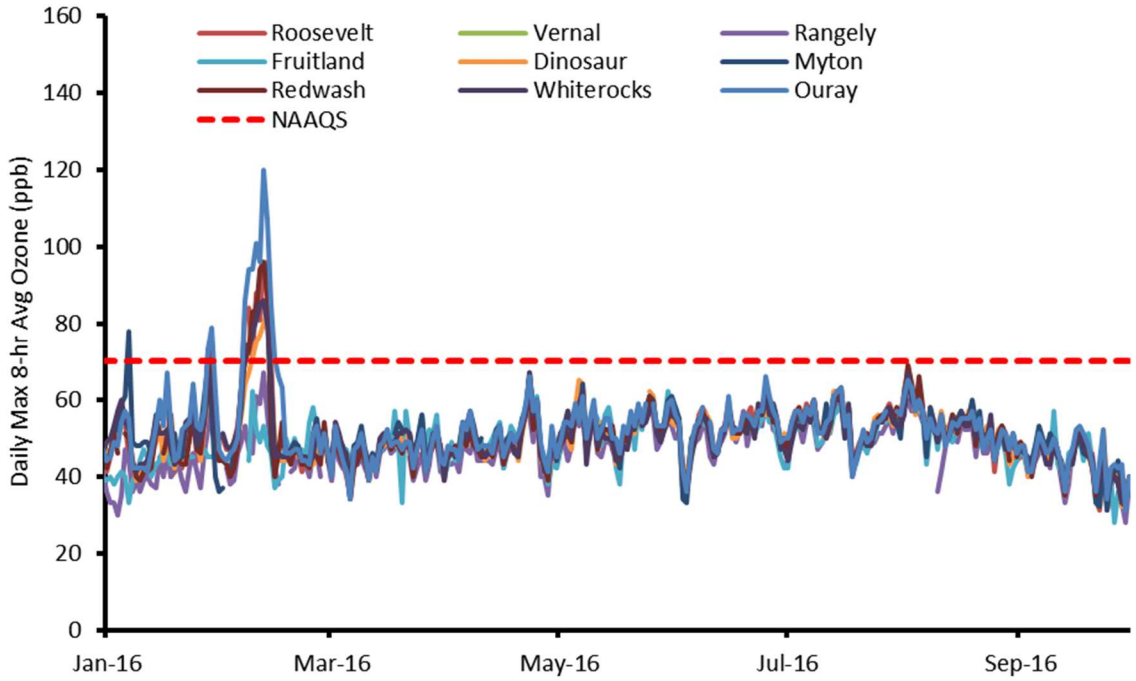

Figure 7-18. Daily maximum 8-hour average ozone from January through September 2016. NAAQS indicates the National Ambient Air Quality Standard for ozone of 70 ppb.

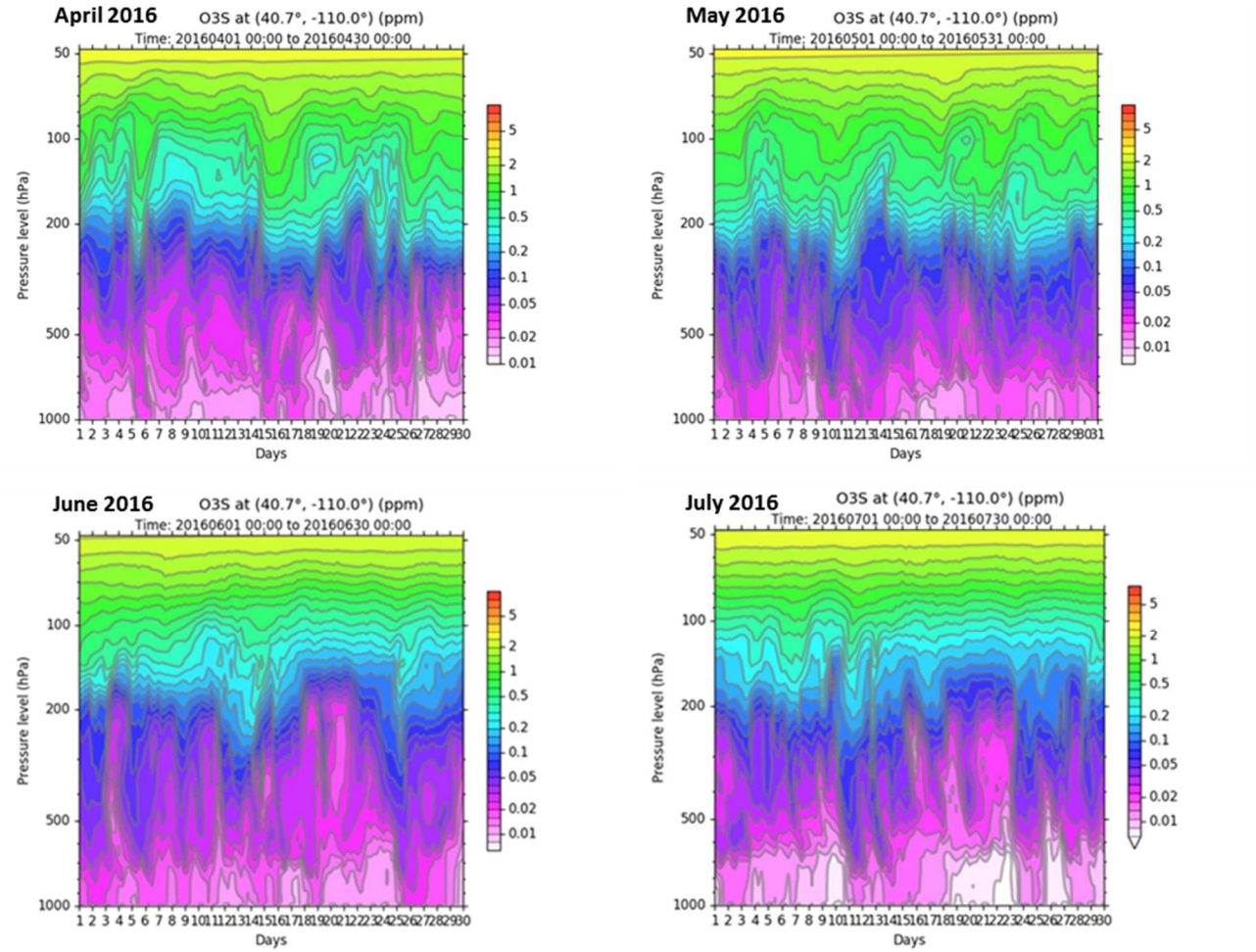

Figure 7-19. Vertical distribution of stratospheric ozone (O3S) in the Uintah Basin during April to July 2016 as simulated by the MOZART-4 Chemical Forecast model. X-axes indicate days of the month. Y-axes indicate atmospheric pressure, a proxy for altitude. Coloration is by ozone concentration in ppm. Descending streaks of blue indicate periods wherein ozone from the stratosphere intruded towards the surface.

8. Statistical Analysis of the Causes of Winter Ozone Exceedances, 2009-2016

8.1. Introduction

The unique factors producing winter ozone in the Uintah Basin are summarized in Figure 20. The topography of the basin is conducive to persistent multi-day wintertime thermal inversions. An extensive oil and natural gas extraction industry generates VOC and NO_x emissions that become trapped under the inversion layer. Snow cover also plays a role, enhancing the surface albedo and providing adequate ultraviolet energy to produce ozone. Furthermore, the ozone system of the Uintah Basin is characterized by the feedback loop represented in Figure 8-1. The high surface albedo of the snowpack stabilizes inversions, which in turn stabilizes the snowpack. The Uintah Basin tends to receive fewer snowstorms than the Wasatch Front. Nevertheless, a single heavy snowstorm can activate the feedback loop, leading to cold temperatures, persistent thermal inversions, a stable snowpack, and numerous exceedances of the ozone National Ambient Air Quality Standard (NAAQS) of 70 ppb until springtime.

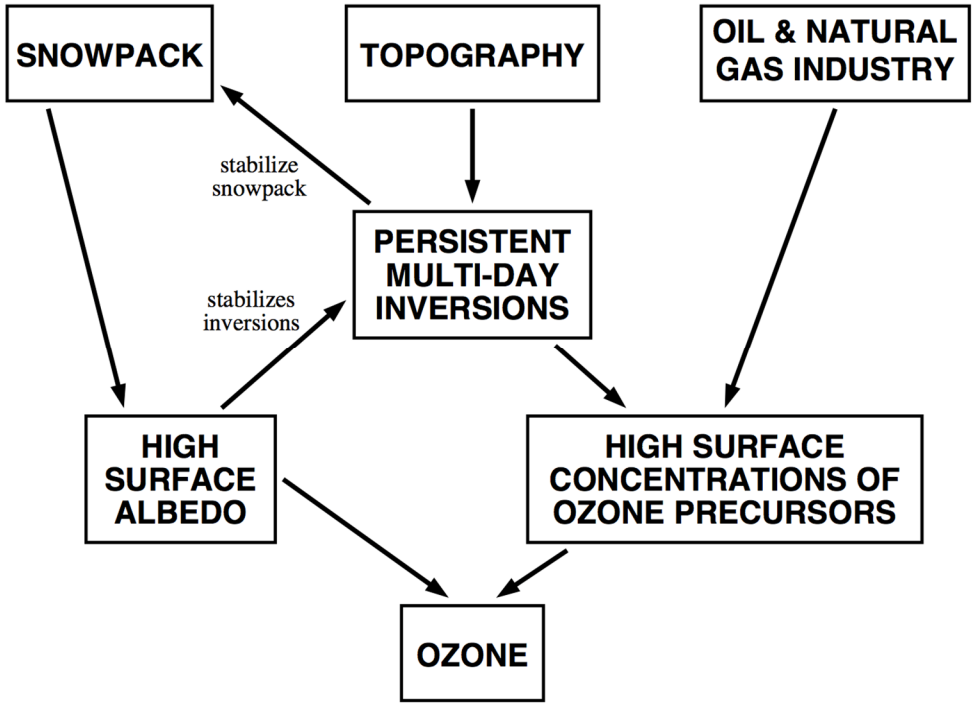

Figure 8-1. Flow chart summarizing the mechanism of the Uintah Basin winter ozone system. Winter ozone requires three basic ingredients, a snowpack, topography conducive to persistent thermal inversions, and an extensive oil or natural gas extraction industry. The industry is the source of ozone precursors, the inversions keep ozone precursors trapped near the surface, and the albedo of the snowpack ensures adequate actinic flux for the production of ozone. The problem is exacerbated in the Uintah Basin by a feedback loop in which the albedo of the snowpack stabilizes inversions, which stabilize the snowpack.

Continuous ozone monitoring has occurred at Ouray, Utah since mid-2009, as shown in Figure 8-2. The usual summertime ozone highs are obvious in the data, with occasional summertime exceedances of the NAAQS. However, these are overshadowed by wintertime exceedances during five winters, 2010, 2011, 2013, 2014, and 2016. Winters 2012 and 2015 had insufficient snow cover to activate the cascade shown in Figure 8-1.

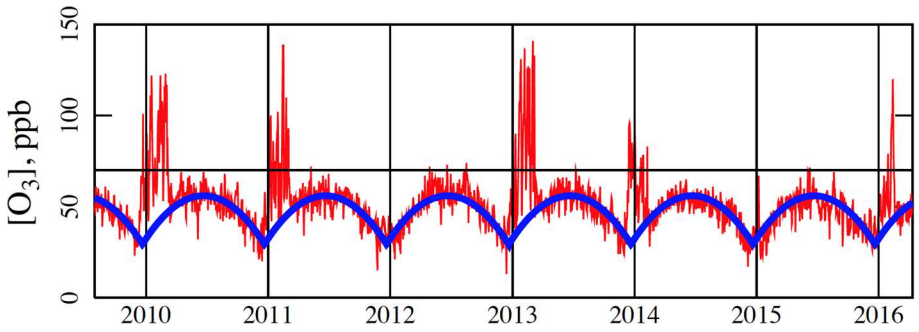

Figure 8-2. Time series of the 8-hour daily ozone maximum at Ouray, Utah, from 31 July 2009 to 11 April 2016. The red trace shows the ozone concentration while the blue trace shows a train of fitted polynomials centered at the summer solstice. The horizontal black line is the NAAQS for ozone, 70 ppb. Each vertical black line indicates 1 January. Five winter seasons out of seven, 2010, 2011, 2013, 2014, and 2016 saw many daily exceedances of the NAAQS. Data were obtained from the EPA AQS database.

In this section of the report, we present a regression analysis of Uintah Basin winter ozone events. Regression analysis consists of an effort to predict a dependent variable, i.e., the daily ozone concentration, from the values of a number of independent variables. Such an analysis has several uses: (1) We can analyze the relative effect of different independent variables on the formation of ozone. (2) By applying the regression to historical data, we are able to predict the contemporary likelihood that any given winter season will have high ozone. (3) It can also serve as a tool for short-range forecasting: If we have reasonable short-term forecasts for each of the independent variables, then the regression provides a short-term forecast of ozone. The first two uses will be explained in this report, while the third is an on-going research effort.

Several years ago, we published a similar regression analysis for the Uintah Basin ozone system (Mansfield and Hall, 2013). However, at that time only three years of ozone data were available to inform the analysis. Since then, fluctuations in the global energy market have produced a downturn in oil and gas activity in the basin. Today, there are ozone data covering seven full winters including a broader range of ozone behavior and years of both relatively high and low industrial activity. An important difference between the current and the previous analysis is that we have now included measures of industrial activity as independent variables. Another difference between the two treatments is that we have refined the computation of daily pseudo-lapse rate, see below.

In the next subsection, we explain the development of several different independent variables and the rationale for their inclusion in the regression analysis. Subsequent subsections describe the development of the regression model, a sensitivity analysis to determine the relative effect of each independent variable, and an application of the model to Uintah Basin historical data. Although we do not present a regression analysis for the Upper Green River Basin ozone system, we have subjected

actual ozone statistics from the Upper Green to similar statistical tests. Those results are also presented below.

Based on our analysis, we are able to make the following prediction about winter ozone in the Uintah Basin: 38% of years are expected to have no exceedances of the NAAQS and 46% are expected to be in attainment with 3 or fewer exceedances. The odds are 12% that a year will be at least as bad as 2010. We also address the question of inter-seasonal trends: Does the number of exceedances in any year exert an influence on the following year? A Markov analysis is unable to unequivocally rule out inter-seasonal trends, but if any are present, they are weak. The analysis has been unable to see the effect of the recent economic downturn. We will also speculate about this failure and propose additional studies.

8.2. Independent Variables in the Regression

8.2.1. Pseudo-lapse rate

Because of the role of thermal inversions, we anticipate that the lapse rate should be an important independent variable. However, routine measurements of the lapse rate do not occur in the Uintah Basin. Therefore, we have developed an analysis based on temperatures at various surface stations to calculate a variable we call the pseudo-lapse rate. We accessed the daily maximum temperature at about 50 stations in the vicinity of the Uintah Basin, as shown in Figure 8-3, over the seven winter seasons from 2010 to 2016 from the Utah Climate Center (https://climate.usurf.usu.edu), an online archive of meteorological data. Figure 8-4 displays the average in the daily maximum temperature for the dates February 1 through February 14 for which the ozone concentration at Ouray was either over (filled symbols) or under (open symbols) the value of the NAAQS. The points corresponding to high ozone days separate naturally into two different groups, one group consisting of 13 filled squares, the other group designated by filled circles. These two groups appear in different regions of the diagram, and exhibit positive and negative correlation, respectively, with altitude. The best-fit correlation lines correspond to average lapse rates of -6.9 and +3.9 K/km. Similar diagrams prepared for any time period between mid-December to mid-March (not shown) display equivalent behavior, singling out the same 13 stations that display a positive correlation between altitude and average temperature during ozone exceedance days. The logical conclusion is that these 13 stations routinely lie below the inversion layer in the basin. This conclusion is fortified when we see the geographic positions of the 13 stations on the map in Figure 8-3. All lie within the lower part of the basin, and sites exterior to the basin at comparable altitudes are not included. Therefore, on any given day, we define the pseudo-lapse rate from the slope of the least-squares line of maximum daily temperature at these 13 stations against altitude. Figure 8-5 shows the time series for the pseudo-lapse rate defined in this way. The most intense inversions as measured by the pseudo-lapse rate are seen in the same years that produce many ozone exceedances.

