April 2019

# 2020 AND 2023 ATTAINMENT DEMONSTRATION MODELING FOR THE DENVER METRO/NORTH FRONT RANGE OZONE NONATTAINMENT AREA

RAMBOLL

# 2020 AND 2023 ATTAINMENT DEMONSTRATION MODELING FOR THE DENVER METRO/NORTH FRONT RANGE OZONE NONATTAINMENT AREA

| | |
|---|---|
| Project name | **Regional Air Quality Council Denver Ozone SIP Modeling** |
| Project no. | **1690010033** |
| Recipient | **Denver RAQC** |
| Document type | **Modeling Protocol** |
| Version | **V8.0** |
| Date | **April 22, 2019** |
| Prepared by | **Ralph Morris, Tejas Shah, Dennis McNally and Patrick Reddy** |

Ramboll
7250 Redwood Blvd.
Suite 105
Novato, CA 94945

T +1 415 899 0700
www.ramboll.com

## CONTENTS

## APPENDICES

## TABLE OF TABLES

## TABLE OF FIGURES

# 1. INTRODUCTION

This document is a Modeling Protocol to address ozone State Implementation Plan (SIP) attainment demonstration modeling for the Denver Metro (DM) and North Front Range (NFR) region in Colorado. Currently there are two ozone National Ambient Air Quality Standards (NAAQS) that the DM/NFR nonattainment area (NAA) is required to address: (1) the 70 parts per billion (ppb) ozone NAAQS promulgated in 2015 (i.e. the "2015 ozone NAAQS"); and (2) the 75 ppb ozone NAAQS promulgated in 2008 (i.e. the "2008 ozone NAAQS"). Both standards are based on maximum daily average 8-hour (MDA8) ozone concentrations with a Design Value (DV) expressed as the three-year average of the fourth highest MDA8 ozone concentration. The 2008 ozone NAAQS cannot exceed 75 ppb and the 2015 ozone NAAQS cannot exceed 70 ppb. The convention is to truncate an ozone DV to a nearest ppb, so 76.0 and 71.0 are the lowest level of ozone DVs that violate the 2008 and 2015 ozone NAAQS, respectively.

## 1.1 Attainment Demonstration Requirements for the 2008 and 2015 Ozone NAAQS

The final SIP implementation requirements rule for the 2015 ozone NAAQS was signed by the EPA Administrator on November 7, 2018 (EPA, 2018a) and is expected to have an effective date of late January 2019. The 2015 ozone NAAQS implementation procedures are similar to those for the 2008 ozone NAAQS (EPA, 2013). In June 2018, the DM/NFR region was classified as a "Marginal" ozone NAA (EPA, 2018b) under the 2015 ozone NAAQS effective August 3, 2018 based on the ozone concentrations monitored during 2014-2016[1]. As a Marginal NAA, the DM/NFR NAA is required to attain the 2015 ozone NAAQS by August 3, 2021, which is during the ozone season, so attainment will be based on ozone concentrations measured during 2018-2020. Since the fourth highest MDA8 ozone during 2018 were 80 ppb or higher at four sites in the DM/NFR NAA, the 2018-2020 ozone DVs will likely not achieve the 70 ppb 2015 ozone NAAQS by 2020. If the DM/NFR NAA fails to attain the 2015 ozone NAAQS by 2020 it would likely be reclassified as ("bumped up" to) a "Moderate" NAA under the 2015 ozone NAAQS with an attainment date of 2024, so a 2023 attainment year. This Modeling Protocol details procedures for conducting attainment demonstration modeling for the 2023 future year to address the DM/NFR NAA as a Moderate NAA under the 2015 ozone NAAQS.

Regarding the 2008 ozone NAAQS, the DM/NFR NAA is currently classified as a "Moderate" NAA with an attainment date of July 2018 so that the 2015-2017 ozone DVs are required to attain the 2008 ozone NAAQS. The DM/NFR NAA failed to attain the 2008 ozone NAAQS by 2017. However, the Colorado Department of Health and Environment (CDPHE) Air Pollution Control Division (APCD) determined that ozone exceedances on September 2 and 4, 2017 were influenced by emissions from wildfires and qualified as Exceptional Events.[2] CDPHE prepared an Exceptional Events demonstration package (CDPHE, 2018) that was submitted to EPA who concurred with the determination. Without the observed ozone values on September 2 and 4, 2017, the observed 4$^{th}$ highest MDA8 ozone concentration in 2017 at all monitoring sites in

[1] https://www3.epa.gov/airquality/greenbook/jbtcw.html

[2] https://www.epa.gov/air-quality-analysis/treatment-air-quality-data-influenced-exceptional-events-homepage-exceptional

the DM/NFR NAA were below the 2008 ozone NAAQS, which qualifies the DM/NFR NAA for a one-year extension to attain the 2008 ozone NAAQS. On November 14, 2018, EPA proposed to grant the DM/NFR NAA a one-year extension to attain the 2008 ozone NAAQS (EPA, 2018c). Higher observed ozone concentrations in 2018, however, resulted in the DM/NFR NAA not attaining the 2008 ozone NAAQS based on 2016-2018 data and the 2018 observed ozone was sufficiently high that the region would not qualify for another one-year extension to attain. Therefore, the DM/NFR NAA will likely be bumped-up to a “Serious” NAA under the 2008 ozone NAAQS with an attainment date of July 2021 so attainment will be based on 2018-2020 ozone DVs. This Modeling Protocol details the procedures for conducting attainment demonstration modeling for the 2020 future year to address the DM/NFR NAA as a Serious NAA under the 2008 ozone NAAQS.

## 1.2 Overview of 2020/2023 Ozone Attainment Demonstration Procedures

This Modeling Protocol describes the modeling activities to be performed to demonstrate that the DM/NFR NAA will attain the 2008 and 2015 ozone NAAQS by, respectively, 2020 and 2023. The DMA/NFR NAA 8-hour ozone modeling is being carried out by a contracting team consisting of Ramboll US Corporation (Ramboll), Alpine Geophysics, LLC (Alpine) and Patrick Reddy under contract to the Denver Regional Air Quality Council (RAQC). Working closely with the RAQC are the Colorado Department of Public Health and Environment (CDPHE) Air Pollution Control Division (APCD), Denver Regional Council of Governments (DRCOG), Colorado Department of Transportation (CDOT), the Northern Front Range Metropolitan Planning Organization (NFRMPO) and other local cities and agencies along with EPA Region 8.

### *1.2.1 EPA Guidance for Ozone Attainment Demonstration Modeling Protocols*

A comprehensive Modeling Protocol for an 8-hour ozone SIP attainment demonstration study consists of many elements. Its main function is to serve as a roadmap for planning and communicating how a modeled attainment demonstration will be performed before it occurs. The protocol guides the technical details of a modeling study and provides a formal framework within which the scientific assumptions, operational details, commitments and expectations of the various participants can be set forth explicitly.

EPA has just (November 28, 2018) released a final 8-hour ozone modeling guidance (EPA, 2018d) that replaces the previous final guidance (EPA, 2007) and draft guidance (EPA, 2014d). The EPA 2018 ozone modeling guidance is similar to the draft 2014 guidance with updates (e.g., slight modification to the recommended ozone DV projection approach). As stated in EPA’s latest modeling guidance (EPA, 2018d, pp. 15):

> “The most important function of the modeling protocol is to serve as a blueprint for planning how the modeled demonstration will be performed. The protocol should be a valuable communication device by which air agencies, EPA, and other stakeholders can assess the applicability of default recommendations and develop area-specific alternatives, where needed, prior to conducting the work to build the modeling system. A suitable protocol should lead to extensive

participation by stakeholders in developing the demonstration. It should also reduce the risk of spending time and resources on efforts that are unproductive or inconsistent with EPA rules, policy, and guidance. While the modeling protocol is initially developed at the beginning of a modeling exercise to foster communication, it is advisable to modify the document as needed throughout the modeling process when alterations from the original modeling plan are necessary. Again, any changes to the protocol should be fully communicated between affected air agencies, stakeholders, and the EPA."

#### 1.2.1.1 Contents of the Modeling Protocol

EPA's 8-hour ozone SIP modeling guidance identifies specific "core elements" that should be part of any ozone SIP Modeling Protocol. These "core elements" are repeated below along with where they are addressed in this DM/NFR NAA 2020/2023 ozone attainment demonstration Modeling Protocol (EPA, 2018d, pp. 15-16):

- Overview of the air quality issue being considered including historical background: Chapter 1 provides an overview of ozone issues in the DM/NFR NAA including past ozone SIP efforts.
- List of the planned participants in the analysis and their expected roles: The lead agencies and principal participants in the DM/NFR NAA ozone SIP modeling effort are listed in Section 1.7.
- Schedule for completion of key steps in the analysis and final documentation: The current schedule is presented in Section 1.9.
- Description of the conceptual model for the area: The Conceptual Model of ozone formation in the DM/NFR NAA is detailed in CDPHE and RAQC (2016a) and paraphrased in Section 1.3.3.
- Description of periods to be modeled, how they comport with the conceptual model, and why they are sufficient: Chapter 3 presents the Episode Selection and justifies the selection of the summer of 2016 modeling period.
- Models to be used in the demonstration and why they are appropriate: Model selection and justification is presented in Chapter 2.
- Description of model inputs and their expected sources (e.g., emissions, meteorology, etc.): The source of data and description of the model inputs are given in Chapters 4, 5 and 6.
- Description and justification of the domain to be modeled (expanse and resolution): Domain selection and justification is provided in Chapter 4.
- Process for evaluating base year model performance (meteorology, emissions, and air quality) and demonstrating that the model is an appropriate tool for the intended use: The procedures for conducting the 2016 base case photochemical modeling and model performance evaluation is given in Chapter 7. Procedures for conducting the meteorological modeling and development emissions are provided in Chapters 5 and 6, respectively
- Description of the future years to be modeled and how projection inputs will be prepared: Future year modeling procedures are provided in Chapter 8.

- Description of the NAAQS attainment test procedures and (if known) planned weight of evidence, and/or description of the procedures for calculating RPGs from the modeling outputs, as applicable: The ozone attainment demonstration procedures for the 2020 and 2023 future years are described in Chapter 9 along with potential additional weight of evidence (WOE) analysis to support the modeled attainment demonstration.
- Expected diagnostic or supplemental analyses needed to develop weight of evidence analyses: Potential WOE analysis are described in Chapter 9.
- Commitment to specific deliverables fully documenting the completed analysis: Deliverables to support the modeling component of the DM/NFR NAA ozone SIP are listed at the end of Chapter 9.

## 1.3 Study Background

This section provides background to the DM/NFR NAA 8-hour ozone issues. It starts with a summary of the history of the DM/NFR NAA 8-hour ozone NAAQS planning process followed by a summary of current ozone levels in the DM/NFR NAA and then presents the Conceptual Model of the reasons for high ozone concentrations in the DM/NFR NAA.