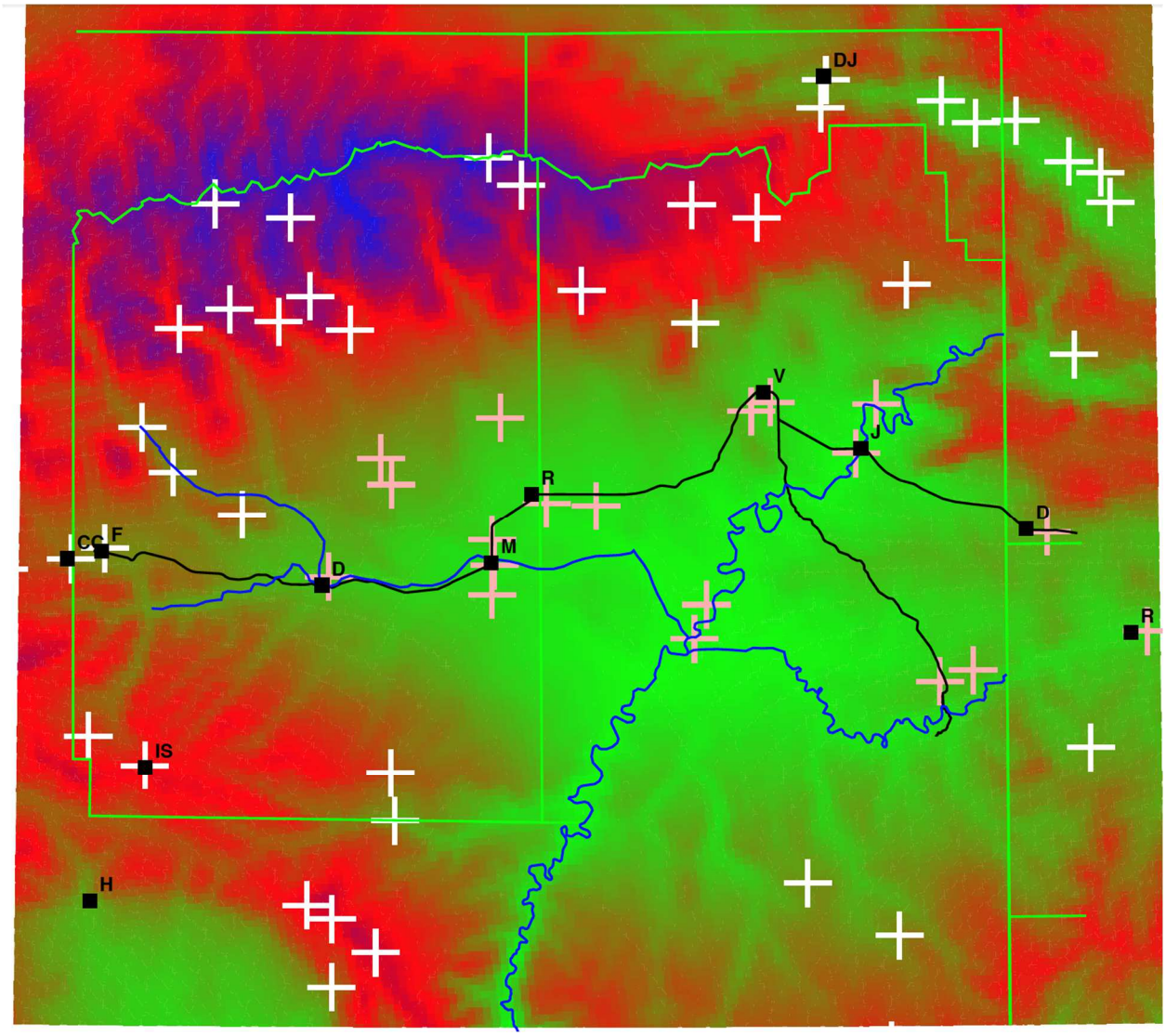

Figure 8-3. Map of the Uintah Basin. Each cross gives the location of a temperature station that was accessed from the Utah Climate Center. Pink crosses indicate the stations that were determined typically to lie under the inversion layer and that were used in the definition of the pseudo-lapse rate.

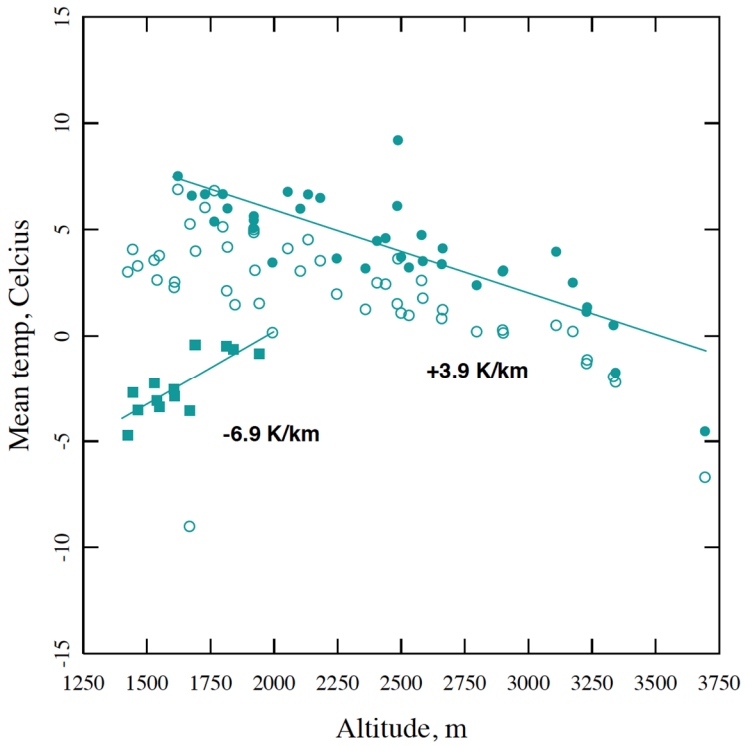

Figure 8-4. Mean temperatures at about 50 temperature stations from 1 February to 14 February on days for which the ozone concentration was either below (open circles) or above (filled circles and squares) the NAAQS. During ozone exceedance events, 13 stations (filled squares) show a temperature behavior distinct from the others (filled circles) because they typically lie below the inversion layer in the basin.

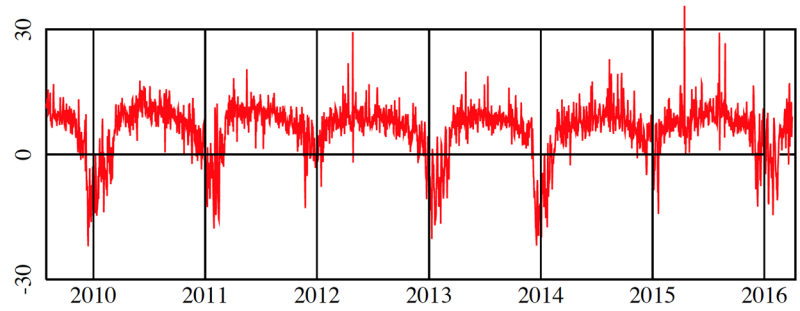

Figure 8-5. Uintah Basin daily pseudo-lapse rate time series (units of K/km), 31 July 2009 to 11 April 2016.

8.2.2. Snow Depth

The Utah Climate Center also archives historical data on snow depth. Figure 8-6 shows the basin snow depth time series averaged over the same 13 stations used to define the pseudo-lapse rate. The average snow depth is greater during the five winters that produced high ozone.

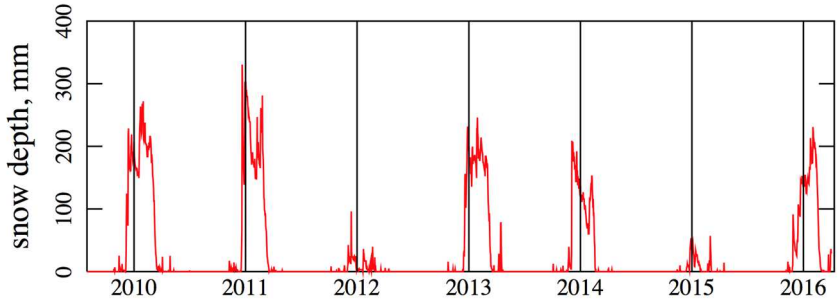

Figure 8-6. Mean Uintah Basin daily snow depth.

8.2.3. Solar Zenith Angle and Length of Day

Several lines of analysis indicate that the solar zenith angle and the length of daylight are also important independent variables. Figure 8-7 shows the probability of experiencing an ozone exceedance at various times throughout an average winter season, computed over the seven years of interest. The odds for a daily ozone exceedance approach a maximum of 40% during the first two weeks of February. However, Figure 8-7 also shows that the average ozone concentration during an exceedance increases steadily during the season. Early in the season, solar radiation is too weak to generate ozone rapidly, while late in the season, when the sun is higher and the day is longer, solar radiation is more effective at disrupting inversions, but also provides more energy for ozone formation. Therefore, ozone exceedances are rarer in early and late winter. However, those occurring in late winter are very strong.

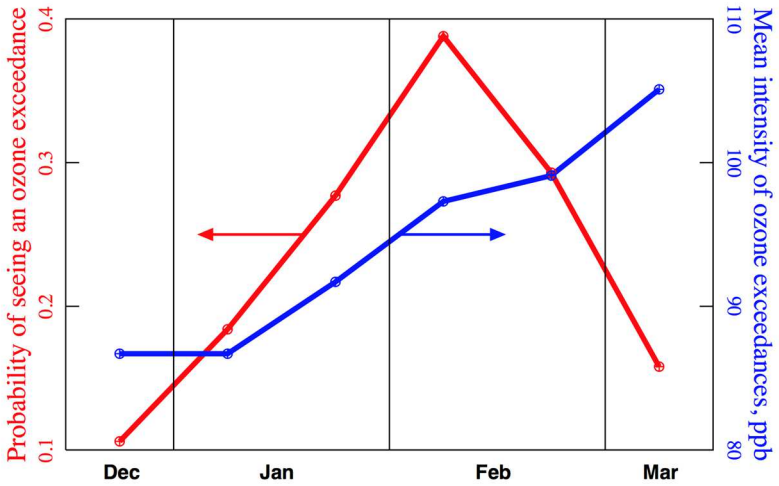

Figure 8-7. Probability of ozone exceedance and intensity of ozone exceedance for each winter month. The probability of a daily ozone exceedance in the Uintah Basin is largest in early February, while the average ozone concentration during an exceedance increases steadily through the season.

Figure 8-8 shows a series of histograms, one for each of six different time periods during the winter season. For example, Dec II consists of the dates 15 December to 31 December, while Jan I consists of the dates 1 January to 14 January, etc. Each histogram gives the number of ozone exceedances occurring during each time period as a function of the pseudo-lapse rate. Intense inversions are required to produce ozone in early winter, but not in late winter. This can also be explained as a result

of the effect of the solar zenith angle and day length. As long as snow cover is present, the longer day and the higher sun produce greater ozone efficiency.

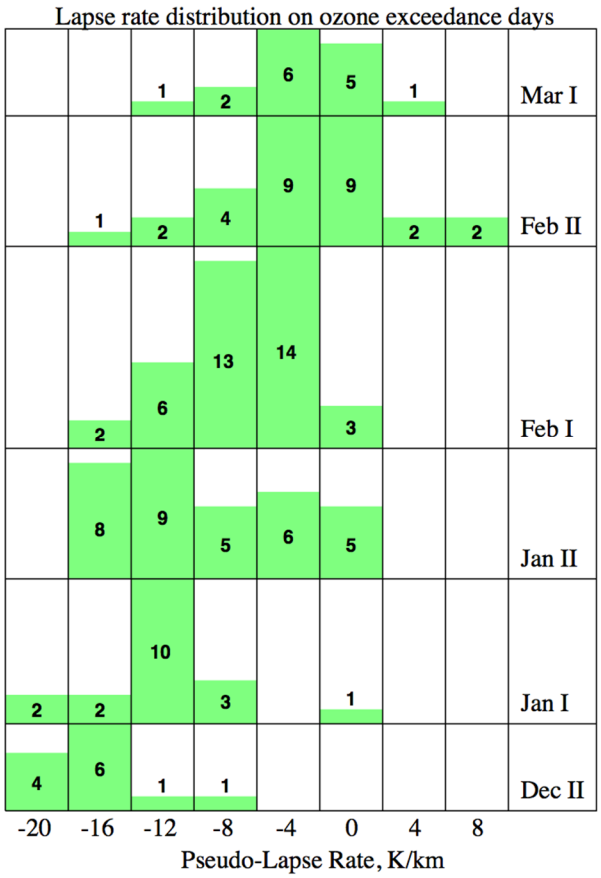

Figure 8-8. Pseudo-lapse rate distribution on ozone exceedance days during six different half-month periods (Dec II = 16-31 Dec, Jan I = 1-15 January, etc.). The x-axis shows the pseudo-lapse rate, and the green bars in each half-month section show the number of exceedance days that have occurred during that period with each pseudo-lapse rate.

It is difficult to determine which of the two variables, day length or solar angle, has a larger influence on the ozone system. However, because the two are so strongly correlated, a regression analysis is probably unable to separate their effects. We have assumed that all the effects of both variables can be subsumed by either, and included only the daily minimum in the solar zenith angle as an independent variable. It is calculated on any given day using the formulas found in Finlayson-Pitts and Pitts Jr (1999). At the latitude of the Uintah Basin, the solar zenith angle varies from 64° at the winter solstice to 40° at the vernal equinox.

8.2.4. Basin Temperature

The chemical processes leading to ozone formation have temperature-dependent rates, so some temperature dependence can be expected. Above we described the linear-least-squares analysis of

temperature vs. altitude to obtain the pseudo-lapse rate. We use the intercept of the least-squares line at an altitude of 1800 m (near the floor of the basin) to define a daily basin temperature.

8.2.5. Consecutive Inversion Days

We usually see the ozone concentration increase over the course of a multi-day inversion event and attribute this effect to the build-up of ozone precursors. To account for this effect in the regression analysis, we define a variable, "consecutive inversion days" or CID, as follows. If on any given date, the pseudo-lapse rate is positive, then let CID for that date equal 0. If the pseudo-lapse rate is negative, then let CID be 1 more than its value on the previous day. According to this definition, CID counts the number of days since the beginning of a multi-day inversion event.

8.2.6. Absolute Humidity

Ambient water vapor concentrations vary considerably throughout the year. This is important because OH radicals are important in ozone production, and the typical summertime OH production pathway, $O(^1D) + H_2O \rightarrow 2\ OH$ (Seinfeld and Pandis, 2016), is suppressed in the Uintah Basin in winter, and the source of OH radicals is not clear. In hopes that the regression analysis would provide some clue, we have also included the daily noontime partial pressure of H_2O as an independent variable. The Utah Climate Center provides dew point data. These were converted using standard formulas (Finlayson-Pitts and Pitts Jr, 1999) to partial pressure of H_2O.

8.2.7. Total petroleum production

Figure 8-9 displays time series for the production of oil and natural gas in the Uintah Basin since 2009. Because of the recent downturn in global energy prices, both oil and natural gas extraction have declined in the basin since *ca*. 2014. If we are able to define an independent variable that correlates well with precursor emissions, then a regression analysis should indicate whether this recent downturn is reflected in the observed ozone concentration. Therefore, we have included the total daily tonnage of petroleum production in the Uintah Basin as an independent variable in the regression, assuming that it can act as a proxy for the emission rate of ozone precursors. Crude oils and natural gases do not all have the same density, and to calculate tonnage, we have assumed the following conversion factors: 19168 tonne / 1 BCF natural gas and 138 tonne / bbl oil.

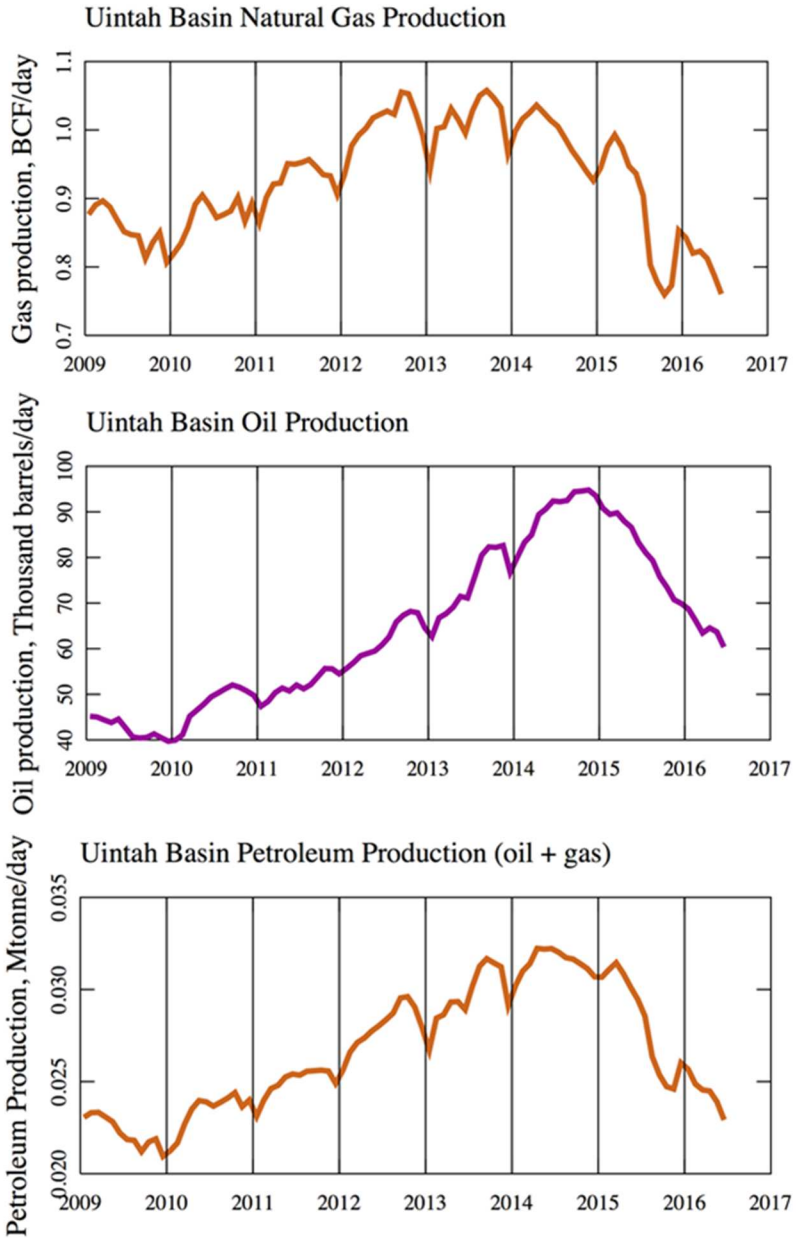

Figure 8-9. Daily petroleum production rates in the Uintah Basin. Data obtained from http://oilgas.ogm.utah.gov/.

8.2.8. Number of Active Drilling Rigs

We will assume that the active drilling of new wells has a different emission footprint than production of oil or natural gas from existing wells. Therefore, we also include a daily "spud" rate as an independent variable. (In the jargon of the industry, "spud" represents a new well.) The State of Utah only tabulates the drilling commencement date. Absent are data on the completion date or the number of active drilling days between commencement and completion. Therefore, to compute a daily spud rate, for each well in the state registry, we have assigned 1/15 of a spud to each of days 1 through 15, where day

1 represents the date on which drilling commenced. In this way, the spud rate is an estimate of the number of drilling rigs in operation on any given day. The choice of 15 days is meant to reflect the average time to drill a well, but in fact, it is arbitrary. However, if it overestimates the average drilling time, then the only real effect is to smooth out a noisy function. Figure 8-10 shows the spud rate computed in this way. The decline in energy prices is responsible for the significant decline near the beginning of 2015.