### *1.3.1 History of 8-Hour Ozone Planning in the DM/NFR NAA*

In 1997, EPA promulgated the first 8-hour ozone NAAQS with a threshold of 0.08 ppm (80 ppb; exceedance defined by values of 85 ppb and higher). The DM/NFR region maximum ozone Design Values were close to the level of this ozone NAAQS for several years. In December 2002, the RAQC, CDPHE/APCD and others entered into an 8-hour ozone Early Action Compact (EAC) with the U.S. Environmental Protection Agency (EPA). EPA's EAC allowed an area to submit an enforceable 8-hour ozone SIP by March 2004 that demonstrates attainment of the 1997 8-hour ozone NAAQS by 2007. In return for the early implementation of an EAC SIP, EPA deferred the classification of an area as nonattainment until 2007. In 2003, the RAQC and APCD contracted with Ramboll[3] and Alpine to perform the photochemical modeling necessary for the Denver 8-hour ozone EAC SIP. At the outset of the EAC modeling, the DM/NFR region attained the 1997 80 ppb 8-hour ozone NAAQS. However, the high monitored ozone concentrations during the summer of 2003 resulted in violations of the 8-hour ozone NAAQS. Because of the EAC, in 2004 EPA designated the DM/NFR region as "nonattainment deferred" with final designation to be determined after the 2007 ozone season. More details on the 2003 Denver 8-hour EAC SIP that was revised in 2006 are available at:

https://raqc.org/postfiles/sip/ozone_8hr/EAC_SIPRev121706.pdf

Based on 2005-2007 observed air quality observations in the DM/NFR region, in fall 2007 the area was designated nonattainment of the 1997 ozone NAAQS with a maximum 2005-2007 8-hour ozone Design Value of 85 ppb at the Rocky Flats North (RFNO) monitoring site. The RAQC, in conjunction with the CDPHE/APCD and local agencies, prepared a 2008 Denver 8-hour ozone SIP with assistance from

[3] In 2003 Ramboll was known as ENVIRON International Corporation.

Ramboll/Alpine that demonstrated Denver would achieve the 1997 ozone NAAQS by 2010, which it did. Details of the 2008 Denver ozone SIP can be found at:

http://www.colorado.gov/airquality/documents/deno308/

In March 2008, EPA lowered the ozone NAAQS to 0.075 ppm (75 ppb). In January 2010, EPA announced they were reconsidering the 2008 ozone NAAQS and intended to lower the ozone NAAQS to somewhere in the 0.060-0.070 ppm range with the final announcement expected in mid-2011. However, EPA ultimately elected not to lower the ozone NAAQS so that the March 2008 75 ppb threshold was retained.

On July 20, 2012, EPA's designations for the 2008 8-hour ozone standard were effective, with the DM/NFR region classified as a Marginal NAA. In the original proposed 2008 ozone NAAQS Implementation Rule (2008 Ozone SSR), published May 21, 2012, the attainment date for a Marginal area was set as December 31, 2015 (based on 2013-2015 observations) and for a Moderate area was December 31, 2018 (based on 2016-2018 observations). However, based on challenge by environmental groups, on December 23, 2014 the DC Circuit revoked portions of the 2012 ozone SIP implementation rule, which resulted in the attainment deadline being set a specific number of years from the effective date of designation, which meant a revised attainment date of July 20, 2015 (attainment by 2014) for a Marginal Area and July 20, 2018 (attainment by 2017) for a Moderate Area as stated in the revised 2008 ozone NAAQS implementation rule that was finalized in March 2015.

Ramboll/Alpine conducted 2017 attainment demonstration modeling using a 2011 photochemical grid model (PGM) modeling platform that indicated the DM/NFR NAA would have a 2017 maximum fourth highest MDA8 ozone concentrations at the 2008 ozone NAAQS level and included a Weight of Evidence (WOE) analysis that 2017 ozone levels would be below the 2008 ozone NAAQS when eliminated days in the baseline observed ozone Design Values where ozone concentrations were influenced by emissions from wildfires.

https://raqc.org/sip/moderate-area-2008-8-hour-ozone-standard-state-implementation-plan/

### *1.3.2 Current Ozone Air Quality in the DM/NFR NAA*

Figure 1-1 displays the trend in 4$^{th}$ highest MDA8 ozone concentrations and ozone Design Values over the last 21 years (1998-2018) and compares them with the 1997, 2008 and 2015 ozone NAAQS. There is a substantial year-to-year variation in the 4$^{th}$ highest ozone concentrations in the DM/NFR NAA, although within that variability there is a downward trend in ozone concentrations over the last two decades. The 1997 85 ppb ozone NAAQS was achieved in 2010 with a maximum ozone DV of 78 ppb (note that the 1997 ozone NAAQS was also achieved in 2009). However, the maximum ozone DV in 2017 was 79 ppb so failed to achieve the 2008 75 ppb ozone NAAQS as required for a Moderate NAA under the 2008 ozone NAAQS. Over the last decade, relatively lower ozone occurred in 2008-2010, 2014 and 2017 with relatively higher ozone in 2011-2013, 2015-2016 and 2018. These lower and higher years of ozone are primarily due to year-to-year variations in meteorology, although the lower emissions during the 2008-2009 recession likely contributed to the lower ozone concentrations in those years.

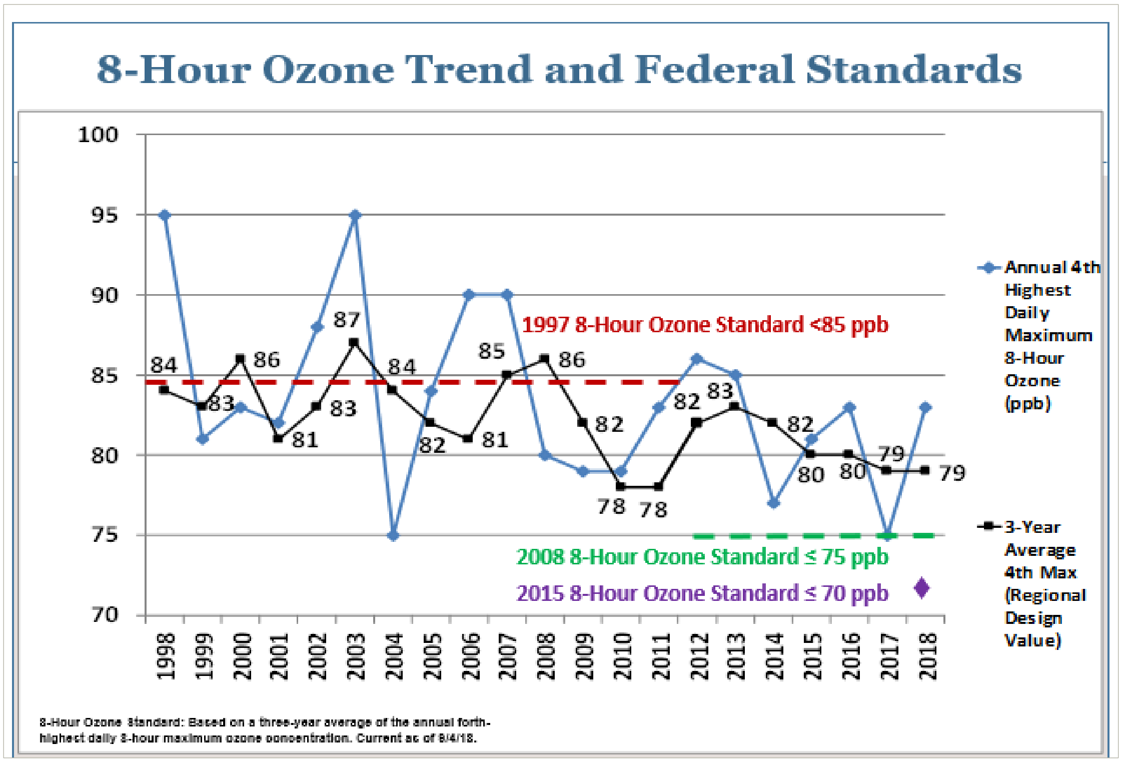



**Figure 1-1. Trend in 4th highest MDA8 ozone concentrations (blue) and ozone Design Values (black) at any monitor in the DM/NFR NAA between 1998 and 2018 and comparisons with the 1997 (red), 2008 (green) and 2015 (purple) 8-hour ozone NAAQS.**

Figures 1-2 and 1-3 display the spatial distribution of the, respectively, 2015-2017 and 2016-2018 ozone DVs in the DM/NFR NAA, with the 4th highest MDA8 ozone concentrations for 2017 and 2018 shown in Figure 1-4. 2017 was the attainment year for the DM/NFR Moderate NAA under the 75 ppb 2008 ozone NAAQS and there were three ozone monitoring sites with 2015-2017 ozone DVs above the 2008 NAAQS, so the area failed to attain: 79 ppb at National Renewable Energy Laboratory (NREL); 77 ppb at Rocky Flats North (RFNO); and 77 ppb at Chatfield (CHAT) reservoir. Higher observed ozone levels in 2018 resulted in 4 monitoring sites in the DM/NFR NAA with ozone DVs above the 75 ppb ozone NAAQS: 78 ppb at NREL, RFNO, and CHAT; and 77 ppb at Fort Collins West (FTCW). In 2017, the maximum 4th highest MDA8 ozone concentration in the DM/NFR NAA was 76 ppb at CHAT, but after the removal of the observed ozone concentrations at CHAT on September 2 and 4, 2017 that were classified as Exceptional Events due to contributions of emissions from wildfires, the 2017 4th highest MDA8 ozone at all sites were below the 2008 ozone NAAQS. This qualified the DM/NFR NAA for a one-year extension to attain the 2008 ozone NAAQS

(Figure 1-4, left panel). EPA has proposed to grant the DM/NFR a one-year extension to 2018 to attain the 2008 ozone NAAQS (EPA, 2018c).

However, in 2018 there were six monitoring sites with 4th highest MDA8 ozone above the 2008 ozone NAAQS. To qualify for another one-year extension to attain the 2008 ozone NAAQS the average of the 4th highest MDA8 ozone for 2017 and 2018 would have to be below the 2008 NAAQS. That did not occur with 2017-2018 two-year average 4th high MDA8 ozone values of 78 ppb at RFNO, CHAT and FTCW and 76 ppb at NREL. Although some of the 2018 ozone concentrations in the DM/NFR NAA were likely influenced by smoke from wildfires, it is unlikely enough days in 2018 could be classified as Exceptional Events to reduce the average 2017-2018 4th highest MDA8 ozone concentrations to below the 2008 ozone NAAQS. Thus, it is anticipated that the DM/NFR NAA will be bumped up to a Serious NAA under the 2008 ozone NAAQS with a July 2021 attainment date (i.e., 2018-2020 ozone DVs are required to be below the 2008 ozone NAAQS).

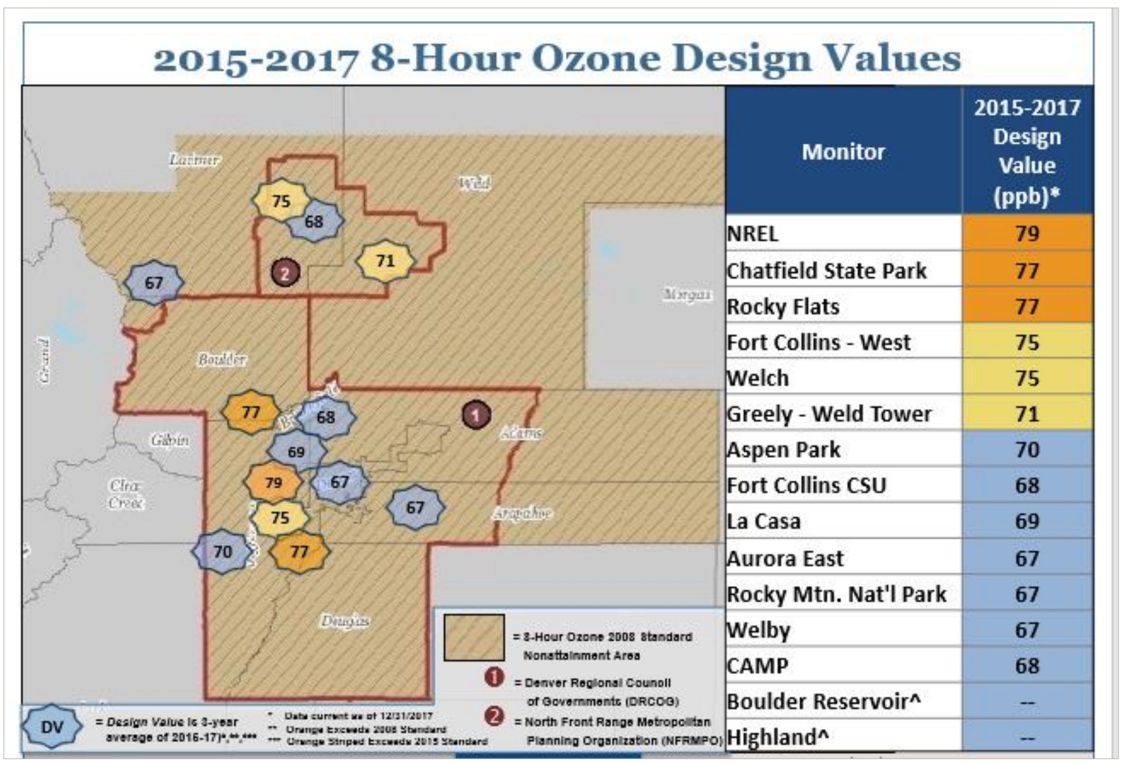
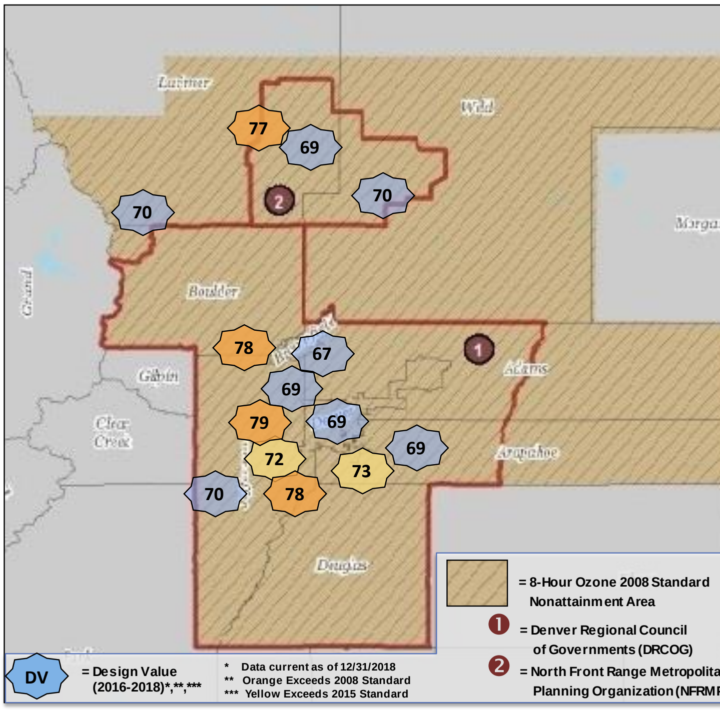



**Figure 1-2. Observed 2015-2017 ozone DVs (ppb) in the DM/NFR NAA.**

# 2016-2018 8-Hour Ozone Design Values




| Monitor | 2016-2018 DV (ppb) |
|---|---|
| NREL | 79 |
| Rocky Flats | 78 |
| Chatfield State Park | 78 |
| Fort Collins - West | 77 |
| Highland | 73 |
| Welch | 72 |
| Greeley - Weld Tower | 70 |
| Aspen Park | 70 |
| Rocky Mtn. Nat'l Park | 70 |
| La Casa | 69 |
| CAMP | 69 |
| Aurora East | 69 |
| Fort Collins - CSU | 69 |
| Welby | 67 |
| Boulder Reservoir | -- |

**Figure 1-3. Observed 2016-2018 ozone DVs in the DM/NFR NAA.**

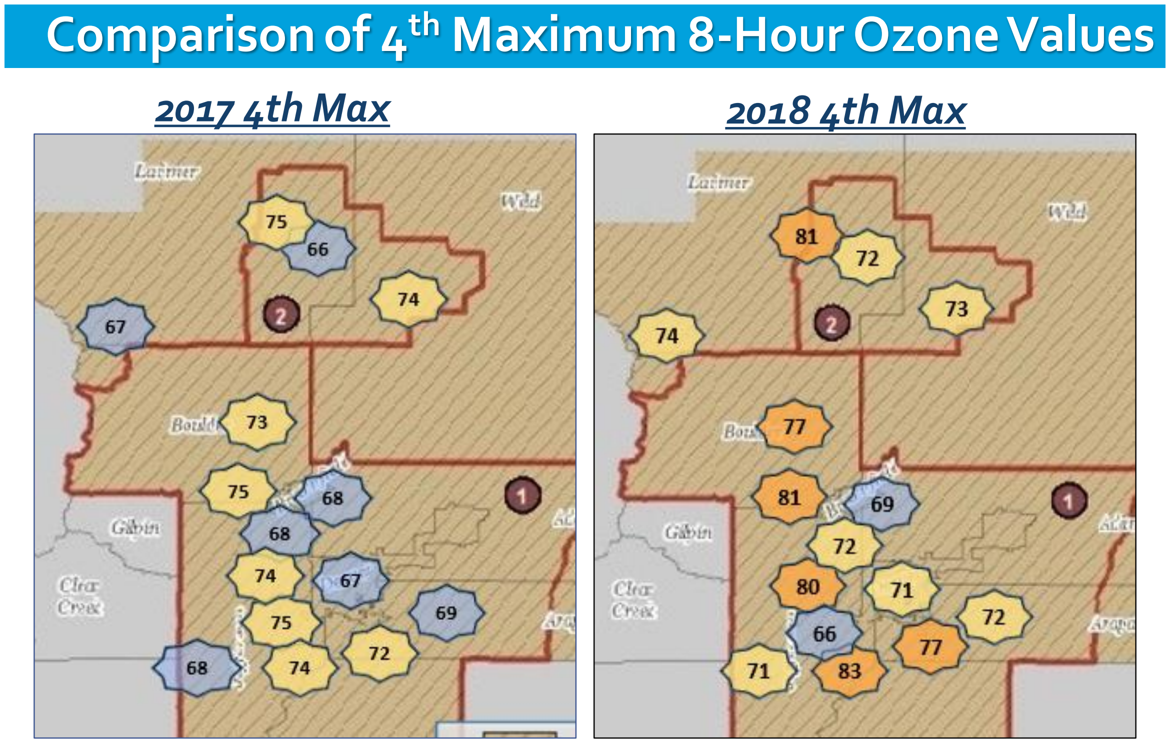



**Figure 1-4. Observed 2017 and 2018 4th highest MDA8 ozone concentrations in the DM/NFR NAA distinguishing between: (1) DM region (southern sites); and (2) NFR region (northern sites).**

### *1.3.3 Conceptual Model of High Ozone Levels in the DM/NFR NAA*

High ozone concentrations events in the DM/NFR NAA are typically associated with specific meteorological conditions that favor optimal ozone photochemistry and limited dispersion. In a recent paper that explores the relationships between meteorology and ozone, Reddy and Pfister (2016) conclude that increases in upper level high pressure strength lead to high July ozone concentrations in much of the western U.S., particularly in areas of elevated terrain near urban sources with high emissions of $NO_2$ and other ozone precursors. In addition to bringing warmer temperatures, upper level ridges in this region reduce westerlies at the surface and aloft and allow cyclic terrain-driven circulations to reduce transport away from sources. Upper level ridges can also increase background concentrations within the ridge. Ozone and $NO_2$ concentrations build locally, and deeper vertical mixing in this region provides a potential mechanism for recapture of ozone in layers aloft. Ozone precursors and reservoir species in large-scale basin drainage flows can be brought back to source areas and nearby mountains by daytime, thermally driven upslope flows. The key elements of a conceptual model for high-concentration episodes along the Front Range include:

- The presence of an upper-level high pressure system or ridge;
- Reduced westerly winds, especially during the day; and

- Thermally-driven upslope flow towards the Continental Divide during the day (i.e., from the east) and downslope drainage flows into the Platte Valley at night.

This diurnal cycle of winds enhances the potential for the accumulation of ozone precursors and ozone within the region, especially when this cyclic pattern recurs over a period of days resulting in the recirculation of pollutants.

Details on the conceptual model of ozone formation in the DM/NFR NAA are provided in a report prepared as part of the 2016 Denver ozone SIP (CDPHE and RAQC, 2016c).

## 1.4 Purpose

This document is the Modeling Protocol for the 2020 and 2023 ozone attainment demonstration modeling for the DM/NFR NAA. It outlines the approach, procedures, participants and other requirements need to conduct photochemical grid model modeling to demonstrate the DM/NFR NAA will achieve the 2008 ozone NAAQS by 2020 and 2015 ozone NAAQS by 2023.

## 1.5 Related Studies

There are numerous other studies related to the Denver 8-hour ozone modeling analysis whose results may be used in the analysis that are summarized below.

### *1.5.1 EPA Modeling Platforms*

EPA routinely develops national PGM modeling platforms that are used to evaluate the air quality impacts of national rules or make transport assessments, such as the Cross-State Air Pollution Rule (CSAPR[4]). The national PGM modeling platforms typically coincide with the triennial National Emission Inventory (NEI[5]) years (e.g., 2008, 2011, 2014). Below we discuss the current (February 2019) status of EPA's more recent national PGM modeling platforms.

2011v6.3 Modeling Platform: The EPA 2011v6.3[6] PGM modeling platform is the most refined and mature of the available platforms and is the result of many years of development and refinements (e.g., v6.0, v6.1 and v6.2[7]). It consists of a base year 2011 meteorological conditions and emissions and three future year emission scenarios: 2017, 2023 and 2028. It is the most fully evaluated, vetted and refined of the modeling platforms available and has been used in numerous EPA rulemakings (e.g., CSAPR Update). As with the other platforms, the 2011v6.3 modeling platform uses a 12-km grid resolution continental U.S. (12US2) modeling domain that is the red domain shown in Figure 1-5.