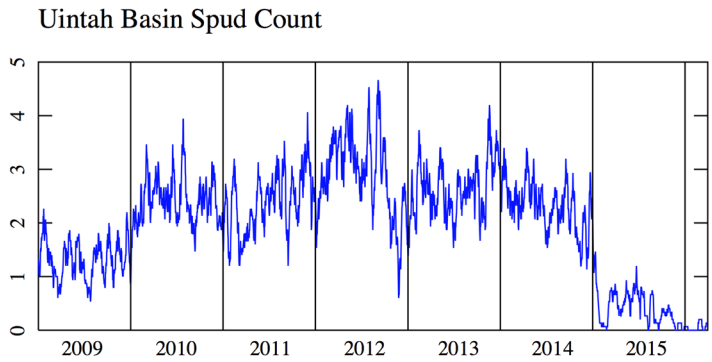

Figure 8-10. Approximate number of active drilling rigs on any given day, divided by 15.

8.2.9. Some Statistical Properties of the Variable Datasets

The regression calculation employed a value of each variable on each day between 15 December to 15 March, inclusive, and for winters 2010 through 2016, including a total of 629 days. (Because of data gaps, a handful of days are not included.) Table 8-1 tabulates statistical properties of the variables.

Table 8-1. Statistical properties of the modeling datasets.

	Mini-mum	Maxi-mum	Mean	Std. Dev	25th-%tile	50th-%tile	75th-%tile	Units
lapse rate	-22.0	13.6	-0.3	7.6	-5.7	1.2	5.9	K/km
temperature	-18.9	21.5	1.0	8.6	-5.2	0.2	7.1	°C
snow depth	0	305	104	86	10	116	178	mm
solar angle	42.3	63.7	56.3	6.7	50.8	58.2	62.6	°C
CDI	0	43	4	8	0	0	4	days
pet. prodxn	0.0209	0.0315	0.0265	0.0320	0.0240	0.0260	0.0302	Mtonne/day
spuds	0.00	3.80	1.85	1.09	1.13	2.13	2.67	rigs/day
h2o pp	0.66	7.47	3.32	1.35	2.29	3.13	4.22	mbar
ozone	21	141	57	24	40	48	68	ppbv

8.3. Development of the Regression Models

Let y_α represent the value of the dependent variable (the ozone concentration) and $x_{j\alpha}$ the value of independent variable *j*, each on day α. We employ a quadratic regression model, which assumes that the dependent variable can be approximated as follows:

$$y_\alpha = A + \sum_j B_j\, x_j \; + \; \sum_{\{j,k\}} C_{jk}\, x_{j\alpha}\, x_{k\alpha} \qquad \text{(Eq. 1)}$$

The coefficients A, B_j, and C_{jk} are obtained by least-squares fitting. We also developed a linear regression model, in which the quadratic coefficients, C_{jk}, are held at zero. However, using quadratic terms usually allows greater flexibility and versatility, and quadratic terms allow the model to respond to any synergistic effects among the dependent variables, including, for example, the interplay between lapse rate and solar angle as the season progresses. The quadratic regression gives better overall performance and so has been adopted for the current treatment.

For reasons to be explained below, we have considered two versions of the model, Uintah-8, employing all eight dependent variables, and Uintah-5, employing only five of the independent variables. The two versions are summarized in Table 8-2. A Microsoft Excel spreadsheet containing the regression coefficients will be made available upon request.

Table 8-2. Summary of predictive multiple regression models.

UINTAH-5	**UINTAH-8**	
Dependent Variable		Data source
Ozone concentration	Ozone concentration	EPA AQS database
Independent Variables		
(1) Pseudo-lapse rate	(1) Pseudo-lapse rate	Utah Climate Cntr.
(2) Mean snow depth	(2) Mean snow depth	Utah Climate Cntr.
(3) Temperature	(3) Temperature	Utah Climate Cntr.
(4) Solar zenith angle	(4) Solar zenith angle	Finlayson-Pitts and Pitts Jr (1999)
(5) Consecutive inversion days	(5) Consecutive inversion days	
	(6) Partial pressure of H_2O	Utah Climate Cntr.
	(7) Spud rate	Utah DOGM
	(8) Gas and oil production rate	Utah DOGM

Figure 8-11 displays the correlation between actual and predicted ozone concentrations for the two models. Pearson's R^2 for the two correlations is 0.75 and 0.78, respectively, and the standard error between actual and predicted ozone concentrations is 12.3 ppb and 11.4 ppb, respectively. Horizontal and vertical lines are drawn at the value of the NAAQS (70 ppb), dividing each plot into quadrants, and the fractions of points falling in each quadrant are shown. A point lying in the lower left quadrant represents a day that was neither actually nor predicted to be in exceedance, while the upper right includes all days that were both actually and predicted to be in exceedance. Counting all the points in these two quadrants indicates that both models have a 90% success rate at predicting whether a day will have an ozone exceedance. Overall performance of the two models is about the same; inclusion of the three additional independent variables has had little effect. Figure 8-12 displays time series of actual and predicted ozone concentrations for the seven winter seasons in question. The model prediction tracks the actual data quite well in both high and low ozone seasons.

A linear regression analysis (equivalent to holding the C_{jk} terms in Eq. 1 equal to 0) using the same five independent variables as Uintah-5 has a standard error of 14.6 ppb, and although it has an 87% success rate for predicting exceedances, it usually underpredicts ozone concentration for any actual concentrations above about 90 ppb and below about 40 ppb.

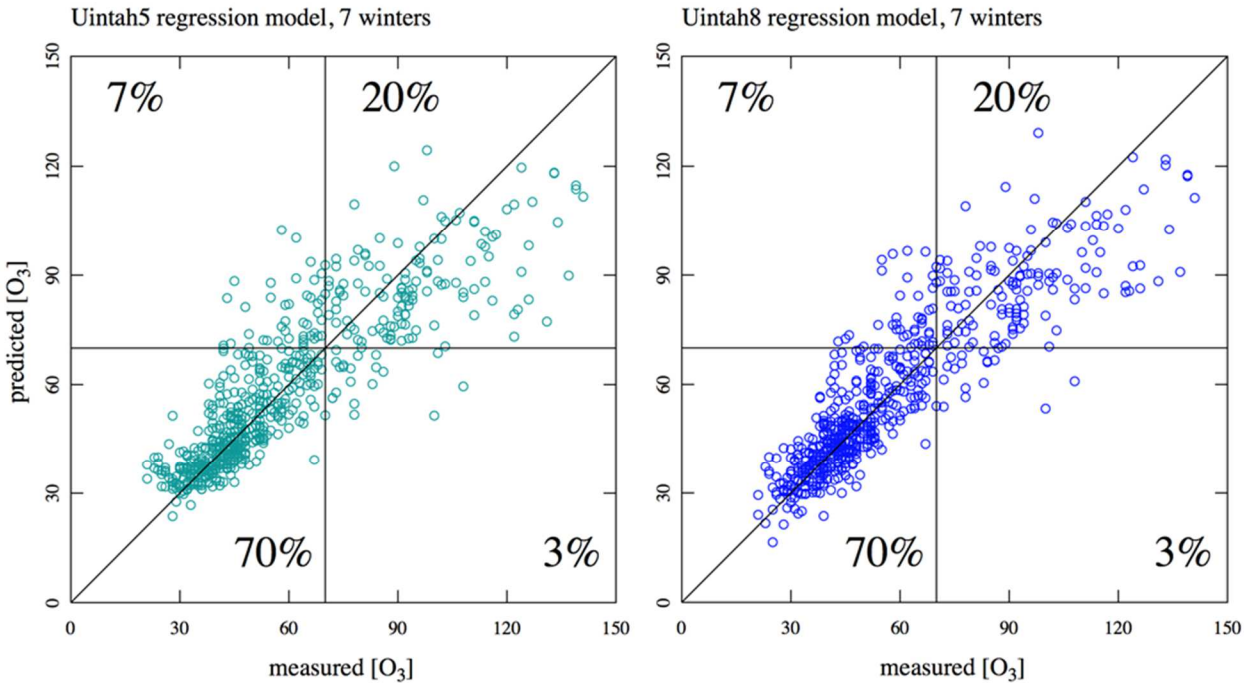

Figure 8-11. Correlations between measured and predicted ozone concentrations for the Uintah5 and Uintah8 regression models.

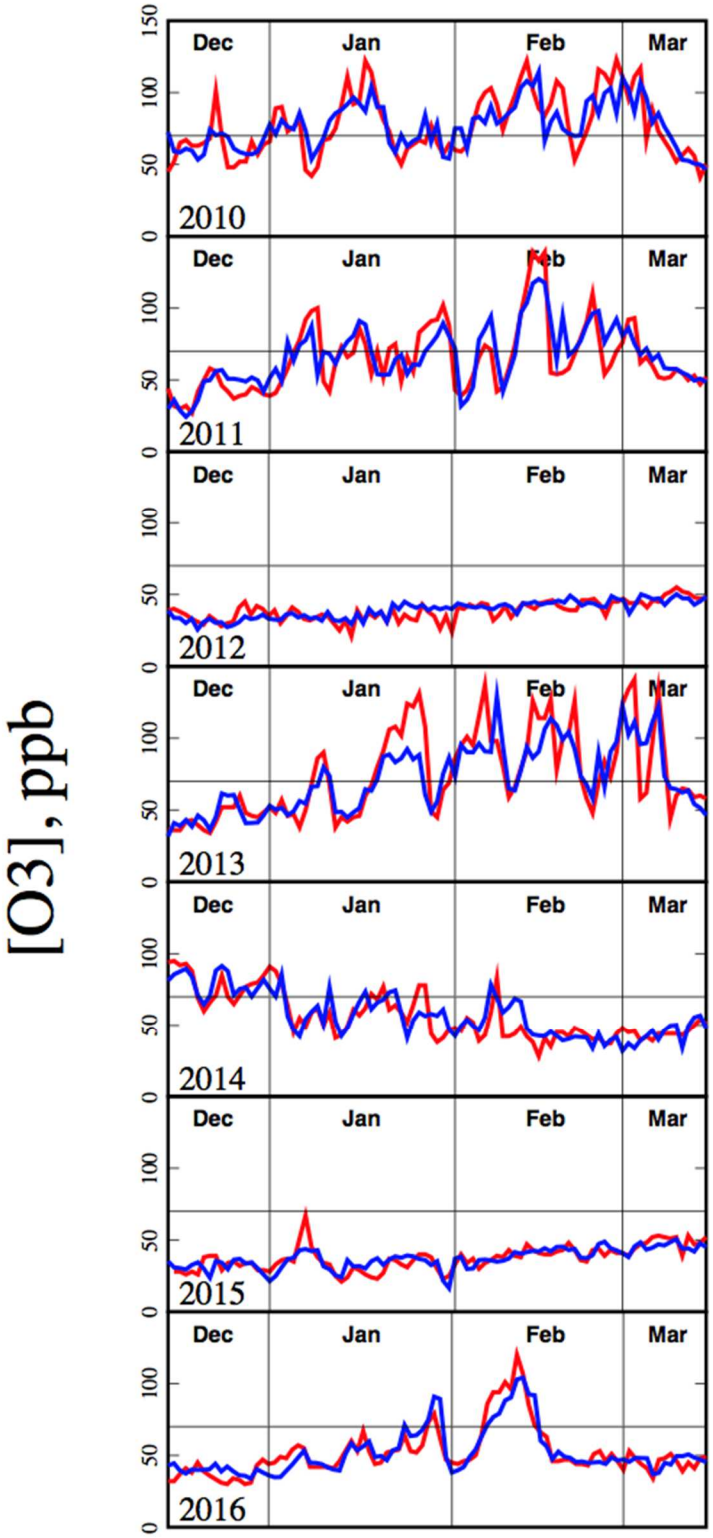

Figure 8-12. Time-series comparisons between actual and predicted ozone concentrations.

8.4. Sensitivity Analysis

Figure 8-13 is presented as a test of the sensitivity of the Uintah-8 model to each independent variable. So that all eight curves could be drawn on the same diagram, the sensitivity is plotted relative to a reduced variable:

$$X_R = \frac{x - x_{50}}{x_{75} - x_{25}} \qquad \text{(Eq. 2)}$$

where x25, x50, and x75 represent 25th, 50th, and 75th percentiles of each dataset.

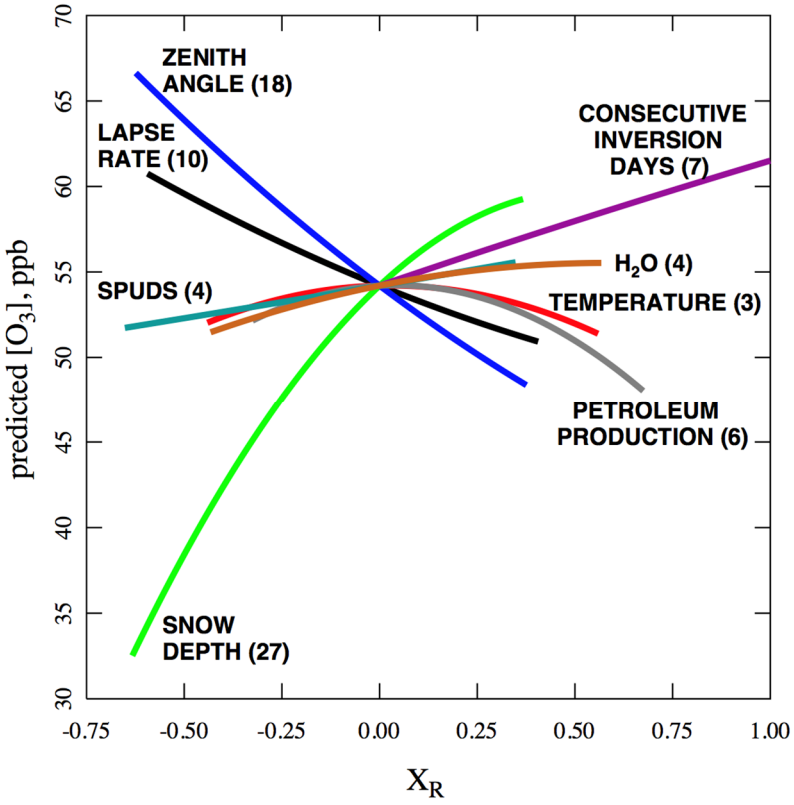

Figure 8-13. Analysis of the sensitivity of the Uintah-8 model to each of its independent variables. The y-axis represents the predicted ozone concentration, and the derivation of the x-axis is described in Equation 2. Zero on the x-axis is the 50th percentile of each of the variables shown in the figure. Each curve represents the Uintah-8 prediction when the indicated variable is allowed to vary between its 25th and its 75th percentile (listed in Table 8-1) while fixing all remaining variables at their 50th percentiles. In this way, we are testing the sensitivity to each variable as it varies over values to which it is typical. The vertical span of each of the eight curves, shown in parentheses, can be taken as a measure of the sensitivity of the model to each independent variable.

Snow depth has the highest sensitivity at 27 ppb (27 ppb is the variance in ozone concentration when snow depth changes from its 25th to its 75th percentile and all other variables remain at their 50th percentile). This, of course, accords with the observation that ozone exceedances only occur when a snow pack is present. A thin layer of snow is insufficient to cover surface irregularities and vegetation, which helps explain the large value of this sensitivity.

The solar zenith angle, with a sensitivity of 18 ppb, is confirmed to be important for predicting ozone concentrations. High angles occur early in the season near the winter solstice and vice versa. The negative trend is, therefore, consistent with the behavior observed in Figure 8-7 and Figure 8-8.

The pseudo-lapse rate has a sensitivity of 10 ppb. Its negative trend is expected since a low (negative) lapse rate corresponds to a thermal inversion. In Figure 8-8 we have seen that weak inversions are capable of producing significant ozone concentrations if the solar angle is low and if a snow pack is present. Therefore, it is not too surprising that the sensitivities of the model to both snow depth and zenith angle are larger than the sensitivity to pseudo-lapse rate.

The number of consecutive inversion days (CID) has a sensitivity of 7 ppb, and it trends in the anticipated direction. Because the CID curve in Figure 8-13 is so flat, we can take the B_j coefficient, 11.6 ppb/day, as another measure of the sensitivity. It indicates that ozone concentrations rise on average 11.6 ppb per day during multi-day inversions. Sensitivity to petroleum production is 6 ppb. Surprisingly, unlike all the variables with higher sensitivities, its downward trend is contrary to our expectation. We do not have a complete understanding of this behavior, but a few observations can be made. As seen in Figure 8-9, petroleum production is low both for 2010 and 2016, yet Winter 2010 has had more exceedances than any season on record. That fact alone could explain the observed trend in the regression. In addition, because of improvements in operating procedures and equipment over the 7-year course of the study, petroleum production may not be a good proxy variable for ozone precursor emissions. Finally, with the standard error in the model at about 11 ppb, sensitivities around 6 ppb or lower may not have strong statistical significance.

Sensitivity to the spud rate is only 4 ppb, but at least its positive trend accords with our expectation. Again, because of improvements in operating procedures and equipment, the spud rate may not be a good proxy for precursor emissions.

The two remaining variables, H_2O partial pressure and temperature, have the weakest sensitivities. The trend in H_2O is positive, which may be an indication that the $O(^1D) \rightarrow OH$ reaction, or perhaps other reactions involving H_2O, are becoming more important. The temperature dependence trends first upwards than downwards, with the maximum almost exactly at 0°C. This may be a result of a confounding effect: We have already mentioned the significance of the snow pack in winter ozone formation. Perhaps effects of the snow pack enter the regression analysis through both the snow depth and the temperature variables. In any case, as already mentioned, sensitivities of 3 or 4 ppb may not be statistically significant.

The relative insensitivity of the Uintah-8 to petroleum production, to the spud rate, and to the H_2O partial pressure explains why Uintah-5 behaves almost as well as Uintah-8. We do little damage to the model by omitting those variables. It also reinforces our assertion that such low sensitivities may be an indication of weak statistical significance.

8.5. How Often Should We Expect Bad Ozone Winters in the Uintah Basin?

As mentioned above, out of seven years of data collection, the Uintah Basin has seen five bad ozone winters. One of the main reasons for developing this regression model was to make a prediction: How often, on average, can we expect a high-ozone winter? One way of answering this question is to

calculate how many ozone exceedance days would have occurred in any past year if modern petroleum activity had been in place at the time. Fortunately, data for the five variables used to construct Uintah-5 are available 66 years into the past. Figure 8-14 displays the number ozone exceedance days predicted by Uintah-5 for each winter season since 1951. Because Uintah-5 has a proven 90% success rate for predicting exceedances, we believe these estimates are reasonable. For comparison, Figure 8-14 also displays the actual number of exceedance days for each winter since 2010. The pair of horizontal lines at 90 and 91 days indicates the total length of the winter season as defined in our analysis (all the days between 15 December and 15 March, inclusive, for non-leap and for leap years, respectively). Based on 66 years of predictions, we can make predictions in terms of the odds each for several different outcomes. These are given in Table 8-3. We also see that 1979 would have been a very bad year for ozone, with exceedances occurring almost every day.

Table 8-3. Long-range predictions of the regression model. The odds in any given winter season for the indicated occurrence.

ODDS FOR:	
No exceedance days	38%
Annual attainment (3 or fewer exceedance days)	46%
A season at least as bad as 2010 (58 or more exceedance days)	12%

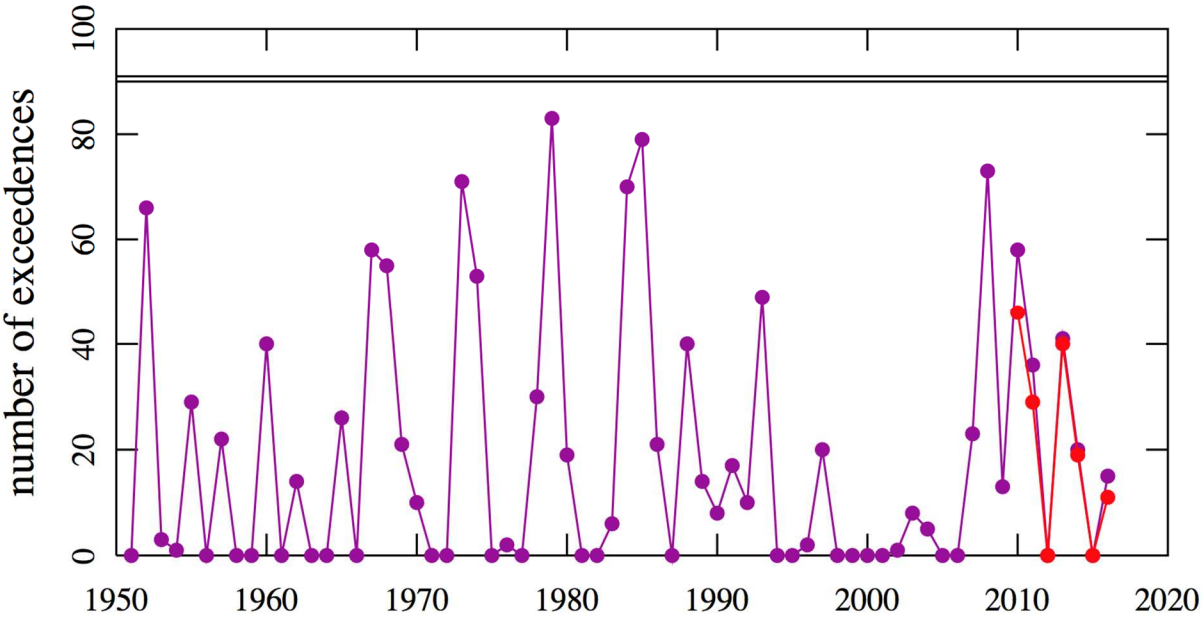

Figure 8-14. Number of predicted ozone exceedances in each year since 1951, assuming no change in ozone precursor emissions. The mauve lines and symbols indicate predictions by the Uintah-5 model of the number of exceedances of the ozone NAAQS that would have occurred in the indicated year, assuming that emissions generated by the modern oil and gas industry had also been present. Red lines and symbols give the actual number of exceedances.

Figure 8-14 stimulates an interesting question. We see several periods of either bad or good ozone seasons in succession (1967-68, 1973-74, 1975 -77, 1981-83, 1984-85, 1994-96) and a nine-year period from 1998 to 2006 of low ozone. Do the data imply that there are inter-seasonal trends or correlations? Such correlations could arise, for example, if the ozone system is being driven by a climate pattern, such

as the El Niño-La Niña or North Atlantic oscillations, that has an average period greater than a year. On the other hand, we do not want to commit the statistical fallacy common to gamblers and athletes: They sometimes think they are in a "winning streak" when in fact there is no scientific basis for believing that the outcome of one game influences the next. We have employed Markov analysis to address this question. The mathematical details of the Markov analysis are provided in the Appendix.

A binary Markov process consists of a system that can exist in one of two states, 0 and 1 for example, and that can undergo transitions between states. In general, a Markov process exhibits correlations between successive states because we assume that the probability of a transition into state 0 or state 1 depends on the current state of the system. For example, a Markov process with a high probability of transitioning into the same state would produce long strings of 0's and 1's. In the other extreme, a high probability for transitioning into the opposite state would generate long strings of alternating 0's and 1's. A Markov process can also occur in the limit of no correlation, in which case it would simulate the tossing of a fair coin. The Markov analysis presented here consists of transforming the data in Figure 8-14 into four different binary sequences by assigning each winter season from 1951 to 2016 to different states. We then determine the Markov processes that have high likelihoods for producing each of the four sequences. These sequences appear in Figure 8-15. The first is generated by assigning states 0 and 1 respectively to seasons with no or with some exceedance days. The other sequences are generated by defining states A (attainment) and N (non-attainment) to seasons with less than four, and four or more exceedances; states L (low) and H (high) are seasons with less than 8 (the median number of exceedance days in the data) and 8 or more exceedances; and finally states B (better than 2010) and W (worse than 2010) correspond to seasons with less than 58 and 58 or more predicted exceedance days. The four binary sequences appearing in Figure 8-15 will be designated 01, AN, LH, and BW, respectively.

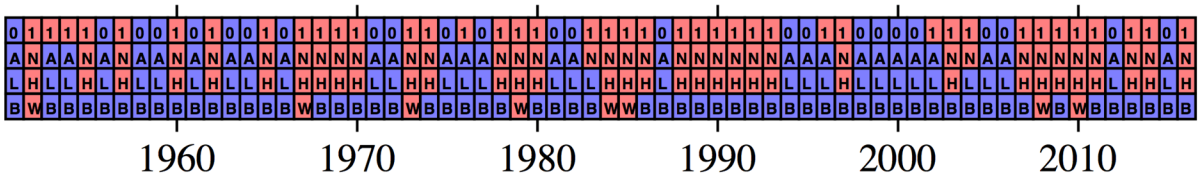

Figure 8-15. Four different binary sequences generated by the data in Figure 8-14.

Following the Markov analysis laid out in the Appendix, we can generate Figure 8-16. The position of each dot represents the value of (p_{00}^*, p_{11}^*) for each of the four sequences 01, AN, LH, and BW. The closed curve of the same color represents the 95% confidence domain for the same sequence. In other words, if each sequence has been generated by a binary Markov process, then the most probable Markov process for each sequence is represented by the dot. Because these all lie close to the $p_{00} + p_{11} = 1$ diagonal, we conclude that the binary sequences, and therefore the sequence of ozone exceedances, are probably uncorrelated. Furthermore, because the diagonal always passes through the 95% confidence domains, we conclude that the dots do not lie so far away from the diagonal that we can rule out the hypothesis of non-correlation.

In summary, we can expect that about 38% of winters in the Uintah Basin will have no exceedances of the NAAQS for ozone. We can expect that about 46% of winters will be in attainment for ozone, i.e., they will have three or fewer ozone exceedance days. Winters as severe as 2010 occur about 12% of the time, or once about every 8 years on average. There is no strong evidence in the data that the ozone

behavior of any one year has any influence on the following year. For example, the string of five low ozone years near the year 2000 is probably a random occurrence.

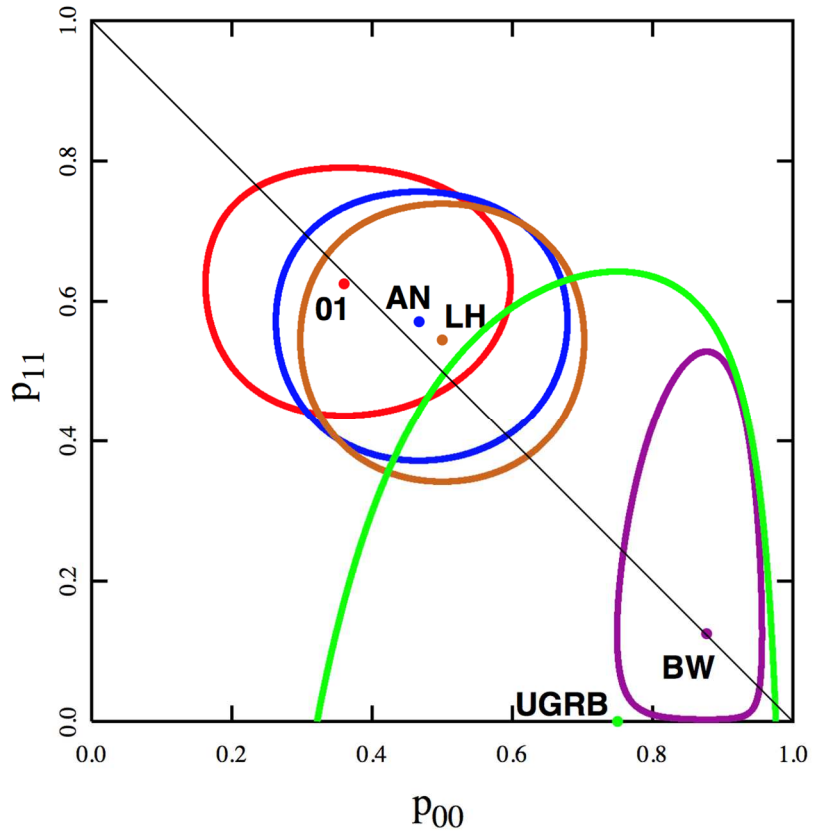

Figure 8-16. Markov analysis of the sequence of predicted ozone exceedances per year. The four dots and closed paths of the same color indicate the maximum-likelihood binary Markov process and the 95% confidence domain for each of the four binary sequences 01, AN, LH, and BW. The green dot and green path indicate the maximum-likelihood Markov process and the 95% confidence domain for the Upper Green River Basin sequence, Table 8-4.

8.6. How Often Should We Expect Bad Ozone Winters in the Upper Green River Basin?

As mentioned above, wintertime exceedances of the NAAQS for ozone have also been observed in the Upper Green River Basin of Wyoming. The ozone system there also follows the flow chart given in Figure 8-1, and several years ago, we also performed a regression analysis using data from the Upper Green (Mansfield and Hall, 2013). We have not prepared a new regression analysis, but it is an informative exercise to apply the same Markov analysis to actual data.

Table 8-4. Daily exceedances of the NAAQS for ozone at Boulder, Wyoming since 2005.

year (20XX)	05	06	07	08	09	10	11	12	13	14	15	16
Exceedances of the NAAQS	8	2	0	14	0	0	13	0	0	0	0	0
Binary sequence	1	0	0	1	0	0	1	0	0	0	0	0

Table 8-4 gives the number of exceedances of the NAAQS for ozone observed at Boulder, Wyoming since 2005 (Paulson et al., 2016). There have been three non-attainment years, 2005, 2008, and 2011. We assign state 0 to attainment years and state 1 to non-attainment years in order to generate the binary sequence appearing in the third row of Table 8-4. According to the analysis in the Appendix, for this binary sequence

$$p_{00}^{*} = 0.75, \quad p_{11}^{*} = 0.$$

Figure 8-16 shows the 95% confidence domain, which covers much more of the p_{00}-p_{11} square than the other cases because the binary sequence is shorter. Therefore, even though the (p_{00}^{*}, p_{11}^{*}) point lies farther from the diagonal, we cannot exclude the hypothesis that winter seasons in the Upper Green are uncorrelated.

As a result of the exceedance years between 2005 and 2008, the Upper Green River Basin went into non-attainment for ozone. There has been a tendency to attribute the five good ozone years 2012-2016 to the emissions controls and other operational practices that went into place as a result of the non-attainment designation. That may well be the case. To continue the athletic analogy, a team can see a non-random winning streak if they have improved their game. However, if we assume that the Upper Green ozone system is following a Markov process whose transition probabilities remain constant from year to year, then the probability of seeing one non-attainment year followed by five attainment years in a row is not very small:

$$p_{10}p_{00}^{4} \cong 0.32$$

According to this interpretation, the Upper Green is just having a string of good luck. To conclude conclusively that this result is non-random will require a few more consecutive years of ozone attainment.

8.7. Conclusions and Future Work

We have developed two versions of a quadratic regression model that predicts the daily ozone concentration during winters (15 December to 15 March) in the Uintah Basin. Depending on the version employed, it has a standard error of about 11 to 12 ppb on any given day. It confirms the effects of snow cover and thermal inversions, and it captures the observed differences between early and late winter exceedance events.

We have also applied the model to every winter season in the Uintah Basin since Winter 1951. In this way, we learn how frequently the meteorological conditions conducive to winter ozone can be anticipated. According to this analysis, 38% of winters will see no exceedances of the 70 ppb NAAQS, and 46% will see three or fewer exceedances. We also performed Markov modeling of these historical

predictions and have been unable to find strong evidence of any correlations persisting from one winter to the next. Such correlations, if they exist at all, are weak.

In future research, we will attempt to apply the model in short-range forecasting. To calculate the five independent variables in UINTAH-5 we need only surface temperatures at various elevations in the basin, the snow depth, and the date. If all these have been forecast 48 to 72 hours in advance, then we can also forecast ozone concentration 48 to 72 hours in advance. We anticipate that this will be a useful tool for both industry and the general population as the basin moves into non-attainment.

The UINTAH-8 model included an attempt to detect the impact of the recent downturn in oil and gas activity in the basin. Unfortunately, no strong impact was observed. However, we assumed that total tonnage of extracted petroleum could serve as a proxy variable to represent ozone precursor emissions. This assumption ignores the fact that a number of pollution controls (e.g., low-bleed pneumatic pumps, self-igniting flares, bottom-filling of tanks, etc.), expected to reduce VOC emissions by thousands of tons per year, have been phased in over the seven-year period covered by this study (http://www.deq.utah.gov/locations/U/uintahbasin/ozone/docs/2014/06Jun/ITEM_V_R307-501_502_503_504.pdf). Therefore, in future research we will directly analyze existing VOC and NO_x concentration data, looking for any trends caused by the recent downturn as well as by the introduction of new pollution controls.

We also applied a Markov analysis to the actual (not predicted) exceedance data from the Upper Green River Basin. As of Winter 2016, the Upper Green had seen five consecutive years with no ozone exceedances. One possible explanation is that the ozone abatement procedures adopted when the region entered non-attainment are working. However, the Markov analysis indicates that the probability of five consecutive years without ozone is not small, meaning that they could have occurred merely by chance.

8.8. Appendix

A binary (two-state) Markov process consists of a system that can exist in one of two states, 0 and 1, and that undergoes transitions between these states. In general, we assume that the outcome of a transition depends on the state occupied just prior to the transition, and we let p_{ij} represent the probability of making a transition into state *j* given that the process occupied state *i* immediately before the transition. These probabilities can be assembled into a transition matrix:

$$\mathbf{T} = \begin{bmatrix} p_{00} & p_{01} \\ p_{10} & p_{11} \end{bmatrix}$$

Obviously, we have $p_{00} + p_{01} = 1$, because upon leaving state 0, the system must go either into state 0 or 1. Likewise, we have $p_{10} + p_{11} = 1$. Therefore, the transition matrix can be written

$$\mathbf{T} = \begin{bmatrix} p_{00} & 1 - p_{00} \\ 1 - p_{11} & p_{11} \end{bmatrix}$$

indicating that any binary Markov process is characterized by only two parameters, p_{00} and p_{11}. Furthermore, all entries of the matrix must be real numbers between 0 and 1, which means that all

possible binary Markov processes are generated by points (p_{00}, p_{11}) that lie somewhere in the unit square.

A special class of Markov processes consists of those for which the current state of the system has no influence on the subsequent state. We call these uncorrelated Markov processes. They occur when $p_{00} = p_{10}$ and when $p_{01} = p_{11}$, or equivalently, when the point (p_{00}, p_{11}) lies on the diagonal $p_{00} + p_{11} = 1$.

Suppose we have a binary sequence such as any of those appearing in Figure 8-15. Can the sequence be modeled by a Markov process? If so, is it a correlated Markov process? Let n_{ij} equal the total number of times that state *j* follows state *i* in the sequence. Then the likelihood that our sequence was generated by the Markov process (p_{00}, p_{11}) is

$$L(p_{00}, p_{11}) = {p_{00}}^{n_{00}} \, (1 - p_{00})^{n_{01}} \, (1 - p_{11})^{n_{10}} \, {p_{11}}^{n_{11}}$$

We let (p_{00}^*, p_{11}^*) represent the maximum-likelihood Markov process, i.e., the values of p_{00} and p_{11} that maximize *L*. These are given by

$$(p_{00}^*, p_{11}^*) = \left(\frac{n_{00}}{n_{00} + n_{01}} , \frac{n_{11}}{n_{10} + n_{11}} \right)$$

If the given sequence was generated by a Markov process, then the above represents the most likely process to have generated it. If (p_{00}^*, p_{11}^*) lies distant from the diagonal $p_{00} + p_{11} = 1$, then it is a correlated Markov process for which current states influence subsequent states. Of course, other processes (p_{00}, p_{11}) that lie close to (p_{00}^*, p_{11}^*) in the unit square also have high likelihoods to have generated the given sequence. Therefore, we can also calculate confidence domains. For example, the 95% confidence domain is the set *C* of all points (p_{00}, p_{11}) in the unit square such that $L(p_{00}, p_{11})$ is greater than *L* at any point outside the domain, and such that the integral of *L* over *C* is 95% of the integral of *L* over the entire square. If the 95% confidence domain contains no points on the diagonal, then our confidence is great that the given sequence was generated by a correlated Markov process. Of course, if we have a long sequence, then the function *L* will be sharply peaked in the neighborhood of (p_{00}^*, p_{11}^*) and the confidence domain will be small.

9. Summary of Air Quality Model Development Efforts Undertaken During 2015-16

Ozone modeling generally consists of three separate stages: (1) meteorology, in which we model the dynamics of the atmosphere; (2) emissions, in which we try to account for all of the pollutants entering the atmosphere; and (3) chemistry, in which we model the chemical reactions by which the primary pollutants entering at stage 2 (e.g., ozone precursors) are transformed into secondary pollutants (including ozone). We have made a number of improvements in the capability of these modeling platforms for winter ozone events in the Uintah Basin. The following paragraphs highlight the accomplishments over the previous year.