[4] https://www.epa.gov/csapr

[5] https://www.epa.gov/air-emissions-inventories/national-emissions-inventory-nei

[6] https://www.epa.gov/air-emissions-modeling/2011-version-63-platform

[7] https://www.epa.gov/air-emissions-modeling/2011-version-6-air-emissions-modeling-platforms

2014v7.1 Modeling Platform: The EPA 2014v7.1[8] PGM modeling platform was used in the 2014 National Air Toxics Assessment (NATA[9]) modeling. It also uses the 12-km 12US2 modeling (Figure 1-5, red domain). 2014 was a relatively low ozone year in the DM/NFR NAA as well as across the eastern U.S. so EPA has not pursued using the 2014 platform for national rulemakings (except for the NATA) and is developing a 2016 modeling platform for ozone, $PM_{2.5}$ and regional haze modeling.

2015 Alpha Modeling Platform: EPA has made data available to model 2015 using data based on the 2014v7.1 platform. However, a full 2015 PGM modeling platform is not available from EPA.

2016 Modeling Platform: The EPA and Multi-Jurisdictional Organizations (MJO) are co-performing a 2016 inventory collaborative study to develop a 2016 emissions inventory of comparable quality to the NEI and EPA is developing a 2016 PGM modeling platform. Currently there is a 2016 Alpha[10] platform available that is based mainly 2014v7.1 emissions. The 2016 Beta platform will consist of more year 2016 emissions than 2016 Alpha and is expected to be available in early 2019. The first full version of the 2016 platform (2016v1) is expected to be available in approximately summer 2019. Details on the status of the EPA/MJO 2016 inventory collaborative study is available on the EPA/MJO study's wiki.[11] The 2016 platform is using the 12-km 12US2 domain embedded in a North America 36-km 36US3 domain, that are shown in Figure 1-5.

[8] https://www.epa.gov/air-emissions-modeling/2014-version-71-platform
[9] https://www.epa.gov/national-air-toxics-assessment
[10] https://www.epa.gov/air-emissions-modeling/2016-alpha-platform
[11] http://views.cira.colostate.edu/wiki/wiki/9169

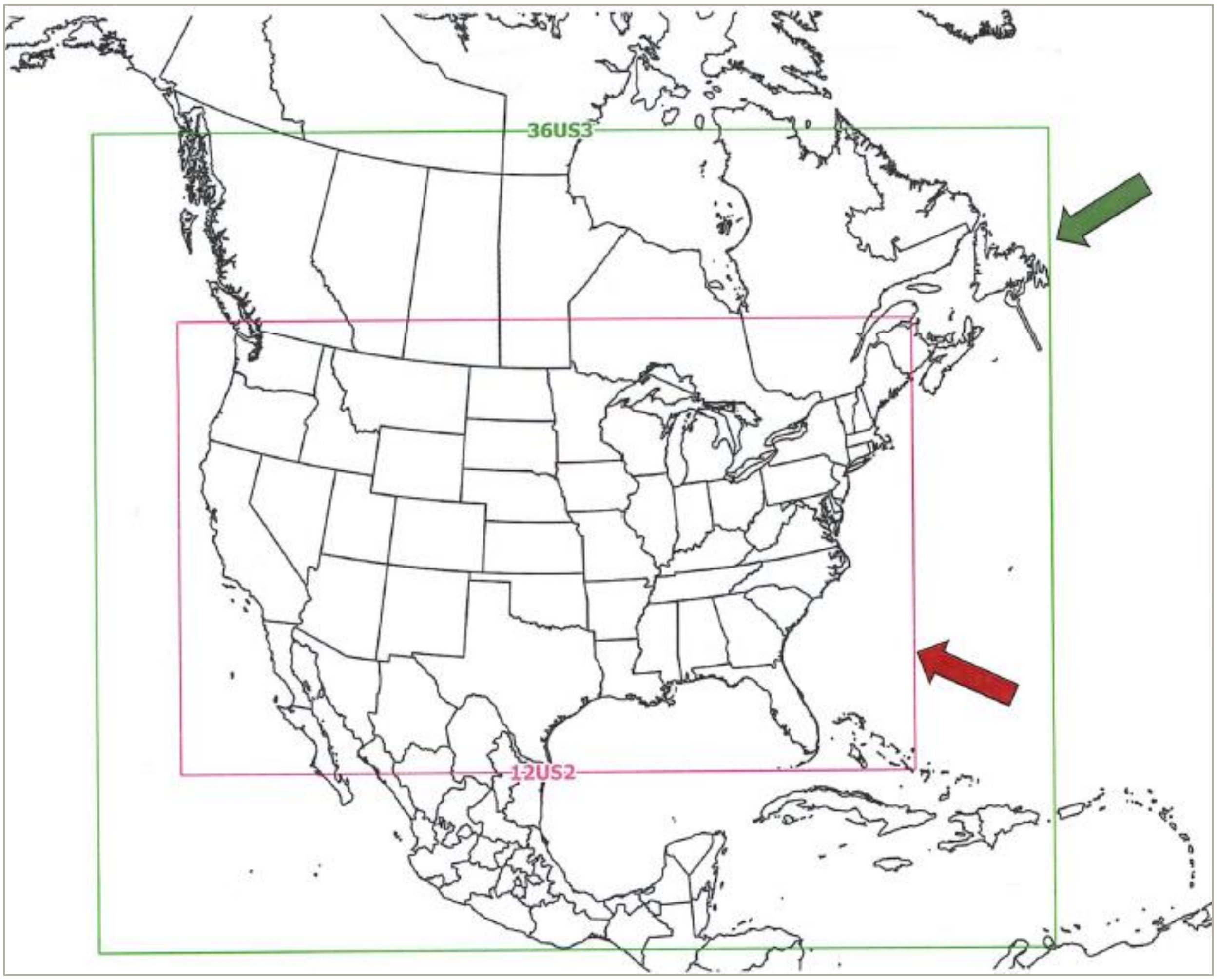



**Figure 1-5. 12-km grid resolution 12US2 domain (red) used in EPA's 2011, 2014, 2015 and 2016 modeling platforms and 36-km grid resolution 36US3 domain (green) that was also used in the EPA/MJO 2016 modeling platform.**

### *1.5.2 2003 Denver EAC SIP Modeling*

The Denver EAC SIP modeling performed 36/12/4/1.33 km photochemical modeling of the DM/NFR NAA for a summer 2002 period using the MM5 meteorological (McNally, Tesche and Morris, 2003), EPS3 emissions and CAMx photochemical grid models. The 1.33-km fine grid was ultimately not used because of little improvement in model performance over using a 4-km resolution grid at the expense of high additional computational requirements. The Denver EAC SIP demonstrated that the region would attain the 1997 ozone NAAQS by 2007 (Morris et al., 2004a,b,c,d). The Denver EAC SIP Ozone Action Plan can be found at:

http://www.colorado.gov/airquality/tech_doc_repository.aspx?action=open&file=EAC_SIP_031104-aqcc_DRAFT.pdf

### 1.5.3 2008 Denver Ozone SIP Modeling

The 2008 Denver ozone SIP modeling used the MM5 meteorological, SMOKE/CONCEPT emissions and CAMx photochemical grid models (Morris et al., 2007). The CONCEPT model was interfaced with link-based Vehicle Miles Traveled (VMT) and other mobile source activity data (e.g., speeds, fleet mix, temporal variations, etc.) from a Traffic Demand Model (TDM) operated by DRCOG, on-road emission factors from the MOBILE6 model and hourly meteorological data from MM5 to generate detailed on-road mobile source emissions for the DMA. Other emission inputs were generated using SMOKE. The MM5/SMOKE/CONCEPT/CAMx modeling system was applied to the June-July 2006 period and used to demonstrate that the DMA/NFR region would attain the 1997 8-hour ozone NAAQS by 2010 (Morris et al., 2008a,b,c; 2009a,b). Details on the 2008 Denver 8-hour ozone SIP modeling can be found at:

https://www.colorado.gov/airquality/documents/deno308/

The 2008 ozone SIP 2006 modeling platform was used to investigate improvements to the modeling system (Morris et al., 2011) and evaluate the VOC/NOx emissions inventory that suggested 2006 oil and gas emissions in Weld County were understated (Morris, Tai and Sturtz, 2011).

### 1.5.4 West-Jump Air Quality Modeling Study

The Western Regional Air Partnership (WRAP) initiated a new round of regional ozone, particulate matter, visibility and deposition modeling for the western U.S. starting with the West-wide Jump Start Air Quality Modeling Study (WestJumpAQMS[12]; ENVIRON, 2011). WestJumpAQMS performed 36/12/4-km modeling for the 2008 calendar year with the 12-km domain focused on the western U.S., and the 4-km domain focused on the states of CO, NM, UT and WY (ENVIRON and Alpine, 2012). The WestJumpAQMS was completed in September 2013 and contains information on the contributions of transport to ozone in the Denver area and contributions of emissions from Colorado (including Denver) to downwind ozone and $PM_{2.5}$ concentrations (ENVIRON, Alpine and UNC, 2013).

### 1.5.5 Intermountain West Data Warehouse and Western Air Quality Study

The WRAP Intermountain West Data Warehouse (IWDW[13]) was developed to be a repository and source of ambient air quality and modelling data that can be used by the western states. The Western Air Quality Study (WAQS) developed 2011 PGM modeling platforms to assess air quality, visibility and deposition in the western states and was used to populate the IWDW. The WAQS started by enhancing the WestJumpAQMS 2008 WRF/SMOKE/CAMx/CMAQ 36/12 km database and making it available through the IWDW. WAQS then developed a new 2011 WRF/SMOKE/CAMx/CMAQ database (Adelman, Shankar, Yang and Morris, 2014; 2016; Adelman and Baek, 2015) that was also made available through the IWDW. IWDW is not only a source of modeling data,

[12] http://www.wrapair2.org/WestJumpAQMS.aspx
[13] http://views.cira.colostate.edu/tsdw/

but also includes data analysis and visualization tools and is a repository of data from other modeling studies.

#### *1.5.6 2016 Denver Ozone SIP Modeling*

The 2016 Denver ozone SIP[14] modeling addressed the 2017 attainment of the DM/NFR Moderate NAA under the 2008 ozone NAAQS (RAQC and CDPHE, 2016). The 2016 ozone SIP used a 2011 36/12/4-km modeling platform based on the WAQS modeling platform with the 4-km domain focused on Colorado (Ramboll and Alpine, 2015; 2016a,b; 2017).

The 2016 Denver ozone SIP 2011 36/12/4-km modeling platform was used to conduct additional future-year sensitivity modeling and other analysis in anticipation of the requirements needed to attain the 2015 ozone NAAQS that was presented at a November 2, 2017 Modeling Forum[15] as follows:

- 2017 local source contributions to ozone concentrations in the DM/NFR NAA;
- Contributions of international anthropogenic emissions to 2011 ozone concentrations in the DM/NFR NAA; and
- Preliminary 2023 ozone projections and sensitivity to VOC/NOx anthropogenic emissions reductions.