9.1. Meteorological model

The performance of the meteorological model for simulating surface meteorological quantities (e.g., temperature, wind) and temperature inversions (or atmospheric stability) plays a critical role in simulating surface ozone pollution during wintertime in the Uintah Basin. We recently compared two Weather Research and Forecasting (WRF) simulations with and without nudging by observational data to examine if nudging improves WRF performance. Atmospheric stability (including the structure of temperature inversions) is an important factor that governs the distribution of O_3 concentrations in Uintah Basin. We nudged temperature and horizontal wind in the surface model layer with observed data collected inside and outside the Uintah Basin (MADIS + AirNowTech data). We nudged temperature, wind and humidity of model layers above the atmospheric boundary layer with NAM-12km analysis data provided by the National Oceanic and Atmospheric Administration. The NAM dataset was derived mostly from radiosonde (i.e., balloon launch) data collected at sites located outside Uintah Basin and so might not be representative of local weather conditions. A sensitivity study for the period of 16 Jan to 9 Feb 2013 showed that the nudged-WRF led to an unrealistic inversion structure that was too intense and shallow and trapped all pollutants in only the lower areas of the Basin. Meanwhile, non-nudged WRF tends to simulate a weaker inversion layer with an excessively deep boundary layer and excessive vertical mixing which leads to underestimation of surface ozone concentrations in the photochemical models.

To evaluate model performance in simulating surface meteorological quantities, we compared data produced by nudge and no-nudge WRF simulations with surface temperature, wind speed and wind direction data collected at six monitoring sites within Uintah Basin. Our sensitivity tests found that nudge-WRF produced larger errors than the no-nudge WRF. Nudge-WRF also created stronger inversion conditions (larger vertical temperature gradient) than the observations (Figure 9-1 – gray vs. blue lines). As the result, nudging led to an unrealistic inversion structure that was too intense and shallow and only favored downslope flows in the Uintah Basin, even during the day, and trapped all pollutants at the lower areas of the Basin (Figure 9-2); while the observed wind data showed upslope flows happened during the day and downslope flows during the night (Lyman and Tran, 2015). The fact that nudge-WRF failed to capture upslope flows could lead to large errors in predicting wind transport patterns within the Uintah Basin that might transport ozone and its precursors from lower elevation areas with intensive oil and gas production to more populated areas at higher elevation like Vernal and Roosevelt. The unrealistic vertical temperature profile in nudge-WRF might be due to using locally observed data to

nudge for the surface model layer and using NAM analysis data which is more representative of areas outside of Uintah Basin (e.g, Wasatch Front area) to nudge for the air above the boundary layer.

On the other hand, no-nudge WRF failed to capture temperature inversions or tended to create weaker inversion conditions than reality (Figure 9-1 – yellow vs. blue lines). It produced a deep boundary layer and too much mixing within the boundary layer near the ground, pushing ozone from the lower toward higher elevation areas (Figure 9-2). Thus, over predicting vertical mixing by no-nudge WRF could contribute to the underestimation of surface ozone concentrations in Uintah Basin by photochemical models.

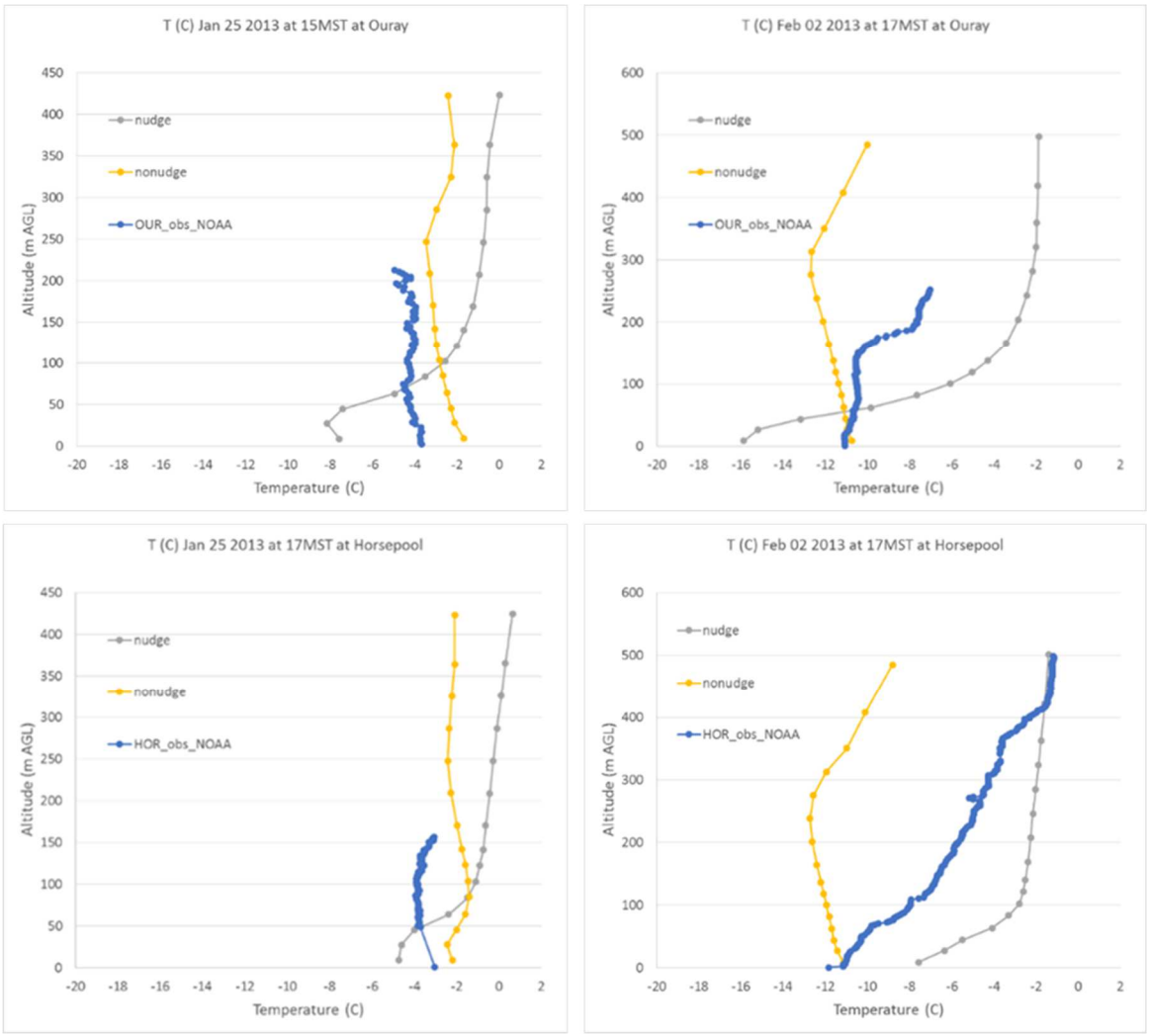

Figure 9-1. Nudge-WRF (gray), no-nudge WRF (yellow) and observed (blue) vertical temperature profiles extracted at Ouray and Horsepool. 25 Jan and 02 Feb were in the middle of two high ozone events in Jan and Feb 2013, respectively.

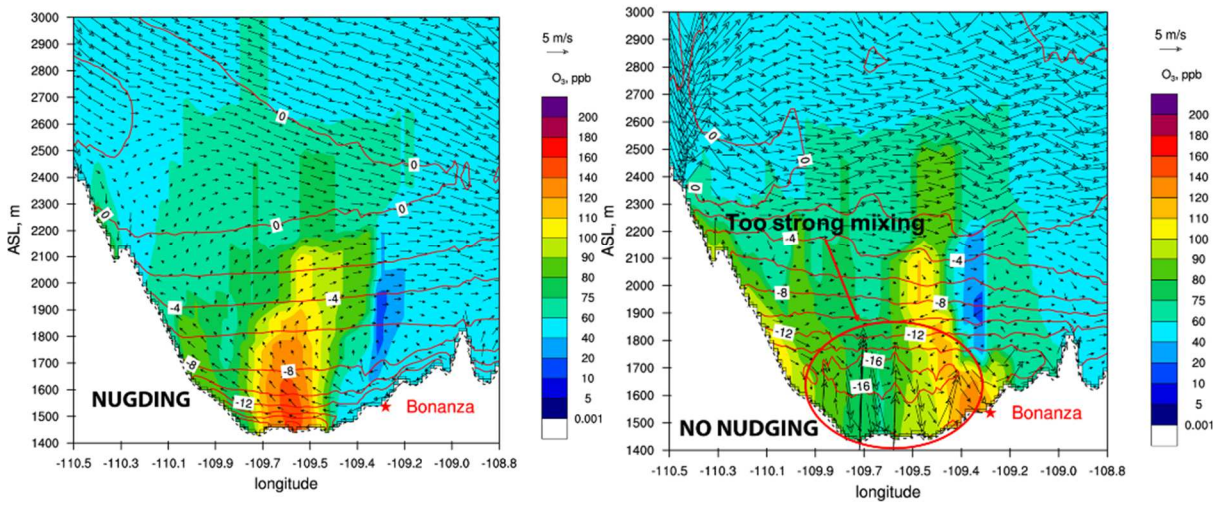

Figure 9-2. CMAQ-simulated O_3 concentration in an east-west cross-section of the Uintah Basin for 14:00 MST 21 January 2013. Arrows indicate wind speed and direction. Vertical wind components were scaled up to 100 times so they could be better visualized. Panel A (left) shows the result when nudging was used, while panel B (right) shows the result without nudging.

In conclusion, although nudged WRF runs create larger biases in some surface meteorological quantities than non-nudged WRF simulations, nudging produces temperature inversion conditions which non-nudged WRF failed to capture. Nudging could be a promising approach to improve model performance in simulating the stability of the Uintah Basin airshed if the model is nudged with a dataset more representative of the entire boundary layer, not just the surface. Tethersonde (i.e., measurement instrumentation borne by a tethered balloon) datasets were collected by NOAA and USU in January and February 2013 at Ouray, Pariette, Horsepool and Fantasy Canyon and provided vertical profiles of temperature, relative humidity, and wind speed and direction from the surface up to about 600 meters. This dataset accurately represents meteorological conditions throughout the boundary layer and could improve characterization of inversion conditions by WRF. Over the next year, we intend to nudge WRF simulations with the balloon dataset and turn off nudging with the NAM-12 km analysis data to determine the value of nudging with balloon data. If balloon data are useful for nudging, we can collect balloon data annually for use in air quality models.

9.2. Chemistry model

As discussed earlier, surface ozone concentrations in the Uintah Basin are strongly influenced by natural sources such as stratospheric intrusion and wildfires during spring and summer seasons. Being able to distinguish ozone contributions from local anthropogenic sources (e.g., oil and gas, vehicular traffic, residential heating) and non-local and natural sources (e.g., transport from outside the Uintah Basin, wildfires, stratospheric intrusions) is important for evaluation of the effect of emissions control strategies to bring the Basin in compliance with federal air quality standards.

We have been developing a model technique to quantify background ozone in the Uintah Basin, which originates from sources outside of the basin. Our approach is to perform global chemical model simulations and then use the model output as a boundary condition for a high-resolution regional model centered at the Uintah Basin. We are using GEOS-Chem (http://acmg.seas.harvard.edu/geos/) as the

global chemical model, and Community Multiscale Air Quality (CMAQ) as the regional model. GEOS-Chem simulations were initialized for one year leading up to the studied ozone episode so that any long-range transport of polluted air (for example, from Asia) is given enough time for mixing before reaching the boundary of the CMAQ model domain. The CMAQ model employs source apportionment algorithms to quantify the amount of ozone in the Basin contributed by non-local and local sources.

We have performed sensitivity analyses to compare model performance in two scenarios in winter 2013 and 2015. In one scenario, ozone was simulated by the CMAQ photochemical model using dynamic background conditions that were generated by GEOS-Chem. In another scenario, ozone was simulated by CMAQ with constant background conditions, which is a standard practice in modeling. Our preliminary results showed that while dynamic background conditions underestimate ozone at low elevations, they better represent ozone concentrations at upper levels (Figure 9-3). The ability to reproduce ozone at upper levels is important to evaluate contributions from non-local sources in spring and summer when there is extensive vertical mixing (including stratospheric intrusions) but is less important in winter when vertical mixing is at a minimum.

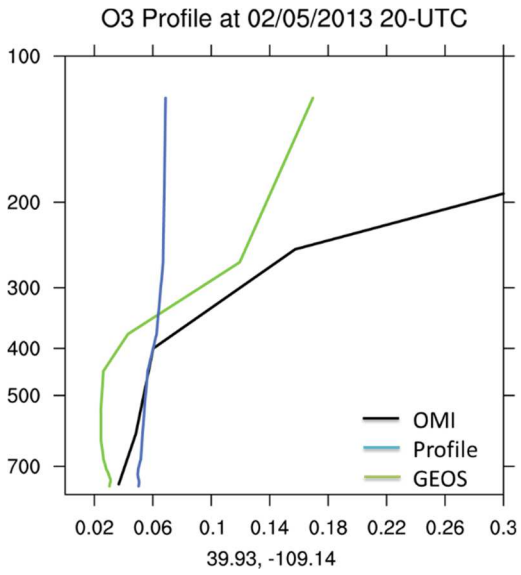

Figure 9-3. Comparison of satellite-observed ozone vertical structure at a location in Uintah Basin (OMI) against modeled structure by CMAQ model with constant boundary condition (Profile) and with dynamic boundary generated by GEOS-Chem model (GEOS). The x-axis shows barometric pressure in mbar (a proxy for altitude). The y-axis shows ozone concentration in ppb at the latitude and longitude indicated.

9.3. Emission model

We have performed ozone simulations using four different emissions inventories (EI) of the Uintah Basin. The first bottom-up inventory is the National Emissions Inventory (NEI), prepared by EPA using data supplied by the states, and is updated every few years. The second bottom-up inventory, WRAP-III, is iteration three of an inventory prepared by the Western Regional Air Partnership, a private consortium working with an environmental consulting firm (Environ), that only includes data from the oil and gas production industry. The third bottom-up inventory is the BLM-ARM inventory, which was sponsored by the Air Resources Management Study (ARMS) of BLM and performed by AECOM, Inc., which also includes only oil and gas data. The fourth inventory we have considered is top-down,

developed by NOAA and University of Colorado researchers based on an aircraft flyover that occurred in February 2013 (Ahmadov et al., 2015). All of our simulations with these EIs significantly underestimate ozone levels in winter episodes. We attribute the underestimates to deficiencies in the inventories and to poor meteorological model performance.

Recognizing the incompleteness of the current EIs, the Utah Division of Air Quality (UDAQ), the Environmental Protection Agency, the Ute Tribe, and others have been working with oil and gas operators in the Uintah Basin to develop a comprehensive oil and gas EI for the Basin for base-year 2014. UDAQ supplied us with this Uintah-2014 EI and we have been working on incorporating it into our emission model. The other EIs are totaled at the county level and must be allocated into model grid cells using spatial surrogates such as well locations, but UDAQ's Uintah-2014 EI is defined at specific facility and well location points and therefore is better at representing the spatial distribution of oil and gas emissions in the Basin (Figure 9-4). We are working to perform sensitivity simulations with the Uintah-2014 EI and compare its results with simulations using other EIs.

The Uintah-2014 EI shows NOx emissions that are almost an order of magnitude greater than previous inventories, but the increase is due entirely to a small number of facilities in eastern Uintah County, and it now appears that those facilities reported NOx emissions incorrectly. Thus, it appears that NOx emissions in the new (corrected) inventory are similar to those in previous inventories. VOC emissions in Uintah and Duchesne counties are 34% and 62% lower, respectively, in the new inventory compared to the most recent National Emissions Inventory. This difference does not appear to be due to a reporting error. Previously, when emissions inventories were used in air quality models, they have only been able to adequately simulate observed high wintertime ozone when VOC emissions were increased above the levels in current inventories. If the lower VOC in the Uintah-2014 EI is correct, some other model error, such as poor simulation of inversion meteorology, must be responsible for simulated ozone that is lower than reality. We will investigate these discrepancies in the coming year.

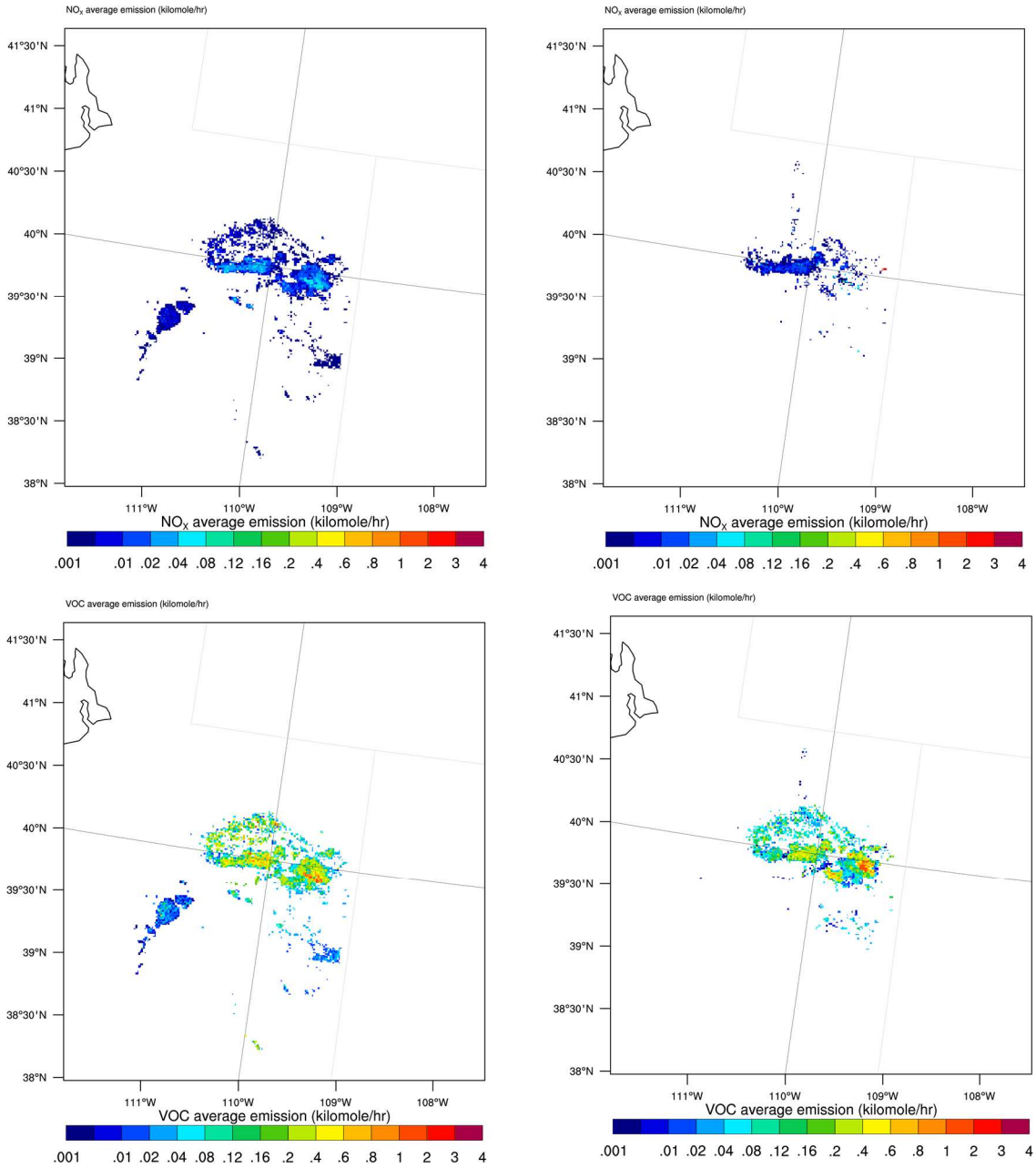

Figure 9-4. Comparisons of NOx and VOC emissions as obtained from ARMS (left column) and Uintah-2014 (right column) oil and gas emission inventory, processed by the SMOKE emission model for the CMAQ simulation domain. As shown in this figure, the Uintah-2014 inventory contains less NOx and more VOC emissions than in ARMS over the gas-producing (eastern) part of the Uintah Basin).

10. Summaries of Additional Studies Completed During 2015-16

10.1. Emissions of Volatile Organic Compounds from Produced Water Ponds

In the Uintah Basin, about 89% of the water extracted from the subsurface with oil and gas is reinjected, but the remaining 11% is disposed of by evaporation from shallow ponds (Chidsey, 2015). Additionally, some of the water that is eventually injected into the subsurface first spends time in holding ponds. The Uintah Basin contains about 170 hectares (420 acres) of produced water ponds. Produced water contains many organic compounds that can volatilize into the atmosphere and contribute to ozone production (Benko and Drewes, 2008).

In 2011, stakeholders in government and industry suggested to Bingham Center scientists that produced water ponds could be an important source of volatile organic compounds (VOC) to the atmosphere. Prior to this time, only one short-term study of produced water pond emissions had been conducted (Thoma, 2009), so the contribution of emissions from produced water ponds to ozone production could not be determined with any degree of certainty. In 2012 and 2013, with funding from the Uintah Impact Mitigation Special Service District and the Utah State and Institutional Trust Lands Administration, we conducted the first measurements of emissions from produced water ponds in the Uintah Basin, and the first wintertime measurements of produced water emissions ever collected. This work led to a contract from the U.S. Department of Energy and the Research Partnership to Secure Energy for America to continue measuring emissions from produced water ponds from 2014 through 2016 (contract no. 12122-15). Detailed information about emissions from produced water ponds is available in USU's final report to the U.S. Department of Energy and the Research Partnership to Secure Energy for America. It is available at http://binghamresearch.usu.edu/reports. We are also preparing several manuscripts about this work for submission to scientific journals. These will become available at the same URL after publication. We give a brief overview of some research results here:

During 2013-2016, we collected about 200 measurements of produced water composition and organic compound emissions from produced water at eight facilities in all seasons. One trend that emerged is that most produced water facilities had three general types of ponds: *skim ponds*, which were the first pond in a series, were usually netted, and were usually at least partially covered with oil (these are called skim ponds because oil is periodically skimmed from the ponds' surfaces); *other active ponds*, which were actively receiving new produced water but were not the first pond in a series; and *inactive ponds*, which had water in them but were not receiving new water. Skim ponds tended to have the highest concentrations of hydrocarbons in water and the highest emissions (Figure 10-1), followed by other active ponds and inactive ponds.

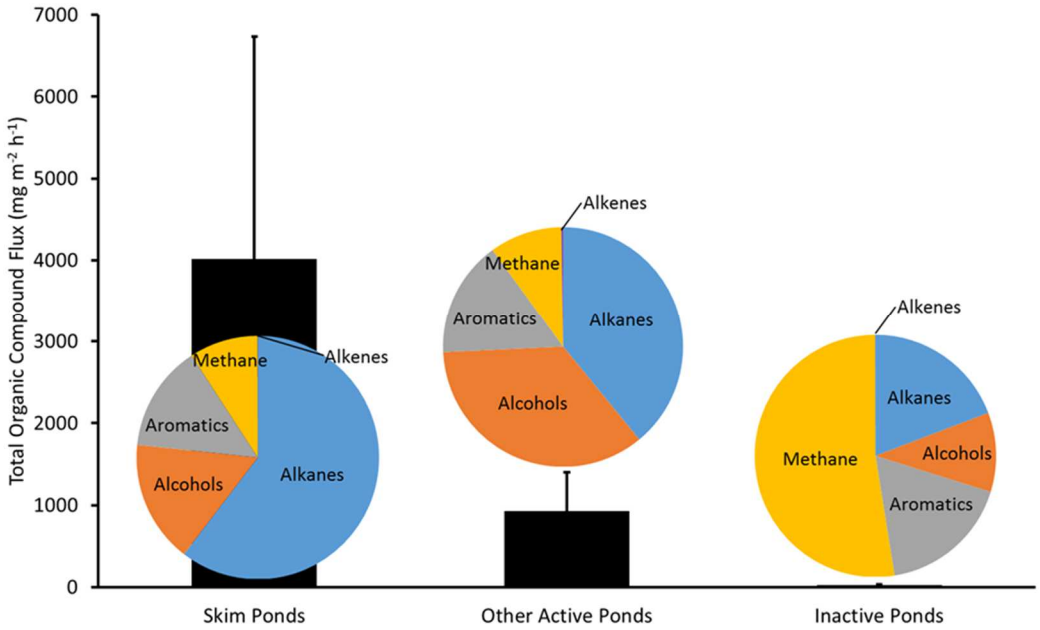

Figure 10-1. Average flux (i.e., emission rate) of total organic compounds (sum of methane, hydrocarbons, and alcohols) from different types of ponds at produced water disposal facilities (black bars). Whiskers show 95% confidence intervals. Overlain pie charts show the fraction of total emissions that were due to alkanes, alcohols, aromatics, methane, and alkenes. Measurements over ice are excluded.

Emission rates and the composition of emissions varied with facility and season. Figure 10-2 shows measurements of total non-methane hydrocarbon (TNMHC; equivalent to VOC) emissions versus methanol emissions, colored by facility and by season. Some facilities had consistently higher emission rates than others, and some had higher or lower emissions of methanol relative to TNMHC than others. Emission rates (i.e., the amount of emissions per amount of water surface area) tended to be highest in winter and lowest in summer (Figure 10-2), but many ponds or portions of ponds froze during some winters, limiting the water surface area and bringing facility-level emissions lower. Emissions from ice surfaces were very low. Because of this, the facility-level emissions of TNMHC and alcohols were similar during winter and non-winter months.

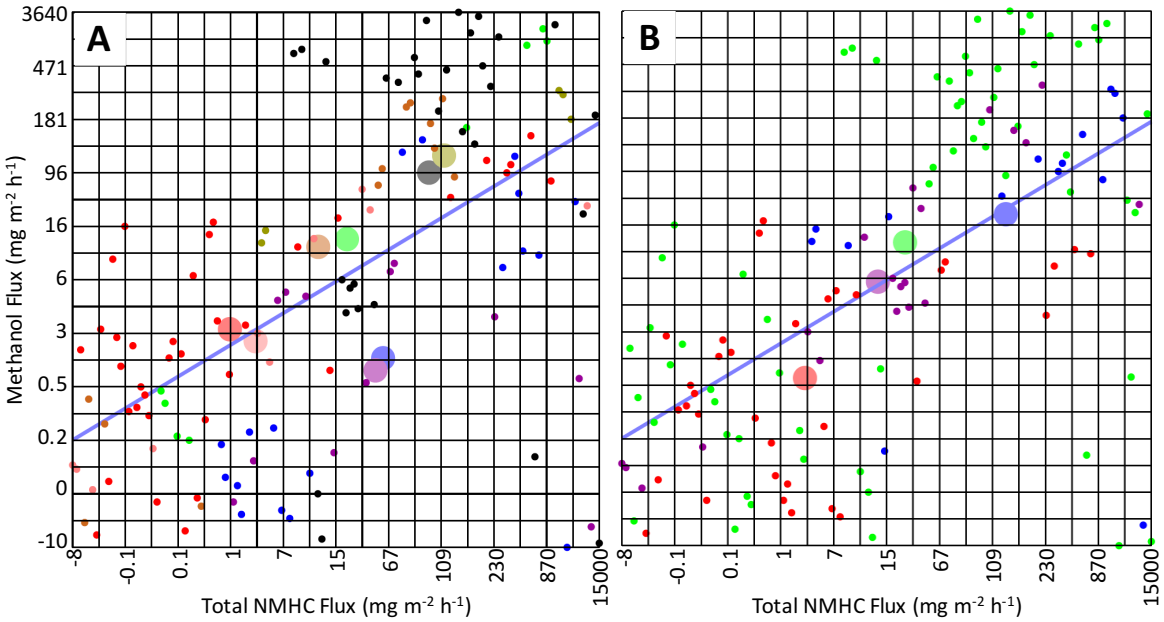

Figure 10-2. Rank correlation plots of methanol and total NMHC fluxes (i.e., emission rates) from produced water ponds (all pond types). The circles in panel A are colored by facility, and the circles in panel B are colored by season. The larger, lighter colored circles indicate centroids. The blue line is the regression line for the entire dataset. In panel B, green = spring, red = summer, purple = fall, and blue = winter.

We used the surface area of each pond type at each facility, including percent ice cover during winter, to scale up emissions to the facility level. Table 10-1 shows the average daily facility-level emissions of carbon dioxide and various organic compounds or groups of compounds. We estimate that emissions from all produced water ponds in the Uintah Basin account for between 1 and 5% of all VOC emissions from the Uintah Basin oil and gas industry. Organic compounds emitted from produced water contain more long-chain alkanes (e.g., butane, octane, etc.), aromatics (e.g., benzene, toluene, etc.), and alcohols than emissions from the oil and gas industry generally. Produced water pond emissions account for between 10 and 15% of all emissions of aromatics and methanol from the Uintah Basin oil and gas industry.

Table 10-1. Facility-level emissions from produced water ponds at disposal facilities in the Uintah Basin (average ± 95% confidence interval). Confidence intervals reflect observed variability in measurements across facilities.

kg day^{-1}	Skim ponds	Other active ponds	Inactive ponds	Total
Methane	6 ± 9	16 ± 17	1 ± 2	23 ± 21
Carbon dioxide	13 ± 28	117 ± 81	212 ± 484	342 ± 313
Alkanes	35 ± 73	60 ± 87	2 ± 3	97 ± 97
Alkenes	0 ± 0	0 ± 1	0 ± 0	0 ± 1
Aromatics	9 ± 17	28 ± 39	1 ± 2	37 ± 36
Alcohols	8 ± 90	82 ± 149	3 ± 35	95 ± 144
Non-methane organics	52 ± 96	171 ± 234	5 ± 7	230 ± 243

10.2. Emissions of Hydrocarbons from Soil Surfaces

With funding from the Bureau of Land Management (cooperative agreement no. L13AC00292) and the U.S. Department of Energy/Research Partnership to Secure Energy for America (contract no. 12122-15), we have been measuring emissions of hydrocarbons from various natural and disturbed surfaces since 2013. Surfaces measured have included landfarm soils, soils on well pads, snow surfaces, undisturbed soils, soils near faults, and outcrops of coal, gilsonite, and oil shale. Information about these findings is available in our final report to DOE/RPSEA, and in our annual performance reports to BLM. These reports are available at http://binghamresearch.usu.edu/reports. The majority of this work has focused on measurements of emissions from well pad soils, and we give a brief overview of findings from that work here:

Hydrocarbon emissions from well pad soils in excess of natural or background emissions result from either (1) leaks of natural gas from subsurface infrastructure, such as well bores, piping, etc. or (2) re-emission of spilled liquid hydrocarbons. Emissions due to natural gas leaks are expected to have similar speciation (i.e., a similar mix of individual organic compounds) as raw natural gas, while emissions due to liquid hydrocarbon spills are expected to be dominated by the longer hydrocarbons that constitute oil. Figure 10-3 shows examples of non-methane hydrocarbon emissions (NMHC) that were due to various sources, including liquid spills and raw gas.

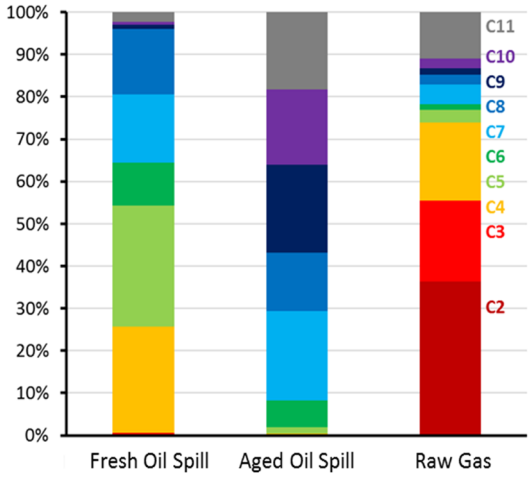

Figure 10-3. Percent of NMHC emissions that were due to C2-C11 hydrocarbon emissions from well pad soils collected during summer 2015. The two leftmost bars represent two measurement locations that were contaminated with spilled oil. The rightmost bar shows the average of all other measurements collected during summer 2015.

We expected that emissions due to subsurface leaks would have the same composition as raw natural gas, but Figure 10-4 shows that emissions from well pad soils contained much more carbon dioxide, and much less NMHC relative to methane, than raw gas analyses showed. Bacteria in soil can consume methane and NMHC, converting them to carbon dioxide, and NMHC can be retained on soil particles, likely accounting for this discrepancy. Bacterial activity diminishes during winter months, and we observed increased emissions of methane and NMHC from well pad soils during winter relative to summer.

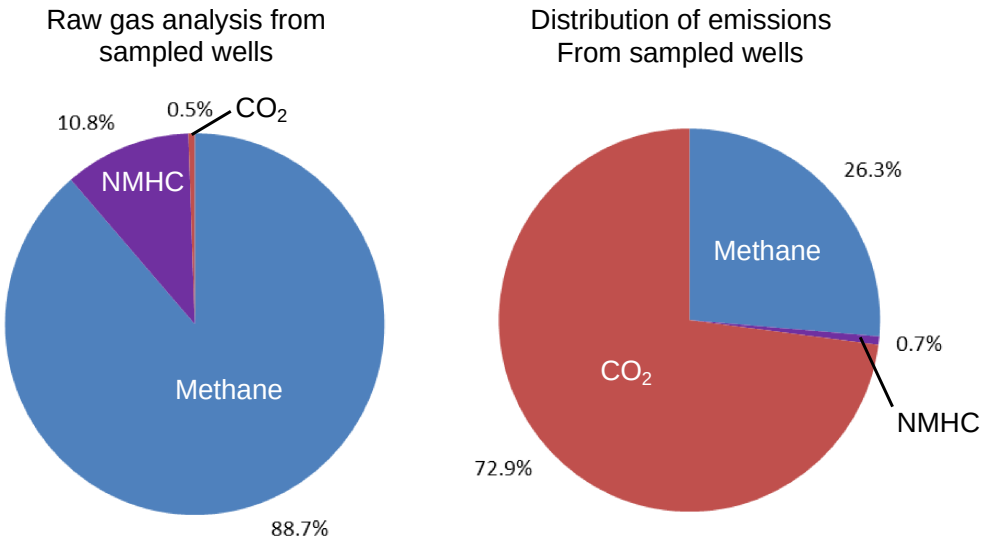

Figure 10-4. Percentage of raw gas from gas analyses at well sites that was methane, NMHC, and carbon dioxide, and the percentage of total emission flux from well pad soils from the same wells that was from the same three components.

Emissions from well pad soils tended to decrease with increasing distance from the well head, and emissions from newer wells tended to be lower than emissions from older wells. Also, emissions from producing wells were lower than emissions from shut-in or natural gas storage wells. Overall, most wells sampled had higher emissions than nearby undisturbed soils, higher emissions than coal, gilsonite, or oil shale outcrops, and higher emissions than soils near faults. Even still, emissions from well pad soils were low overall. We estimate that natural gas well pad soils account for less than 0.01% of total methane emissions from the Uintah Basin oil and gas industry, and constitute an even lower percentage of NMHC (equivalent to VOC) emissions.

11. Report on Project Performance Measures for 2015-16

The Uintah Basin Air Quality Research Project began in July 2016 and so has only been active for four months. The Bingham Center's air quality research activities, however, have been ongoing since 2010. We report here on performance measures for air quality research we conducted in the Uintah Basin for the period of October 2015 through September 2016. We also provide some information about earlier periods.

11.1. Data Quality

Table 11-1 shows a summary of data quality results for measurements we collected during 2015-16.

Table 11-1. Data quality summary for ozone, NO_x, and organic compound data collected during 2015-16. Results are shown as average ± 95% confidence intervals for all locations at which the indicated measurements were collected, where applicable. For a list of measurements collected and sites of collection, see Table 7-1. Percent uptime indicates the percent of the measurement period for which valid measurements were obtained. TNMHC indicates total non-methane hydrocarbons. N/A means not applicable.