#### *1.5.7 Front Range Atmospheric Photochemistry Experiment (FRAPPE)*

During July-August 2014, the National Center for Atmospheric Research (NCAR) conducted the Front Range Atmospheric Photochemistry Experiment (FRAPPE[16]) field study that was also coordinated with NASA's DISCOVER-AQ aircraft measurements. Results of the FRAPPE/DISCOVER-AQ field study were published in a July 2017 Final Report (Pfister and Flocke, 2017[17]). The key findings of FRAPPE were:

- Typical summer high ozone days exhibit upslope winds during the day characterized by transport of emissions to the west and into the mountains. Sometimes a partial separation between air masses originating further north (oil and gas related emissions) and further south (Denver area urban and industrial emissions) were observed; some mixing can occur, especially if the upslope winds have a north-easterly component.
- Specific meteorological conditions such as the Denver Cyclone can have a large influence on the magnitude of ozone production by more efficiently mixing VOC from oil and gas sources with NOx emissions in the urban areas. This causes a different, more local distribution of ozone, concentrated in eastern Boulder, Gilpin, and northern Jefferson counties.
- Mobile sources and oil and gas related emissions are the largest contributors to local ozone production in the DM/NFR NAA. On average, oil and gas emissions show a stronger influence in the northern part of the NAA and the northern foothills, while mobile emissions dominate farther south and in the southern

[14] https://raqc.org/sip/moderate-area-2008-8-hour-ozone-standard-state-implementation-plan/
[15] https://raqc.org/reports/?titlePost=Modeling+Forum
[16] https://www2.acom.ucar.edu/frappe
[17] https://www.colorado.gov/airquality/tech_doc_repository.aspx?action=open&file=FRAPPE-NCAR_Final_Report_July2017.pdf

foothills. Both sectors contribute, on average, 30-40% each to total DM/NFR NAA ozone production on high ozone days.

Industrial emissions contribute somewhat less to DM/NFR NAA ozone on average, but can dominate locally, as is the case in and around Commerce City. NOx from power plant emissions as well as from Denver International Airport causes ozone titration locally due to large NOx emissions in a confined area. Further downwind the additional NOx can result in net ozone production in the western part of the DM/NFR NAA on high ozone days, albeit over a limited area. Reduction of NOx from these sources will result in higher ozone locally and slightly lower ozone in areas further downwind

### *1.5.8 Other Studies*

There are numerous other studies that may also be relevant to the DM/NFR NAA attainment demonstration modeling. The National Park Service (NPS), CDPHE/APCD and others have conducted analysis of air quality and deposition for the Rocky Mountain National Park (RMNP) that included the Rocky Mountain Atmospheric Nitrogen and Sulfur Study (ROMANS) to study nitrogen deposition and potential mitigation scenarios at RMNP. RMNP studies have included data collection, data analysis, modeling and the development of a nitrogen deposition reduction plan. Details on these activities can be found at:

https://www.colorado.gov/pacific/cdphe/rocky-mountain-national-park-initiative

http://www.nature.nps.gov/air/studies/romans.cfm

The Bureau of Land Management (BLM) has conducted several iterations of the Colorado Air Resource Management Modeling Study (CARMMS) using a CAMx 4-km modeling database with a 4-km grid resolution domain covering Colorado. Future year source apportionment modeling was conducted to assess the ozone, $PM_{2.5}$, visibility and sulfur and nitrogen deposition impacts due to oil and gas and mining development on Federal lands in Colorado and northern New Mexico.

https://www.blm.gov/sites/blm.gov/files/documents/files/program_natural%20resources_soil%20air%20water_airco_quicklins_CARMMS2.0.pdf

## 1.6 Overview of the Modeling Approach

The 2020 and 2023 ozone attainment demonstration modeling for the DM/NFR NAA includes emissions, meteorological and ozone model simulations using a nested 36/12/4-km grid with the 4-km grid domain focused on the state of Colorado, including the DM/NFR NAA and vicinity.

### *1.6.1 Episode Selection*

Episode selection is an important component of an 8-hour ozone attainment demonstration. EPA guidance recommends that 10-days be used to project 8-hour ozone Design Values at each critical monitor (EPA, 2018d). The RAQC and CDPHE/APCD specified that the baseline modeling period be either the summer of 2016 or 2017. Based on the analysis in this document, we propose to use the summer of

2016 period (episode) for the 2020 and 2023 attainment demonstration modeling for the following reasons, as explained in more detail in Chapter 3:

- 2016 has higher ozone concentrations than 2017 and the annual 4th high MDA8 ozone for key monitors in 2016 are generally closer to the 2014-2016, 2015-2017 and 2016-2018 ozone DVs than 4th high MDA8 ozone concentration that occurred in 2017;
- 2016 is not an unusually low ozone year (see Figure 1-1);
- Ozone concentrations in 2016 are less influenced by emissions from wildfires than in 2017;
- 2016 emissions are being developed by a joint EPA/MJO study and EPA is developing a 2016 36/12-km PGM modeling platform that can be leveraged to reduce the amount of resources and time needed to develop a completely new modeling platform, as would be needed for 2017.

### *1.6.2 Model Selection*

Details on the rationale for model selection are provided in Chapter 2. The Weather Research Forecast (WRF) prognostic meteorological model was selected for the Denver ozone modeling using a 36/12/4-km resolution grid, with the 4-km grid covering Colorado. Emissions modeling will be performed using the Sparse Matric Operator Kernel Emissions (SMOKE) model for most source categories. The Model of Emissions of Gases and Aerosols from Nature (MEGAN) will be used for biogenic emissions and there are special processors for fires, windblown dust (WBD), lightning NOx (LNOx) and sea salt (NaCl) and Dimethyl Sulfide (DMS) emissions. The 2014 version of the MOtor Vehicle Emissions Simulator (MOVES2014b) on-road mobile source emissions model will be used with SMOKE-MOVES and WRF meteorological data to generate on-road mobile source emissions PGM modeling. The use of link-based vehicle activity data within the DM/NFR NAA will be evaluated (i.e., SMOKE-MOVES/OTIS).

The Comprehensive Air-quality Model (CAMx) and Community Multiscale Air Quality (CMAQ) photochemical grid models (PGMs) will be used. The CAMx model will be the lead model because it supports two-way grid nesting, includes a subgrid-scale Plume-in-Grid module and has ozone source apportionment capabilities. CMAQ will likely be used for 2016 base case modeling and to support the 2020 and 2023 future year attainment demonstration modeling as part of the weight-of-evidence (WOE).

### *1.6.3 Domain Selection*

The same 36-km 36US3 and 12-km 12US2 modeling domains as used in the EPA/MJO 2016 emissions and EPA 2016 modeling platform will be used in the DM/NFR NAA 2020/2023 attainment demonstration modeling (Figure 1-5). The same 4-km grid resolution Colorado domain as used in the 2016 Denver ozone SIP modeling will be used and nested within the 36/12-km grid structure to provide higher resolution within the DM/NFR NAA and throughout Colorado. New 2016 36/12/4-km WRF meteorological modeling will be conducted to provide the higher resolution meteorological fields needed for the 4-km Colorado domain and provided consistent meteorological fields among the three 36/12/4-km nested grid domains.

### 1.6.4 Base and Future Year Emissions Data

The 2016 base year emissions data will be based on the EPA/MJO 2016 Beta or Version 1 emission estimates augmented by 2016 emissions for Colorado provided by the CDPHE/APCD. New emissions will be generated for some natural emission sources (e.g., biogenics and LNOx) as needed. 2020 and 2023 future year emissions will be used for the attainment demonstration modeling as those are the attainment years for a Serious NAA under the 2008 ozone NAAQS, and Moderate NAA under the 2015 ozone NAAQS, respectively.

The EPA/MJO 2016 collaborative emissions and EPA 2016 modeling platform development studies plan to include future year emission projections for 2023 and 2028. For modeling the 2023 future year, the EPA/MJO 2016 platform 2023 anthropogenic emission projections will be used for the 36-km 36US3 and 12-km 12US2 domains. 2023 emissions projections provided by the CDPHE/APCD will be used for the 4-km Colorado domain. SMOKE-MOVES would be run for the 4-km Colorado domain using 2016 4-km WRF data, vehicle activity data approved by CDPHE and 2023 MOVES2014 emissions factor look-up tables for Colorado representative counties. 2023 link-based on-road mobile source emissions modeling may also be performed depending on the evaluation results from the 2016 base case modeling. Natural emissions (e.g., biogenic, LNOx, etc.) will be held constant at 2016 base case levels.

For modeling the 2020 future year, our current plan is to interpolate between the EPA/MJO 2016 platform 2016 and 2023 emission estimate for the 36-km 36US3 and 12-km 12US2 modeling domains and use 2020 emissions provided by the CDPHE/APCD for Colorado. EPA is considering developing 2020 SMOKE-MOVES on-road mobile source and potential other source sector emissions for the 36US3 and 12US2 domains that would be used instead of the interpolated data if available. For the 4-km Colorado domain we would run SMOKE-MOVES using 2020 vehicle activity data, 2020 emissions factors for representative Colorado counties from MOVES2014 and the 2016 4-km WRF data. We would also evaluate the EGU emissions to determine when shut-downs and new generation is expected to occur.

The use of average or typical baseline emissions for fires and EGUs for the 2016 base case and future year (2020 and 2023) modeling when making ozone DV projections may be desirable, but is not currently funded. Since 2016 was a relatively low wildfire year this may not be necessary for fires. An analysis should be conducted to determine when modeled ozone from fire emissions is occurring so that sensitivity analysis could be conducted on their effects (e.g., exclude such days from the ozone projections as part of the weight of evidence).

### 1.6.5 Input Preparation and QA/QC

Quality assurance (QA) and quality control (QC) of the emissions datasets are some of the most critical steps in performing air quality modeling studies. Because emissions processing is tedious, time consuming and involves complex manipulation of many different types of large databases, rigorous QA measures are a necessity to prevent errors in emissions processing from occurring. The DM/NFR 2020 and 2023 attainment demonstration modeling study will perform a multistep emissions QA/QC approach as developed for the WRAP 2002 modeling (Adelman, 2004) and following the procedures in EPA's latest ozone modeling guidance (EPA, 2018a, pp. 60) and Section 2.20 of the SMOKE User's Manuel (UNC, 2018, pp. 94). This includes the initial emissions QA/QC by the CDPHE/APCD of their emissions for Colorado including the DM/NFR NAA and surrounding areas, as well as QA/QC by the RAQC, CDPHE/APCD and the Ramboll/Alpine modeling team as the dataset is processed and made available for modeling.

### *1.6.6 Meteorology Input Preparation and QA/QC*

The CAMx and CMAQ 2016 36/12/4-km meteorological inputs will be based on the 2016 WRF meteorological modeling conducted by the Ramboll/Alpine team. The 2016 36/12/4-km WRF output will be processed by WRFCAMx and MCIP processors to generate meteorological inputs for CAMx and CMAQ, respectively. Details on the DM/NFR 2016 36/12/4-km WRF modeling are provided in Chapter 5.

### *1.6.7 Initial and Boundary Conditions Development*

Initial concentrations (IC) and Boundary Conditions (BCs) are important inputs to PGMs. We intend to run 10-15 days of model spin-up on the 36/12/4-km domains before the first high ozone days occur in the DM/NFR region. This will "wash out" the ICs before the first high ozone day of the summer 2016 modeling episode. BCs for the 36-km 36US3 domain will be based on a 2016 simulation of the GEOS-Chem global chemistry model; the GC2CAMx and GC2CMAQ processors will be used to generate day-specific diurnally varying BCs extracted from the global chemistry model to define the lateral boundaries around the 36-km 36US3 modeling domain (i.e., GCBC). Depending on availability of emissions and resources, for the 2020 and 2023 future year modeling the 2016 GCBCs will either be held constant or new 2020 and/or 2023 GEOS-Chem GCBCs will be used.