Measurement	Zero Calib. (ppb)	Span Calib. (% recov.)	Percent Uptime
Ozone	1.0 ± 0.4	100 ± 1	90 ± 6
NO	0.0 ± 0.1	101 ± 0	92
NO_x (NO calib.)	0.6 ± 0.3	99 ± 1	92
NO_y (NO calib.)	0.2 ± 0.2	98 ± 1	93
NO_x (GPT calib.)	N/A	97 ± 1	92
NO_y (GPT calib.)	N/A	98 ± 1	93
Methane	0 ± 0	97 ± 0	59
TNMHC	0 ± 0	96 ± 1	59
Speciated VOC	0.2 ± 0.1	104 ± 1	77
$PM_{2.5}$ (filter)	N/A	N/A	87
$PM_{2.5}$ (BAM)	N/A	N/A	50

11.2. Reporting and Publications

11.2.1. Reports

In addition to this annual report, we have produced a number of reports related to Uintah Basin air quality research. These reports have included annual reports of research activities and the status of wintertime air quality, as well as project specific reports of measurement campaigns, data analyses, and modeling projects undertaken. Where appropriate, we have provided copies of these reports at http://binghamresearch.usu.edu/reports.

11.2.2. Peer-reviewed Publications

A full list of peer-reviewed publications authored or co-authored by members of the Bingham Center air quality research team can be found at http://binghamresearch.usu.edu/reports. The following is a list of papers published by our team during the previous twelve months that stem from our Uintah Basin air quality research. Full citation information can be found in the References section of this report.

- The Magnitude of the Snow-Sourced Reactive Nitrogen Flux to the Boundary Layer in the Uintah Basin, Utah, USA (Zatko et al., 2016)
- Numerical Tools for Obtaining Power-law Representations of Heavy-tailed Datasets (Mansfield, 2016)
- Inversion Structure and Winter Ozone Distribution in the Uintah Basin, Utah, U.S.A. (Lyman and Tran, 2015)

11.3. Utilization of Research Output by Stakeholders

Our research team engages frequently with elected officials, industry, and regulatory agencies to share and disseminate the results of our air quality research and to ensure that plans for additional work consider the needs of all stakeholders. Over the past year, these engagements have included emails, phone calls, and in-person meetings. In addition to these routine and often informal activities, we highlight three particular areas in which our team has worked over the past year to ensure that our research outputs are relevant to and utilized by stakeholders.

11.3.1. Exceptional Event Designation for 2015 Stratospheric Intrusion Episode

Our modeling team has been developing improved tools for modeling background ozone (i.e., ozone due to natural sources or sources from outside the region) in the Uintah Basin. While conducting this research, we discovered that a storm system that moved through the Western U.S. during the first half of June 2015 caused ozone-rich air from the stratosphere to descend to the surface, elevating ozone concentrations in the Uintah Basin above the 70 ppb EPA standard. Events like this are known as stratospheric intrusions. They are a natural source of ozone and occur most often during late spring and early summer. EPA allows naturally-caused ozone exceedances to be designated as exceptional events, and if a period is approved by EPA as an exceptional event, ozone data from that period are excluded from the regulatory record.

The June 2015 stratospheric intrusion episode led to two ozone exceedance days at the Ouray monitoring station. The Ouray station is operated by the Ute Indian Tribe and has higher ozone than any other regulatory monitoring station during wintertime inversion episodes. In general, the regulatory monitor with the highest ozone in an airshed determines the ozone standard attainment status for the whole airshed, so ozone values at the Ouray station will very likely determine the attainment status of the entire Uintah Basin. With this in mind, we contacted the Ute Tribe about our findings and then worked with the Tribe, the Utah Division of Air Quality, and EPA Region 8 to determine how best to develop the necessary documentation to establish the June 2015 stratospheric intrusion episode as an exceptional event for the Ouray station. The final documentation produced by these agencies contained analyses we conducted, including air quality model analyses. The public comment period has now closed for the documentation, and we are waiting for EPA to approve the exceptional event designation.

Ozone data for the Ouray station during 2016 are still preliminary and the year 2016 is not complete. Values shown in Table 11-2 could change due to data corrections or high wintertime ozone that could occur in December 2016. Table 11-2 shows the 4th-highest 8-hour average daily maximum ozone concentration for the Ouray station for 2014, 2015, and 2016 (2016 data are preliminary), as well as the 3-year average value (preliminary) EPA uses to determine whether an airshed is in compliance with the 70 ppb ozone standard. As shown, exclusion of the days during June 2015 when a stratospheric intrusion episode led to exceedances of the ozone standard causes a 1 ppb decrease in the 4th-highest 8-hour average ozone value for 2015, leading to a 1 ppb decrease in the 3-year average (EPA truncates, rather than rounds, decimals, leading to a larger-than-expected decrease in the 3-yr average).

Table 11-2. 4th-highest daily maximum 8-hr average ozone at the Ouray monitoring station, including and excluding days during June 2015 when a stratospheric intrusion episode led to exceedances of the 70 ppb standard. Values for 2016 are still preliminary and may change, which could lead to a change in 3-year average values.

	4th highest daily maximum 8-hr average ozone			3-yr average
Units of ppb	2014	2015	2016	2014-16
Including stratospheric intrusion days	*79*	***68***	*96*	81
Excluding stratospheric intrusion days	*79*	***67***	*96*	80

EPA has indicated that areas with regulatory monitoring stations registering 3-year average ozone values of 81 ppb or greater will be given a moderate non-attainment classification, while stations with 3-year average values below 81 ppb will be classified as in marginal non-attainment (see EPA's proposed plan for implementation of the new ozone standard at https://www.epa.gov/sites/production/files/2016-11/documents/o3_sip_requirements_nprm_preamblerule.pdf). Thus, if the preliminary ozone values shown in Table 11-2 become final values, we expect that categorizing stratospheric intrusion days that occurred during June 2015 as exceptional events will result in the Uintah Basin being classified as in marginal, rather than moderate, nonattainment of the 70 ppb standard. Marginal nonattainment areas are subject to less strict emissions control requirements, less onerous permitting requirements, and less strict planning requirements for regulatory agencies compared to moderate nonattainment areas. This would result in large cost savings for industry and government.

11.3.2. Participation in Air Quality Modeling Working Group

The Utah Division of Air Quality established a Uintah Basin air quality model working group during summer 2016. The purpose of this group is to share model results, methods, and other information among those working to develop computer models to simulate air quality in the Basin. The group includes the Division of Air Quality, representatives from EPA, and our modeling team. Air quality models are used by regulators and industry to develop emissions reduction plans. We are participating in monthly webinars with the model working group, providing information and data to the group, and working with the group to ensure the research we conduct results in better modeling tools that allow industry and regulatory agencies to make effective emissions reduction plans.

11.3.3. Development of Emission Estimates for Produced Water Ponds

We have completed the field data collection portion of a large project to measure emissions of hydrocarbons from produced water ponds. Produced water ponds have been excluded from most air emissions inventories because insufficient measurement data has existed to develop emissions estimates for them. Our measurements have filled this data gap and allowed us to develop Uintah Basin-wide emissions estimates of emissions from these sources. Over the coming year, we will work with the Utah Division of Air Quality to incorporate these emissions estimates into the current emissions inventory for the Uintah Basin, improving the accuracy of this inventory and improving the inventory's utility for development of emissions reduction plans.

12. Project Objectives for 2016-17

The following is a summary of activities planned for November 2016 through October 2017. The following activities are proposed:

1. Engagement of stakeholders and the Uintah Basin community to disseminate the results of air quality research and help ensure that decisions made by industry, elected officials, and regulators are based on the best available science.
2. Ambient air monitoring to continue a long-term record of atmospheric conditions during the Uintah Basin winter at a few key monitoring stations. This work will include an investigation of the spatial and temporal trends in volatile organic compounds (VOC) over the five years for which we have measurement data.
3. Air quality model improvements, with the goal of improving modeling tools that are used by industry and regulators to make decisions. Our team will collaborate with Utah DAQ in all aspects of this work. Specific research tasks will include (1) collaboration with Utah DAQ in monthly modeling working group meetings, (2) continued efforts to improve meteorological models, (3) incorporation of the new Utah DAQ emissions inventory, (4) further investigation of methods to understand the contribution of background sources to Uintah Basin ozone, and (5) investigation of the feasibility of forecasting high ozone days.
4. Characterization of sources of ozone precursors in the Uintah Basin, including (1) evaluation of available VOC emissions speciation datasets and recommendation of priorities for additional measurements to improve these datasets, and (2) a preliminary investigation of the ability of snowpack to collect, process, and emit VOC.

12.1. Stakeholder and Community Engagement

Community engagement has been central to Uintah Basin air quality research carried out by USU since the establishment of the Bingham Research Center in 2010. During 2016-17, we will continue these efforts in the following ways:

- We will continue operation of our real-time air quality data website, ubair.usu.edu. A screenshot from the website is shown in Figure 12-1. This website now receives hundreds of hits each month from within the Uintah Basin and around the world. The site is used regularly by elected officials and other stakeholders to monitor air quality in the Uintah Basin.
- We will participate in meetings with industry, government officials, and other stakeholders to keep all parties informed of new research and regulatory developments.
- We will provide air quality data and other information as requested by any and all stakeholders, including the public. This information may be disseminated informally through phone calls and emails, formally through reports on specific air quality topics, or via download from our website, binghamresearch.usu.edu.

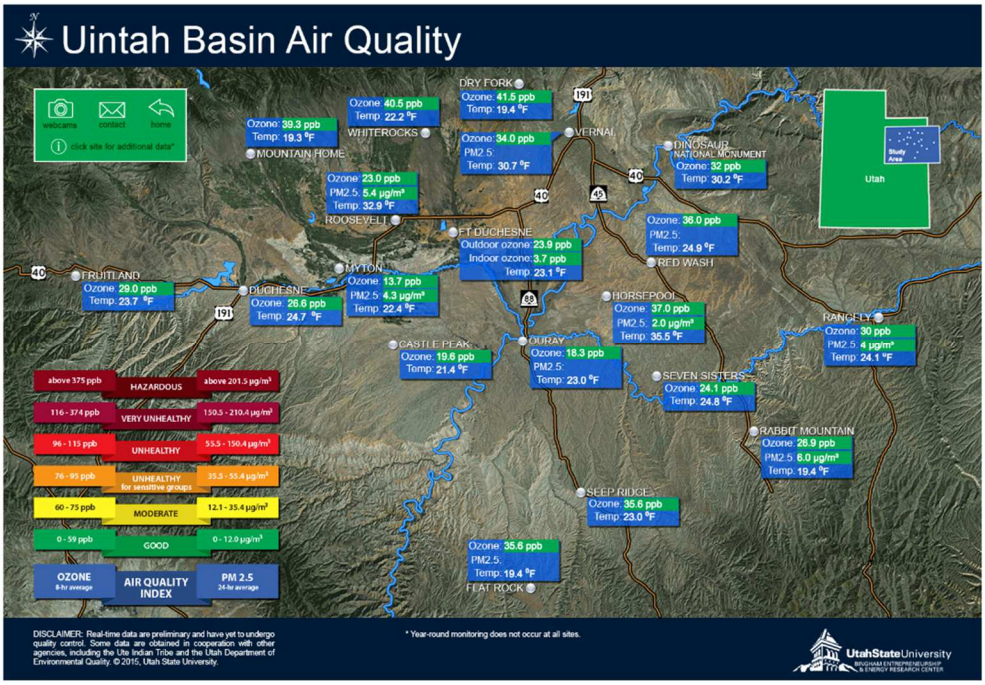

Figure 12-1. Screenshot from ubair.usu.edu.

12.2. Ambient Air Monitoring

Large investments in funding, equipment and time were made by several agencies and donors to establish air quality monitoring stations around the Uintah Basin. The Roosevelt monitoring station, one of two flagship stations, is shown in Figure 12-2. Continuation of air monitoring, especially of key ozone precursors and related atmospheric constituents like methane, nitrogen oxides (NOx), volatile organic compounds (VOC), total reactive nitrogen (NOy) and particulate matter, is critically needed to maintain a record of changes to Uintah Basin air quality due to meteorological fluctuations and changes to emissions.

Figure 12-2. Photograph of Roosevelt air quality monitoring station.

We will maintain the following air quality monitoring stations this winter. All stations will be operated from 15 November 2016 through 15 March 2017:

12.2.1. Horsepool

At the Horsepool monitoring station we will operate instruments that measure the following:

- Ozone
- CO
- True NOx (measured with a photolytic converter, which does not suffer from the bias that afflicts regulatory NOx monitors during winter inversion periods)
- NOy (NOx + other reactive nitrogen compounds)
- Methane and total non-methane hydrocarbons
- Daily canister-based measurements of speciated VOC (C2-C11 hydrocarbons and C1-C3 alcohols).
- Particulate matter smaller than 2.5 microns in size ($PM_{2.5}$)
- Meteorological parameters, including snow depth, upwelling and downwelling solar radiation (shortwave, longwave, UV-A, and UV-B), temperature at two heights, humidity, barometric pressure, and wind conditions.

12.2.2. Roosevelt

The Utah Division of Air Quality (DAQ) and USU jointly operate an air quality monitoring station in Roosevelt, Utah. The following parameters are measured at the station:

- Ozone (DAQ)
- NOx (DAQ)
- PM2.5 (DAQ)

- True NOx (measured with a photolytic converter, which does not suffer from the bias that afflicts regulatory NOx monitors during winter inversion periods; USU)
- NOy (USU)
- Daily canister-based measurements of speciated VOC (C2-C11 hydrocarbons and C1-C3 alcohols; USU).
- Methane and total non-methane hydrocarbons (USU)
- Snow depth (USU)
- Upwelling and downwelling solar radiation (shortwave, longwave, albedo; USU)
- Temperature and humidity (USU)
- Barometric pressure (DAQ)
- Wind (DAQ)

12.2.3. Rabbit Mountain

The Rabbit Mountain air quality monitoring station is in east-central Uintah County on Enefit American Oil's property, and the station and its equipment are owned by Enefit and operated by USU. We will measure the following at Rabbit Mountain in the coming winter:

- Ozone
- NOx (NO + NO2)
- Carbon Monoxide
- Meteorological parameters, including temperature, wind, humidity, precipitation, and barometric pressure.

12.2.4. Castle Peak

The Castle Peak site is the only air quality monitoring station in the oil field on the west side of the Uintah Basin. We will measure the following at Castle Peak in the coming winter:

- Ozone
- True NOx (measured with a photolytic converter, which does not suffer from the bias that afflicts regulatory NOx instruments during winter inversion periods)
- Meteorological parameters, including temperature, wind, humidity, precipitation, and barometric pressure.
- If canisters are available, we may collect weekly canister-based speciated VOC measurements at this site.

12.2.5. Fruitland

An air quality monitoring station has been operated by Utah DAQ over the past several years. Fruitland is within the Uintah Basin but is at high elevation (greater than 2000 m above sea level) and has never experienced elevated ozone during wintertime inversion episodes. The site has been used by DAQ and others to demonstrate what "background" ozone would be in the absence of wintertime inversions. We will assist DAQ by operating ozone and meteorology monitoring equipment at the Fruitland station.

12.2.6. Seven Sisters

We will continue measurements of ozone and meteorological parameters at Seven Sisters, located near the White River in Uintah County.

12.2.7. Measurements Supported by the Ute Indian Tribe

We also conduct air quality measurements with support from the Ute Indian Tribe. Current measurements we collect with the Tribe include ozone at Mountain Home, Flat Rock, and Fort Duchesne; measurements of particulate matter at Flat Rock, Fort Duchesne, Randlett, and Myton; and VOC measurements at Randlett and Wolf Flat. Some or all of these measurements may continue in the coming year and are not restricted to the winter season.

12.2.8. Data Collection and Management

We will operate instrumentation and manage data at all sites according to a comprehensive maintenance and QA/QC plan that follows manufacturer recommendations and EPA protocols. Data collected will be automatically uploaded to our database and shared with the public on our real-time air quality website, ubair.usu.edu.

12.2.9. Investigation of Spatial and Temporal Trends in Uintah Basin VOC

Oil and gas production activities in the Uintah Basin account for more than 90% of Volatile Organic Compound (VOC) emissions in the Basin, according to the latest UDAQ 2014 emission inventory, but a number of state and federal regulations were recently put in place with the goal of reducing VOC emissions by the oil and gas industry in the Uintah Basin. (See http://www.deq.utah.gov/locations/U/uintahbasin/ozone/docs/2014/06Jun/ITEM_V_R307-501_502_503_504.pdf and https://www.epa.gov/controlling-air-pollution-oil-and-natural-gas-industry.) For example, the Air Quality Board of the State of Utah has mandated, effective December 1, 2015, that oil and gas "operating and maintenance procedures be ... consistent with good air pollution control practices," that low-bleed pneumatic devices replace high-bleed ones, that flares be equipped with self-igniters, and that tank trucks be filled through submerged or bottom filling. The Utah Division of Air Quality has estimated that these modifications would reduce VOC emissions by thousands of tons per year. In addition, economic conditions have forced a downturn in the oil and gas industry in the Basin, which we can assume has also had an impact on VOC emissions. Our team has recorded ambient VOC concentrations going back to 2012. Therefore, we propose to analyze these data to see if either the new regulations or the economic downturn have had a measurable impact on ambient VOC.

To see a strong correlation between ambient concentrations and emissions, we will need to control for the presence or absence of inversions, and for other meteorological variables. Because of the economic downturn, the drilling of new wells has almost completely ceased. Oil and gas production are also down, but only to 2010 rates. Therefore, we will also need to control for well completions and for oil/gas production rates. The study will include a regression analysis, comparable to our analysis of ozone concentrations in the Basin. It will also employ a technique known as Positive Matrix Factorization, which allows for the determination of sources of VOC in ambient air. Since the downturn in industrial activity occurred over approximately the same time frame as the implementation of the

new regulations, it may be difficult to determine which has had the greater impact. Therefore, it may also be advantageous to continue the study beyond this fiscal year. This analysis will seek to answer the following questions:

1. What are the trends in total VOC and individual organic compounds over the past several winter seasons? Is there a relationship between ambient VOC and the downward trend in oil and gas activities and production or the enactment of new regulations?
2. What sources contribute to ambient VOCs collected at Horsepool and Roosevelt? Has the source makeup changed over time?
3. How do ambient VOC concentrations change seasonally or with short-term weather conditions (i.e., inversion versus no inversion)?

Answering questions 1 and 2 will have implications for improving oil & gas emission inventories that are an important part of ozone modeling studies in the Uintah Basin. Utah DAQ has recently made the 2014 oil and gas emission inventory available. This inventory will be used in photochemical modeling to simulate ozone in past and future years. Emissions data will be projected from the inventory's base year (2014) to other model years using scaling factors which are developed mainly based on oil & gas activities record in the Utah Division of Oil, Gas and Mining (DOGM) database. Answering questions 1 and 2 will help us develop appropriate scale factors for the EI. Answering question 3 is important for model performance evaluations and improvements.

12.3. Air Quality Model Development

Air quality models have been widely employed as scientific and regulatory tools for studying elevated ozone events. EPA requires regulatory agencies to use air quality models to show the effectiveness of mitigation efforts. Meteorological and air chemistry models that researchers and regulators use to simulate air quality, however, were designed for summertime urban conditions and are, therefore, inadequate to the task of accurately simulating the winter ozone episodes of rural oil and gas producing areas like the Uintah Basin. Unless modified to overcome such deficiencies and updated to incorporate new research findings, current models will fall short of the understanding necessary to responsibly address winter ozone challenges.

In partnership with federal and state agencies and other academic institutions in the state, we have worked over the past several years to develop a modeling framework that is specific to wintertime inversion episodes in northeastern Utah. Our platform utilizes the Weather Research and Forecasting (WRF) model, the Sparse Matrix Operator Kernel Emissions (SMOKE) model, the Comprehensive Air Quality Model with Extensions (CAMx), and the Community Multiscale Air Quality Model (CMAQ). Our goal is to develop modeling tools that better represent reality so they can be used more effectively to design pollution control strategies. We propose to carry out the following activities to improve Uintah Basin air quality models:

12.3.1. Participation in the Uintah Basin Air Quality Model Working Group

Over the past year, we have been participating with Utah DAQ and EPA Region 8 in an air quality model working group. The purpose of this group is to share and coordinate information and model platforms among USU and regulatory agencies and to ensure that the model development activities our team

pursues are useful for regulatory modeling efforts. This group meets by phone monthly and will continue to meet throughout this project.

12.3.2. Incorporation of the New Utah DAQ Emissions Inventory and other DAQ Model Parameters into USU Air Quality Model

Utah DAQ recently released a new oil and gas emissions inventory for the Uintah Basin. Like all emissions inventories, this new inventory is imperfect, and we have already helped DAQ discover errors in NOx emissions in the inventory. Despite its imperfections, however, this inventory will be used by DAQ and likely by EPA to develop ozone mitigation strategies for the Uintah Basin. It is important for USU and DAQ to use the same basic modeling information and framework as a point of common reference, so the work USU carries out with regards to air quality modeling will be understandable and useful to DAQ. As we continue air quality model development, we will work to incorporate the new DAQ emissions inventory into our own modeling efforts and we will use other DAQ model parameterizations, resolutions, etc., as a base from which to conduct research and make improvements.

12.3.3. Continued Efforts to Assimilate Meteorological Data into Models

The Weather Research and Forecasting (WRF) model has been used to create meteorological quantities for photochemical models to study winter ozone events in the Uintah Basin. WRF is the state-of-the-science model to predict synoptic-scale (large scale) weather systems such as front, storm, or hurricane forecasting. However, WRF has difficulty predicting meso- to micro-scale weather systems such as horizontal and vertical transports over areas with complex terrain, such as the Uintah Basin. To improve model performance in such cases, several approaches have been used. One option is to increase model grid resolution, but this is computationally expensive and so not always feasible. Another option is a "nudging" approach. Nudging is a four-dimensional data assimilation method that uses dynamical relaxation to adjust (nudge) the model towards observations. This approach was shown to improve model performance in some previous studies, including the BLM-ARMS modeling study for the Uintah Basin that was performed by AECOM.

We recently compared two WRF simulations with and without nudging with observational data to examine if nudging improves WRF performance in simulating surface meteorological quantities (temperature, wind) and temperature inversions in the Uintah Basin during winter 2013. Although nudge-WRF created larger biases in some surface meteorological quantities than no-nudge WRF simulations, nudging was able to produce temperature inversion conditions which no-nudge WRF failed to capture. Nudging could be a promising approach to improve model performance in simulating atmospheric stability in the Uintah Basin if the model is nudged with the dataset that is more representative of the Uintah Basin for the entire boundary layer, not just surface measurements. Tethersonde (i.e., meteorological instruments borne by a balloon that is tethered to the ground) datasets were collected by NOAA and USU in Jan and Feb 2013 at Ouray, Pariette, Horsepool and Fantasy Canyon and provided vertical profiles of temperature, relative humidity, and wind speed and direction from the surface up to about 600 meters. This dataset accurately represents meteorological conditions throughout the boundary layer and could improve characterization of inversion conditions. For this project, we will nudge WRF simulations with the balloon dataset to determine the value of nudging with balloon data. If balloon data are useful for nudging, we could collect balloon data annually for use in air quality models.

12.3.4. Contributions of Natural and Non-Local Sources to Uintah Basin Ozone

The 8-9 June 2015 exceptional event demonstrated the importance of natural forces (i.e., stratospheric ozone in this specific case) on ozone at ground level in the Uintah basin. Being able to distinguish ozone contributions from local anthropogenic sources (e.g., oil and gas, vehicular traffic, residential heating) and non-local and natural sources (e.g., transport from outside the Uintah Basin, wildfires, stratospheric intrusions) is important for evaluation of the effect of emissions control strategies to bring the Basin in compliance with federal air quality standards.

We have been developing a modeling technique to quantify background ozone in the Uintah Basin. We define background ozone as ozone or ozone precursors that did not originate from sources located within the geographical nonattainment boundary. We are using the GEOS-Chem global chemical model (http://acmg.seas.harvard.edu/geos/). We used this model to identify and demonstrate the ozone exceptional event in June 2015, and we will further investigate its applicability in modeling background ozone. We will work to improve GEOS-Chem performance in simulating background ozone in the Uintah Basin. We will then use GEOS-Chem to investigate the seasonal contribution of background ozone to observed ozone in the Uintah Basin.

12.3.5. Investigation of Ability to Forecast High Ozone Days

The ability to predict high ozone days in the Uintah Basin would allow the industry to curtail optional emissions-generating activities and provide the public with information they could use to limit exposure to air pollution. Currently, a national operational air quality forecast system exists (http://airquality.weather.gov/) as a collaborative effort by EPA, NOAA and State and local agencies. For ozone air quality, the forecast system provides a 48 hourly forecast over the U.S. at a 12 km spatial resolution. These model-based forecasts have poor horizontal resolution (12 km) and poor performance for ozone during winter seasons.

Over the past year, we have investigated the relationship of ozone with meteorological parameters and oil and gas activities in the Basin in the past winter seasons (see discussion above). We developed statistical regression models that predict ozone concentrations based on conditions such as snow depth, temperature, lapse rate, gas and oil production rates, etc. Comparison of estimated ozone with observed values has shown good agreement. Based on the successfulness of this regression model in estimating ozone during past winters, we will investigate its applicability as a forecasting tool for ozone in the Uintah Basin. Current Uintah Basin conditions (e.g., snow depth, inversion conditions, oil and gas activity) and forecast outputs from models (e.g., forecast temperature and atmospheric pressure) will be employed as inputs for estimating ozone. Outputs from the North American Model (NAM, 5km horizontal resolution, 60-hour forecasts) and the High-Resolution Rapid Refresh model (HRRR, 3 km resolution, 18-hour forecasts), both of which are freely available from the National Weather Service, are being considered as inputs for the regression model. This statistical-based forecast will be tailored to Uintah Basin conditions and will not suffer from the shortcomings of model-based forecasts.

We will perform statistical-based ozone forecasting for winter 2016-17. Hindcasts for winter 2015-2016 and their comparisons with observed values will be used to “tune” the regression model. We will compare model-based and statistical-based forecasts to determine the best forecasting approach for ozone in the Uintah Basin. We will then consider publishing air quality forecasts to our website during subsequent winters.

12.4. Emissions Characterization

12.4.1. Development of Model-Ready Emission Factors for Produced Water Ponds

We are completing a project to characterize emissions from produced water ponds in the Uintah Basin (see discussion above). We will use data collected during this project to develop emission factors for produced water that can be incorporated into the 2014 Uintah Basin emissions inventory. We will work with Utah DAQ to ensure that the emissions factors developed are useful for their emissions inventory development efforts. We will run air quality models with and without the produced water emission factors incorporated and determine their impact on air quality in the Uintah Basin.

12.4.2. Evaluation of Speciation Profiles for VOC and Recommendation of Actions for Improvement

With funding from the Bureau of Land Management (BLM) and the U.S. Department of Energy (DOE), USU is completing projects to characterize emissions of methane and VOC from produced water ponds and well pad soils. We have found that, while produced water is a significant source of VOC to the Uintah Basin atmosphere, well pad soils are not. Each of these efforts has been an expensive undertaking because of the specialized equipment and time required to collect measurements from enough facilities and source types to obtain a representative sample of emissions. We know, however, that more detailed studies like these are needed to better characterize the amount and speciation of VOC emitted from various oil and gas sources and to improve current emissions inventories. Because of the time and cost required to carry out an emissions characterization study, we feel that the best way to use available resources will be to work with Utah DAQ and other agencies to evaluate available emissions information and identify the most important areas for further study.

One particular area of uncertainty in available emissions data is in the speciation of VOC emissions. Emissions inventories typically provide information to air quality models about total VOC emitted from various sources or source categories, and VOC speciation profiles are then applied to those sources in models to assign the percentage of total VOC emissions comprised by each VOC compound or group of compounds. Ozone concentrations predicted by photochemical models are highly sensitive to VOC speciation, especially to the amount of formaldehyde (or carbonyls) in total VOC emissions. Unfortunately, most available VOC speciation profiles are not representative of emissions sources in the Uintah Basin. For example, VOC speciation profiles provided with the EPA national emission inventory (NEI2011) database assign a profile for natural gas flares, which has an extremely high percentage of formaldehyde emissions, to both combustion and non-combustion emission sources in the Uintah Basin. Other VOC profiles developed by AECOM for BLM or those included with the WRAP III inventory are based on data provided by oil and gas producers and result in very low formaldehyde emissions.

Utah DAQ has been coordinating with federal, Tribal and research institutions (including USU) to improve VOC speciation profiles. As part of that ongoing effort, we were involved in a DAQ-funded project in 2014 in which we measured carbonyl emissions from several emission sources in the Uintah Basin, including glycol dehydrators, condensate tanks, oil tanks, water tanks, pneumatic pumps and pump jack engines. EPA is also collecting VOC speciation data from oil and gas producers on the Tribal lands and plans to update their emission inventory with new data from this effort.

We will continue work to review available VOC speciation profiles, including updates made by Utah DAQ and EPA. We will make a database of speciation profiles that includes the source of the profile data and the source types the profiles have been applied to. We will also test different profiles with photochemical simulations to examine which speciation profiles compare best against observed ozone and VOC concentrations in the Uintah Basin atmosphere. We will share the speciation profile database and model results with Utah DAQ and determine together which speciation profiles for which source types have the most uncertainty, and we will develop a plan to collect measurements of VOC speciation from those sources in the following year.

12.4.3. Snowpack Processing of VOC

We have carried out a number of flux chamber-based emissions measurements from snow surfaces over the past several years as part of studies to investigate emissions of VOC and methane from soils on and off well pads (with funding from RPSEA, DOE, and BLM). Figure 12-3 displays the range of emission rates (i.e., fluxes) of individual VOC compounds from snow surfaces (only measurements distant from oil and gas sources are included). This snowpack dataset is characterized by a large central peak near zero, implying that many VOC species have statistically zero emissions. However, both data sets also have heavy positive tails that are almost certainly not statistically zero, indicating that these snow packs are discharging gases to the atmosphere.

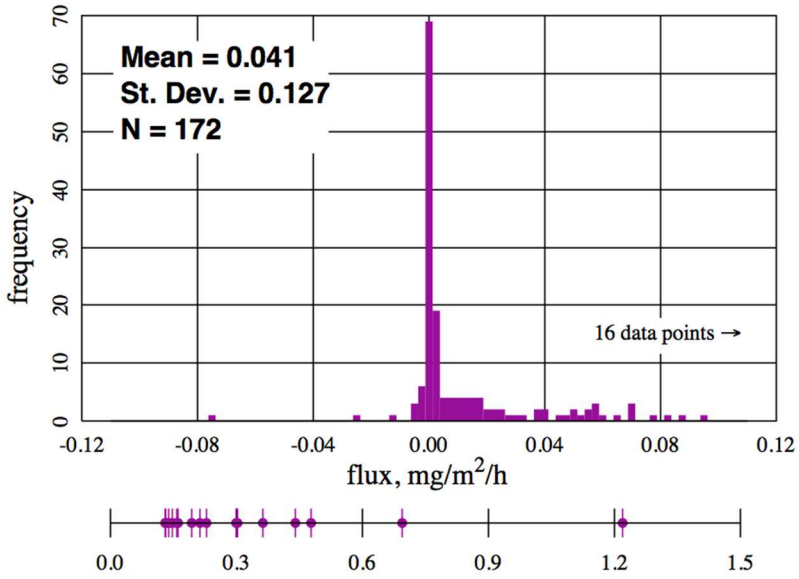

Figure 12-3. The range of measured VOC fluxes from snow packs distant from oil and gas sources. 16 outliers are displayed on a separate linear scale below.

It is difficult to know with certainty the ultimate source of these emissions, but an appropriate hypothesis is that they result from organics that had previously adsorbed onto or dissolved into the snowpack. One possible scenario is that organics adsorb or dissolve overnight and then are emitted upon sublimation (i.e., evaporation from the solid snow surface) during the day. All our experiments

occurred in daylight hours, but a possible outcome is that nighttime measurements would reveal more negative fluxes. It is also possible that VOC are trapped in snow when it falls, and that they exit from snow into the atmosphere when it melts, such that days with significant snow melt could experience a pulse of VOC to the atmosphere, impacting ozone production. Finally, it is possible that VOC are chemically processed within the snowpack to more reactive compounds like carbonyls.

Photochemical grid models include deposition effects, meaning that molecules coming in contact with the ground or the snow are removed from the modeled atmosphere at some given rate. However, it seems that more realism can be achieved by permitting some of those molecules to return to the atmosphere, as our measurements show to be occurring. More extensive measurements of VOC fluxes into and out of the snow, as well as of water vapor freezing and sublimation rates on and off the snowpack, are needed to confirm the importance of VOC emission from and deposition to snowpack.

We will measure VOC emissions from snow at the Horsepool monitoring station this winter to further explore the dynamics of VOC deposition to and emission from snow surfaces. A great deal of research is needed to fully characterize these processes, and available time and funding are limited. Thus, we will only perform enough work this winter to allow us to better understand whether snow-VOC interactions are an important enough process that it needs to be included in photochemical models. If we determine from these measurements that it does need to be included, we will pursue additional funding (probably from the National Science Foundation) to explore this phenomenon further.

We will use our flux chamber system and vertical gradient measurements at the Horsepool site to measure deposition to and emissions from snow by speciated hydrocarbons and carbonyls. We will collect emissions measurements during early, middle, and late winter seasons, and we will target periods of active snowfall, extreme cold, and snowmelt.

13. Acknowledgements

The work presented in this report was funded by the Utah Legislature, the Uintah Impact Mitigation Special Service District, the Ute Indian Tribe, the Bureau of Land Management, the Research Partnership to Secure Energy for America, the U.S. Department of Energy, GSI, Inc., and the Utah School and Institutional Trust Lands Administration. We also thank the Bureau of Land Management for providing equipment for remote ozone monitoring, the Utah Department of Environmental Quality for providing space, shelter, and power for our instruments at Roosevelt, QEP Resources for providing space and power for the Horsepool station, Enefit American Oil for allowing us to operate their Rabbit Mountain station, and Newfield Exploration for providing space and power for the Castle Peak station.

14. References

Ahmadov, R., McKeen, S., Trainer, M., Banta, R., Brewer, A., Brown, S., Edwards, P.M., de Gouw, J.A., Frost, G.J., Gilman, J., Helmig, D., Johnson, B., Karion, A., Koss, A., Langford, A., Lerner, B., Olson, J., Oltmans, S., Peischl, J., Petron, G., Pichugina, Y., Roberts, J.M., Ryerson, T., Schnell, R., Senff, C., Sweeney, C., Thompson, C., Veres, P.R., Warneke, C., Wild, R., Williams, E.J., Yuan, B., Zamora, R., 2015. Understanding high wintertime ozone pollution events in an oil- and natural gas-producing region of the western US. Atmos. Chem. Phys. 15, 411-429.

Benko, K.L., Drewes, J.E., 2008. Produced water in the Western United States: geographical distribution, occurrence, and composition. Environ. Eng. Sci. 25, 239-246.

Chidsey, T., 2015. Oil and Gas in the Uinta Basin, Utah: What to Do with the Produced Water, American Association of Petroleum Geologists Annual Convention, Denver, Colorado.

Finlayson-Pitts, B.J., Pitts Jr, J.N., 1999. Chemistry of the upper and lower atmosphere: theory, experiments, and applications. Academic press.

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

Mansfield, M.L., 2016. Numerical tools for obtaining power-law representations of heavy-tailed datasets. The European Physical Journal B 89, 1-13.

Mansfield, M.L., Hall, C.F., 2013. Statistical analysis of winter ozone events. Air Quality Atmosphere and Health 6, 687-699.

Paulson, L., Deppe, A., Keslar, C., 2016. Upper Green River Basin, WY, Historical Analysis of Pollutant Concentrations, Air and Waste Management Association Aerosols and Visibility Conference, Jackson Hole, Wyoming.

Seinfeld, J.H., Pandis, S.N., 2016. Atmospheric chemistry and physics: from air pollution to climate change. John Wiley & Sons.

Thoma, E., 2009. Measurement of emisisons from produced water ponds: upstream oil and gas study #1. U.S. Environmental Protection Agency, Cincinnati, Ohio, http://nepis.epa.gov/Adobe/PDF/P100EACG.pdf.

Zatko, M., Erbland, J., Savarino, J., Geng, L., Easley, L., Schauer, A., Bates, T., Quinn, P.K., Light, B., Morison, D., Osthoff, H.D., Lyman, S., Neff, W., Yuan, B., Alexander, B., 2016. The magnitude of the snow-sourced reactive nitrogen flux to the boundary layer in the Uintah Basin, Utah, USA. Atmos. Chem. Phys. Discuss. 2016, 1-53.