### *1.6.8 Air Quality Modeling Input Preparation and QA/QC*

Each step of the air quality modeling will be subjected to QA/QC procedures. These procedures include verification of model configurations, confirmation that the correct data were used and were processed correctly and other procedures. Visualization of model inputs are a critical component of the QA/QC process.

### *1.6.9 Model Performance Evaluation*

The Model Performance Evaluation (MPE) will follow EPA's MPE recommendations in their ozone modeling guidance (EPA, 2007; 2014d; 2018a), other sources (e.g., Simon, Baker and Phillips, 2012; Emery et al., 2016) and use many elements in EPA Region 8's MPE checklist (EPA, 2015a). However, many of the recommendations in EPA's checklist pertain to particulate matter, visibility and deposition model performance that are not the primary focus of the DM/NFR NAA 2020/2023 attainment demonstration modeling whose MPE will focus on ozone and related species. Details on the MPE are provided in Chapter 7.

### 1.6.10 *Diagnostic Sensitivity Analyses*

Depending on the results of the CAMx and CMAQ 2016 base case modeling and MPE, diagnostic sensitivity tests may be conducted to try and improve model performance. The definition of these diagnostic sensitivity tests will depend on the results of the initial MPE.

### 1.6.11 *Weight of Evidence Analyses*

EPA's guidance (EPA, 2018d) recommends three general types of "weight of evidence" (WOE) analyses in support of the future year attainment demonstration: (1) additional modeling analysis, (2) analysis of trends in ambient air quality and emissions, and (3) other models and tools.  The DM/NFR NAA 2020 and 2023 ozone attainment demonstration will include supporting evidence from each of these three types of WOE analysis as described in Chapter 9.

### 1.6.12 *Future Year Control Strategy Modeling*

Future year modeling for ozone will be performed for the 2020 and 2023 future years to demonstrate attainment of the 2008 and 2015 8-hour ozone NAAQS, respectively. The procedures to be used to demonstrate attainment of the ozone NAAQS will follow the EPA's latest guidance (EPA, 2018d).  These procedures use the modeling results in a relative fashion to scale the current year observed 8-hour ozone Design Values (DVCs) to project future year ozone Design Values (DVFs).  The scaling factors are called Relative Response Factors (RRFs) and are the ratio of the future-year to current-year modeling results for the 10 highest base year modeled MDA8 ozone days near the monitoring site.  EPA has developed the Modeled Attainment Test Software (MATS[18]; Abt, 2014) and Speciated Modeled Attainment Test (SMAT[19]) tools that includes the recommended procedures in the latest EPA guidance for projecting ozone DVFs.

Future year control strategy may be performed for the 2020 and 2023 future years. The future year controls will be defined by the RAQC in conjunction with the CDPHE.

### 1.6.13 *Assessment of the Contributions of International Emissions to Ozone in the DM/NFR NAA*

Appendix B describes how the contributions of international emissions to ozone concentrations in the DM/NFR NAA will be estimated.  2016 GEOS-Chem global chemistry simulations will be conducted with and without the contributions of anthropogenic emissions from sources outside of the U.S.  The results from the two 2016 GEOS-Chem simulations will be processed to provide BCs to the CAMx model and two 2016 CAMx 36/12/4-km simulations conducted with and without anthropogenic emissions from Mexico and Canada.  The CAMx 4-km modeling results will be processed to determine the 2016 contributions of international emissions to ozone concentrations and ozone DVs in the DM/NFR NAA.

[18] http://www.epa.gov/scram001/modelingapps_mats.htm

[19] https://www.epa.gov/scram/photochemical-modeling-tools

## 1.7 Project Participants and Contacts

The Denver Regional Air Quality Council (RAQC) and Colorado Department of Public Health and the Environment (CDPHE) Air Pollution Control Division (APCD) are the lead agencies in the development of the DM/NFR NAA 8-hour ozone SIPs. They will work closely with other local agencies, including the Denver Regional Council of Governments (DRCOG), North Front Range Metropolitan Planning Organization (NFRMPO), Colorado Department of Transportation (CDOT), local cities (e.g., Denver and Fort Collins) and other local agencies as well as EPA Region 8 in the SIP development, including the sharing of interim results as they become available. The Denver RAQC has contracted with a modeling team of Ramboll US Corporation (Ramboll), Alpine Geophysics, LLC (Alpine) and Patrick Reddy to perform the DM/NFR NAA 2020/2023 attainment demonstration modeling under direction of and with assistance from the RAQC and CDPHE/APCD. RAQC and CDPHE/APCD will also work with local agencies and stakeholders in the DM/NFR NAA SIP development, where stakeholders include environmental groups and industry. Key participants in the Denver 8-hour ozone study and their contact information are provided in Table 1-1.

**Table 1-1. Key participants and contact information for the DM/NFR 2020 and 2023 ozone attainment demonstration modeling study.**

| Organization | Individual(s) [Roll] | Address | Contact Numbers |
|---|---|---|---|
| **Denver Regional Air Quality Council** | | | |
| RAQC | Mr. Mike Silverstein | Executive Director<br>1445 Market Street, Suite 260<br>Denver, CO 80202 | bus: (303) 629-5450 x250<br>fax: (303) 629-5822<br>e-mail: msilverstein@raqc.org |
| RAQC | Ms. Amanda Brimmer [RAQC Project Manager] | Technical Program Manager<br>1445 Market Street, Suite 260<br>Denver, CO 80202 | bus: (303) 629-5450, x240<br>fax: (303) 629-5822<br>e-mail: abrimmer@raqc.org |
| **Colorado Department of Public Health and Environment (CDPHE) - Air Pollution Control Division (APCD)** | | | |
| CDPHE/APCD | Mr. Curtis Taipale [APCD Contact] | Air Pollution Control Division<br>4300 Cherry Creek Dr. South<br>Denver, CO 80222 | bus: (303) 692-3265<br>fax: (303) 782-5493<br>e-mail: curtis.taipale@state.co.us |
| CDPHE/APCD | Mr. Kevin Briggs [APCD Modeling] | Air Pollution Control Division<br>4300 Cherry Creek Dr. South<br>Denver, CO 80222 | bus: (303) 692-3222<br>fax: (303) 782-5493<br>e-mail: kevin.briggs@state.co.us |
| CDPHE/APCD | Mr. Dale Wells [APCD Emissions] | Air Pollution Control Division<br>4300 Cherry Creek Dr. South<br>Denver, CO 80222 | bus: (303) 692-3237<br>fax: (303) 782-5493<br>e-mail: dale.wells@state.co.us |
| **U.S. EPA Region 8** | | | |
| EPA R8 | Ms. Gail Tonnesen [EPA Contact] | Regional Meteorologist<br>EPA Region VIII<br>Denver, CO | bus: (303) 312-6113<br>fax: (303) 312-6064<br>e-mail: tonnesen.gail@epa.gov |
| **Contractors (modeling team)** | | | |
| Ramboll | Mr. Ralph Morris [Project Manager and Co-Principal Investigator] | Managing Principal<br>7250 Redwood Blvd., Suite 105<br>Novato, CA 94998 | bus: (415) 899-0708<br>e-mail: rmorris@ramboll.com |
| Alpine | Mr. Dennis McNally [Co-Principal Investigator] | Partner<br>7341 Poppy Way<br>Arvada, CO 80007 | bus: (303) 421- 4221<br>fax: (303) 421- 9553<br>e-mail: dem@alpinegeophysics.com |

## 1.8 Communication

Frequent communication between the RAQC, CDPHE/APCD and the modeling team and other participants is anticipated. These communications will include e-mails, conference calls and face-to-face meetings. The RAQC and CDPHE/APCD envisions that EPA and others will review interim products as they become available so that comments can be received during the study to allow for corrective action as necessary. These interim deliverables would include, but not be limited to, preliminary WRF and PGM MPEs, preliminary current and future-year emissions assumptions and results, and preliminary future year 8-hour ozone projections.

## 1.9 Schedule

The schedule for the 2020 and 2023 attainment demonstration modeling depends on the timing of funding sources for the RAQC. The Ramboll Team proposal contained a detailed schedule in Appendix A (Ramboll., 2018). However, that proposal only addressed the 2023 attainment demonstration modeling for the 2015 ozone NAAQS. The 2020 attainment demonstration modeling now has a higher priority so will be done first. Table 1-2 below summarizes a revised proposed schedule through the end of 2019 with key milestone deliverable dates that results in an Air Quality Technical Support Document (AQTSD) for the DM/NFR Serious NAA SIP under the 2008 ozone NAAQS available by the end of 2019. This schedule will likely be revised as the study progresses.

**Table 1-2. Draft schedule for DM/NFR NAA 2020 and 2023 attainment demonstration modeling through 2019 (updated from Proposal to conduct 2020 attainment demonstration modeling first).**

| Work Item | Draft | Final |
|---|---|---|
| Modeling Protocol | Dec 2018 | Feb 2018 |
| WRF 2016 36/12/4-km Meteorological Modeling | Feb 2019 | Mar 2019 |
| 2016 36-km 36US3 Domain Boundary Conditions | Feb 2019 | Mar 2019 |
| 2016 MOVES for Colorado Counties | Feb 2019 | Mar 2019 |
| 2016 4-km Colorado Domain SMOKE-MOVES | Feb 2019 | Apr 2019 |
| 2016 4-km Colorado Domain SMOKE | Mar 2019 | Apr 2019 |
| 2016 36/12/4-km CAMx Base Case and MPE[1] | May 2019 | Jun 2019 |
| 2020 MOVES for Colorado Counties | Jun 2019 | Jul 2019 |
| 2020 4-km Colorado Domain SMOKE-MOVES | Jul 2019 | Aug 2019 |
| 2020 4-km Colorado Domain SMOKE | Jul 2019 | Aug 2019 |
| 2020 3612/4-km CAMx Base Case & Attainment Demonstration[2] | Oct 2019 | Nov 2019 |
| AQTSD for Serious NAA SIP for 2008 NAAQS[3] | Nov 2019 | Dec 2019 |
| **Draft and Final Reports** | | |
| 1. 2016 Base Case Modeling and Model Performance Evaluation<br>2. 2020 Base Case Modeling and Attainment Demonstration<br>3. 2008 Ozone NAAQS Serious Area SIP AQTSD | | |

# 2. MODEL SELECTION

This section introduces the models to be used in the DM/NFR NAA 2020 and 2023 ozone attainment demonstration modeling for the, respectively, 2008 and 2015 ozone NAAQS. The selection methodology presented follows EPA's guidance for regulatory modeling in support of ozone attainment demonstrations (EPA, 2007; 2014d; 2018d). Unlike some of EPA's previous ozone modeling guidance that specified a particular ozone model (e.g., EPA, 1991 that specified the Urban Airshed Model [UAM; Morris and Myers, 1990]), the EPA now recommends that models be selected for ozone SIP studies on a case-by-case basis. The latest EPA ozone guidance (EPA, 2018d) explicitly mentions the CMAQ and CAMx PGMs as the most commonly used PGMs that would satisfy EPA's selection criteria but notes that this is not an exhaustive list and does not imply that they are "preferred" over other PGMs that could also be considered and used with appropriate justification. EPA's ozone modeling guidance lists several criteria for model selection that are paraphrased as follows (EPA, 2018d, pp. 24-27):

- It should not be proprietary;
- It should have received a scientific peer review;
- It should be demonstrated to be applicable to the problem on a theoretical basis;
- It should be used with data bases which are available and adequate to support its application;
- It should be shown to have performed well in past modeling applications;
- It should be applied consistently with an established protocol on methods and procedures;
- It should have a user's guide and technical description;
- The availability of advanced features (e.g., probing tools or science algorithms) is desirable; and
- When other criteria are satisfied, resource considerations may be important and are a legitimate concern.

For the DM/NFR NAA 2020/2023 ozone attainment demonstration modeling, we will use the same WRF/SMOKE/MOVES2014/MEGAN/CAMx modeling system as used in the 2016 Moderate Area SIP for the 2008 ozone NAAQS (RAQC and CDPHE, 2016) as the primary tool for demonstrating attainment of the ozone NAAQS. We also propose to use CMAQ as an alternative model to corroborate the primary modeling as part of the weight of evidence (WOE). The CAMx modeling systems was used in the 2003 EAC (Morris et al., 2004c,b,c,d), 2008 (Morris et al., 2007; 2008a,b,c) and 2016 (Ramboll and Alpine, 2016a,b; 2017a; RAQC and CDPHE, 2017) Denver ozone SIPs for the DM/NFR NAA as well as by the Western Regional Air Partnership (WRAP) West-wide Jump Start Air Quality Modeling Study (WestJumpAQMS; ENVIRON, 2011; ENVIRON and Alpine, 2012; ENVIRON, Alpine and UNC, 2013) and Western Air Quality Study (WAQS; Adelman, Shankar, Yang and Morris, 2014; 2016) so has a long history of demonstrated success for simulating ozone concentrations within the DM/NFR NAA and surrounding areas. The main difference between the modeling system proposed for the

2020/2023 ozone attainment demonstration modeling and that used in the 2017 Denver ozone SIP are updates to the latest versions of the WRF, SMOKE, MOVES, MEGAN, CAMx CMAQ models. Thus, the justification for using these models is similar to those put forward in the Modeling Protocol for the 2016 Denver ozone SIP l (Ramboll and Alpine, 2015).

## 2.1 Meteorological Model

The Weather Research and Forecasting (WRF) Model is a mesoscale numerical weather prediction system designed to serve both operational forecasting and atmospheric research needs (Skamarock, 2004; 2006; Skamarock et al., 2005). The Advanced Research WRF (ARW) version of WRF will be used in the DM/NFR NAA 2020/2023 attainment demonstration modeling study. It features multiple dynamical cores, sophisticated data assimilation system, and a software architecture allowing for computational parallelism and system extensibility. WRF is suitable for a broad spectrum of applications across scales ranging from meters to thousands of kilometers. The effort to develop WRF has been a collaborative partnership, principally among the National Center for Atmospheric Research (NCAR), the National Oceanic and Atmospheric Administration (NOAA), the National Centers for Environmental Prediction (NCEP) and the Forecast Systems Laboratory (FSL), the Air Force Weather Agency (AFWA), the Naval Research Laboratory, the University of Oklahoma, and the Federal Aviation Administration (FAA). WRF allows researchers the ability to conduct simulations reflecting either real data or idealized configurations. WRF provides operational forecasting a model that is flexible and efficient computationally, while offering the advances in physics, numerics, and data assimilation contributed by the research community.

WRF is publicly available, has full documentation and has demonstrated success in simulating meteorological conditions in the DM/NFR NAA and Intermountain West (IMW) to support PGM modeling efforts in numerous studies (e.g., previous Denver ozone SIPs, WestJumpAQMS, WAQS, FRAPPE).

## 2.2 Emissions Models

### *2.2.1 Sparse Matrix Operator Kernel Emissions (SMOKE)*

The Sparse Matrix Operator Kernel Emissions (SMOKE) is an emissions modeling system that generates hourly gridded speciated emission inputs of mobile, non-road, area, point, fire and biogenic emission sources for PGMs (Coats, 1995; Houyoux and Vukovich, 1999; UNC, 2018). As with most "emissions models," SMOKE is principally an emission processing system and not a true emissions modeling system in which emissions estimates are simulated from "first principles." This means that, except for mobile and biogenic sources, its purpose is to provide an efficient, modern tool for converting an existing base emissions inventory data that is typically at the county or point source level into the hourly gridded speciated formatted emission files required by a PGM. SMOKE will be used to prepare emission inputs for non-road mobile, non-point (area) and point sources. SMOKE performs three main functions to convert emissions to the hourly gridded emission inputs for a PGM: (1) spatial allocation, spatial allocates county-level emissions to the PGM model grid cells typically using a surrogate distribution (e.g., population); (2) temporal allocation, allocates annual emissions to time of year (e.g., monthly or seasonally) and day-of-week (typically weekday, Saturday and Sunday); and (3) chemical speciation, maps the emissions to the species in the chemical mechanism used by the PGM, most important for VOC and $PM_{2.5}$ emissions.

### *2.2.2 MOtor Vehicle Emissions Simulator (MOVES)*

The MOtor Vehicle Emissions Simulator (MOVES2014b) is EPA's latest on-road mobile source emissions model that was first released in July 2014 (EPA, 2014a,b,c). MOVES2014 includes the latest on-road mobile source emissions factor information. The DM/NFR 2020/2023 attainment demonstration modeling will use a version 2014b of MOVES (MOVES2014b[20]) with CB6 species that was released in August 2018.

### *2.2.3 SMOKE-MOVES*

SMOKE-MOVES uses an Emissions Factor (EF) Look-Up Table from MOVES, gridded vehicle miles travelled (VMT) and other activity data and hourly gridded meteorological data (typically from WRF) and generates hourly gridded speciated on-road mobile source emissions inputs. SMOKE-MOVES will be used to generate on-road mobile source emissions two ways: (1) a standard SMOKE-MOVES application using representative county data as provided by EPA for outside of Colorado and CDPHE activity data within Colorado to generate on-road mobile source emission inputs for the 36/12/4 km domains; and (2) for the DM/NFR NAA use of SMOKE-MOVES with Colorado-specific MOVES2014/CB6 EF Look-Up Table and gridded vehicle activity data based on link-based travel demand model (TDM) output from DRCOG and NFRMPO.

### *2.2.4 OTIS*

The Open Data Base Connectivity (ODBC) Transportation Inventory System (OTIS) is a model developed by CDPHE/APCD for gridding link-based activity data for use in generating on-road mobile source emissions for conformity demonstrations. The Denver Regional Council of Governments (DRCOG) and North Front Range Metropolitan Planning Organization (NFRMPO) have provided TransCAD TDM output for the DM and NFR regions, respectively. These data include link-specific capacities, volumes, and speeds for a typical weekday for the 10-time periods in each day in the TransCAD model (3 morning peak, 3 afternoon peak, and 4 off-peak time). The OTIS model is a MS Access database application that links MOVES2014 emissions rate lookup tables using the ODBC connection. ODBC is a standard programming language middleware API for accessing database management systems, which is aimed to make it independent of database systems and operating systems. OTIS uses Weekday, Saturday and Sunday-specific link-level volume and speed data by time period from the TDM model and VMT mix to calculate hourly gridded VMT by vehicle type. The lookup tables are queried to retrieve appropriate emissions factors and combined with gridded hourly VMT estimate emissions. OTIS, as used by CDPHE/APCD for calculating mobile source conformity emission budgets, uses constant temperature so does not consider the day-to-day variations of meteorological data on emissions rates as needed for photochemical modeling. For the 2016 Denver ozone SIP, the gridding of link-based

[20] https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100V7H1.pdf

vehicle activity data (e.g., VMT and speeds) feature of OTIS was used with the SMOKE-MOVES model, MOVES2014 emission factors and gridded hourly WRF meteorology to generate on-road mobile source PGM model inputs for the DM/NFR NAA (Morris, Shah and Lindhjem, 2014). For the current 2020/2023 attainment demonstration, we will evaluate the OTIS tool for use in the next round of DM/NFR NAA ozone SIP modeling to determine whether using link-based data for on-road mobile source emissions inputs in the DM/NFR NAA is appropriate given the uncertainties in emissions and additional costs associated with its application and continued maintenance.

#### *2.2.5 Model of Emissions of Gases and Aerosols from Nature (MEGAN)*

Biogenic emissions will be generated using version 3 of the Model of Emissions of Gases and Aerosols from Nature (MEGAN). MEGAN is the latest biogenic emissions model that was originally developed by researchers from the National Center for Atmospheric Research (NCAR) and is currently supported by the University of California at Irvine. MEGAN includes the full range of ozone and PM precursor species from biogenic sources (Guenther and Wiedinmyer, 2004; Wiedinmyer, Sakulyanontvittaya and Guenther, 2007). The DM/NFR NAA 2020/2023 attainment demonstration modeling will use the latest version of MEGAN3 that includes more western states plant emissions data that were implemented by WRAP (Sakulyanontvittaya, Yarwood and Guenther, 2012).

### 2.3 Evaluation of On-Road Mobile Source Emissions in the DM/NFR NAA

The 2003 Denver ozone SIP PGM modeling, using a 2002 modeling platform, exhibited depressed ozone (ozone hole) within the DM urban core that spread downwind and affected monitoring sites where high observed ozone concentrations occurred (e.g., RFNO). This resulted in an ozone underestimations bias in the modeled ozone estimates. Although observed ozone concentrations within the DM urban core were also depressed, the model overstated the spatial extent of the ozone hole. This was due in part to overstated morning NOx emissions; the mobile source modeling tools used a uniform county-level fleet distribution that overstated the fraction of heavy duty diesel trucks (HDDTs) during the morning commute hours. HDDTs have much higher NOx emissions than passenger cars so overstating the fleet fraction of HDDTs in the morning commute results in overstated NOx emissions.

The 2008 ozone SIP (2006 modeling platform) used the CONCEPT emissions modeling system (ENVIRON and Alpine, 2005) that uses link-based vehicle activity and fleet distributions data from the DRCOG/NFRMPO transportation demand model (TDM) output that accounts for spatial and temporal variations in vehicle miles travelled (VMT), cold and hot starts, speeds and fleet distribution. CONCEPT accounted for the fact that the fraction of HDDT vehicles during the morning commute in the DM urban area are lower than average so obtained reduced morning NOx emissions. Use of the link-based vehicle activity resulted in a reduction of the modeled DM urban area ozone hole and improved ozone model performance at the downwind high ozone monitoring sites.

The 2016 Denver ozone SIP (2011 modeling platform) used on-road mobile source emission inputs based on the SMOKE-MOVES tool in Colorado outside of the DM/NFR NAA and used the SMOKE-MOVES/OTIS tool for within the DM/NFR NAA (Morris, Shah and Lindhjem, 2015). As described above, the OTIS tool is custom built for the DM/NFR NAA to provide an interface between the DRCOG/NFRMPO TDM link-based vehicle activity data and SMOKE-MOVES and is not used anywhere else. With the reduction in on-road mobile source VOC and NOx emissions in more recent years it is unclear whether the additional effort in running the SMOKE-MOVES/OTIS tool is warranted given uncertainties in the emissions estimates, the additional costs, the OTIS tool not being supported (unlike SMOKE-MOVES) and there being limited number of people with expertise using the tool. Thus, the use of SMOKE-MOVES vs. SMOKE-MOVES/OTIS for on-road mobile source emissions in the DM/NFR NAA will be evaluated for portions of the 2016 base modeling period. CAMx sensitivity tests will be conducted to determine whether the use of TDM link-based activity data appreciably affects model performance given the uncertainties in emissions, additional costs and other factors.

## 2.4 Photochemical Grid Models

### *2.4.1 Comprehensive Air-quality Model with extensions (CAMx)*

The Comprehensive Air-quality Model with Extensions (CAMx; Ramboll, 2018a) is a state-of-science "One-Atmosphere" multi-scale photochemical grid model capable of addressing ozone, particulate matter (PM), visibility and acid deposition at regional, urban and local scale typically for periods of a year. CAMx is a publicly available open-source computer modeling system for the integrated assessment of gaseous and particulate air pollution. Built on today's understanding that air quality issues are complex, interrelated, and reach beyond the urban scale, CAMx is designed to (a) simulate air quality over many geographic scales, (b) treat a wide variety of inert and chemically active pollutants including ozone, inorganic and organic $PM_{2.5}$ and $PM_{10}$ and mercury and toxics, (c) provide source-receptor, sensitivity, and process analyses and (d) be computationally efficient and easy to use.

The U.S. EPA has approved the use of CAMx for numerous ozone and PM State Implementation Plans throughout the U.S. (including the Denver 2003, 2008 and 2016 ozone SIPs) and has used this model to evaluate regional mitigation strategies including those for most recent national transport rules, such as the Cross-State Air Pollution Rule (CSAPR) and CSAPR Update. The current version of CAMx is Version 6.5, which was released in April 2018 and will be used in the DM/NFR 2020/2023 attainment demonstration study unless a newer version is available at the time of the modeling. Unlike some of EPA's previous ozone modeling guidance that specified a particular ozone model (e.g., EPA, 1991 that specified the Urban Airshed Model [UAM; Morris and Myers, 1990]), the EPA now recommends that models be selected for ozone SIP studies on a case-by-case basis. The latest EPA ozone guidance (EPA, 2018d, pp. 24) explicitly mentions the CMAQ and CAMx PGMs as the most commonly used PGMs that would satisfy EPA's selection criteria but notes that this is not an exhaustive list and does not imply that they are "preferred" over other PGMs that could also be considered and used with appropriate justification. EPA has conducted an analysis of the appropriateness for using CAMx and CMAQ for single-source ozone and secondary $PM_{2.5}$ modeling justifying their use (EPA, 2017c).

### *2.4.2 Community Multiscale Air Quality (CMAQ) Modeling System*

The Community Multi-Scale Air Quality (CMAQ; EPA, 2018e) PGM modeling system will also be used to corroborate CAMx as part of the WOE portion of the attainment demonstration. CMAQ shares many of the science attributes with CAMx (e.g., CB6 photochemistry and ISSOROPIA aerosol thermodynamics), but has some differences (e.g., treatment of particle size distribution and some particulate matter processes). Probably the biggest difference between CMAQ and CAMx are their additional features including probing tools. For example, CAMx has the following features not in CMAQ: (1) a Plume-in-Grid module to treat the near-source chemistry and dispersion of point source plumes; (2) two-way grid nesting; (3) OpenMP multiprocessing capability (both CAMx and CMAQ can use MPI multiprocessing); and (4) more fully tested and useful Ozone and Particulate Source Apportionment Technology (OSAT and PSAT). On the other hand, CMAQ has following features not in the current public released version of CAMx, such as bi-directional ammonia scheme and inline LNOx and WBD emissions.

## 2.5 Final Justification for Model Selection

At the beginning of this Chapter we presented EPA's criteria for model selection (EPA, 2018d). The proposed WRF/SMOKE/MOVES/CAMx-CMAQ modeling system satisfies all of these criteria as follows:

- It should not be proprietary: The WRF[21], SMOKE[22], MOVES[23], MEGAN[24], CAMx[25] and CMAQ[26] models are all publicly available at no cost and can be downloaded from their websites.
- It should have received a scientific peer review: All the models considered have been published in 100s of peer-review journal articles. The CAMx and CMAQ models have been subject to their own peer-review reports[27] and an assessment by EPA that they are suitable for ozone SIP modeling (EPA, 2018d).
- It should be appropriate for the specific application on a theoretical basis: The WRF model was designed to simulate time varying three-dimensional meteorological fields and provide all the meteorological information necessary for ozone modeling. The SMOKE, MOVES and MEGAN models provide the hourly gridded speciated emissions information required for ozone modeling. And the CAMx and CMAQ models were designed to have all the processes necessary to simulate ozone formation in the troposphere.
- It should be used with data bases which are available and adequate to support its application: The procedures outlined for the development of the 2016 modeling platform to support ozone modeling of the DM/NFR NAA use databases that are adequate to support the meteorological, emission and photochemical model applications.

[21] https://www.mmm.ucar.edu/weather-research-and-forecasting-model
[22] https://www.cmascenter.org/smoke/
[23] https://www.epa.gov/moves
[24] http://lar.wsu.edu/megan/
[25] http://www.camx.com/
[26] https://www.epa.gov/cmaq/access-cmaq-source-code
[27] https://hero.epa.gov/hero/index.cfm/reference/details/reference_id/1399874

- It should be shown to have performed well in past modeling applications: The WRF/SMOKE/CAMx modeling system has a demonstrated history in simulating ozone formation in the DM/NFR NAA and surrounding areas including the 2008[28] and 2016[29] Denver ozone SIPs and the WRAP WestJumpAQMS[30] and WAQS[31] modeling projects.
- It should be applied consistently with an established protocol on methods and procedures: The WRF/SMOKE/CAMx application methodology follows the established procedures used in the past (e.g., 2008 and 2016 Denver ozone SIPs and WestJumpAQMS/WAQS discussed above) with enhancements (e.g., larger 36-km 36US3 domain and use of latest model versions).
- It should have a user's guide and technical description: Each of the models cited has a technical description and procedures for application (see websites in footnotes). The CAMx model has an up-to-date and comprehensive user's guide (Ramboll, 2018a) that has a detailed technical description and procedures for application. And the CMAQ model has an operations guide (EPA, 2018e).
- The availability of advanced features (e.g., probing tools or science algorithms) is desirable: One of the reasons for selecting CAMx as the lead PGM over CMAQ is due to the availability of advanced features such as the Plume-in-Grid module and Ozone Source Apportionment Technology (OSAT) in addition to advanced features shared by the two models (e.g., CB6 chemistry and Decoupled Direct Method).
- When other criteria are satisfied, resource considerations may be important and are a legitimate concern: Another reason for selecting CAMx as the lead PGM model over CMAQ is that it is more computationally efficient and supports both MPI and OpenPM multi-processing approaches, whereas CMAQ just supports MPI.

[28] https://www.colorado.gov/airquality/documents/deno308/

[29] https://raqc.org/sip/moderate-area-2008-8-hour-ozone-standard-state-implementation-plan/

[30] http://wrapair2.org/WestJumpAQMS.aspx

[31] http://views.cira.colostate.edu/tsdw/

# 3. EPISODE SELECTION

EPA's current and past 8-hour ozone modeling guidance (EPA, 2007; 2014d; 2018d) contains recommended procedures for selecting modeling episodes for demonstrating attainment of the ozone NAAQS. The DM/NFR NAA 2020/2023 attainment demonstration modeling will use the summer of 2016 as the base year modeling period because it is representative of high ozone conditions and, as presented at the end of this Chapter, 2016 satisfies the most criteria in EPA's modeling guidance episode selection discussion.

Appendix A presents details on some of the technical analysis that is highlighted below used in this Chapter to justify the selection of the summer of 2016 as the base year for the DM/NFR NAA attainment demonstration modeling. The RAQC suggested that the summers of 2016 or 2017 are the candidate base years for the next round of Denver ozone SIP modeling, unless the analysis indicates that neither summer would be appropriate.

## 3.1 Analysis of Historical Ozone and Meteorological Data

To determine which of the two candidate base modeling years to select (2016 or 2017), we analyzed the meteorological and ozone conditions in and around the DM/NFR NAA for a longer period to ensure that the selected baseline year did not represent atypical or unusual conditions.

### *3.1.1 Broad Brush Analysis of Meteorological and Other Conditions in the Western U.S.*

The Regional Technical Operations Working Group (RTOWG) of the Western Regional Air Partnership (WRAP) evaluated the representativeness of several recent years (2014, 2015 and 2016) for their updated annual western regional photochemical modeling platform (Stoeckenius et al., 2018). They noted that for regional air quality planning:

> "As significant resources are required to develop and exercise an annual air quality modeling platform for analysis of the issues of concern (primarily ground-level ozone, particulate matter, regional haze, and nitrogen deposition), it is important to establish the "degree of representativeness", or the degree of difference between calendar base year(s) selected for simulation and analysis….the objective of this study is to compare and contrast the key characteristics of each year analyzed both with respect to each other and with respect to long-term averages"

The key characteristics analyzed included: meteorology (e.g., 500 hPa heights, hydrology, surface temperatures); fires; emissions (EGUs and on-road); air quality (visibility, nitrogen deposition, ozone and PM). The RTOWG study considered a large area of interest (i.e. entire western and central U.S. including the WRAP states and selected adjacent CenSARA states). We extended the analysis to include 2017 so that 4-years (2014-2017) were analyzed in this broad-brush fashion. For some of the key characteristics analyzed, specific years were shown to exhibit particular characteristics. For example, 2015 exhibited severe drought conditions west of Rockies and significant fire activity in western Canada and northwestern U.S. that had impacts on air quality in 2015. 2017 also had large impacts of wildfires on air quality in the western U.S., especially for ozone in the DM/NFR NAA. For many characteristics, however, seasonal variations and regional variations lead the authors to conclude that each year exhibits its own unique characteristics and ideally multiple base modeling years is desirable to capture these differences (Stoeckenius et al., 2018). Neither 2016 or 2017 exhibited anomalous conditions

### *3.1.2 Comparison of 2011-2018 High Ozone Levels in the DM/NFR NAA*

Appendix A presents figures of the maximum (1st highest), 4th highest and average of the 20 highest observed MDA8 ozone concentrations at monitoring sites in the DM/NFR NAA for 2011 through 2018, with the 4th highest MDA8 ozone figure repeated is Figure 3-1 below. There is a lot of year-to-year variability in the ozone trends in the DM/NFR NAA and even spatial variability in the trends across monitoring sites. 2014 and, to a lesser extent, 2017 appear to be dips in the ozone trends with 2018 and earlier years (2011-2013) being high points.

Of the two candidate years, neither 2016 nor 2017 look atypical, although 2016 ozone appears to be higher than average and 2017 lower than average for the most recent years. Based on maximum, 4th highest and 20 highest MDA8 ozone in the DM/NFR NAA, the summer of 2016 appears to be a more appropriate base year than 2017.

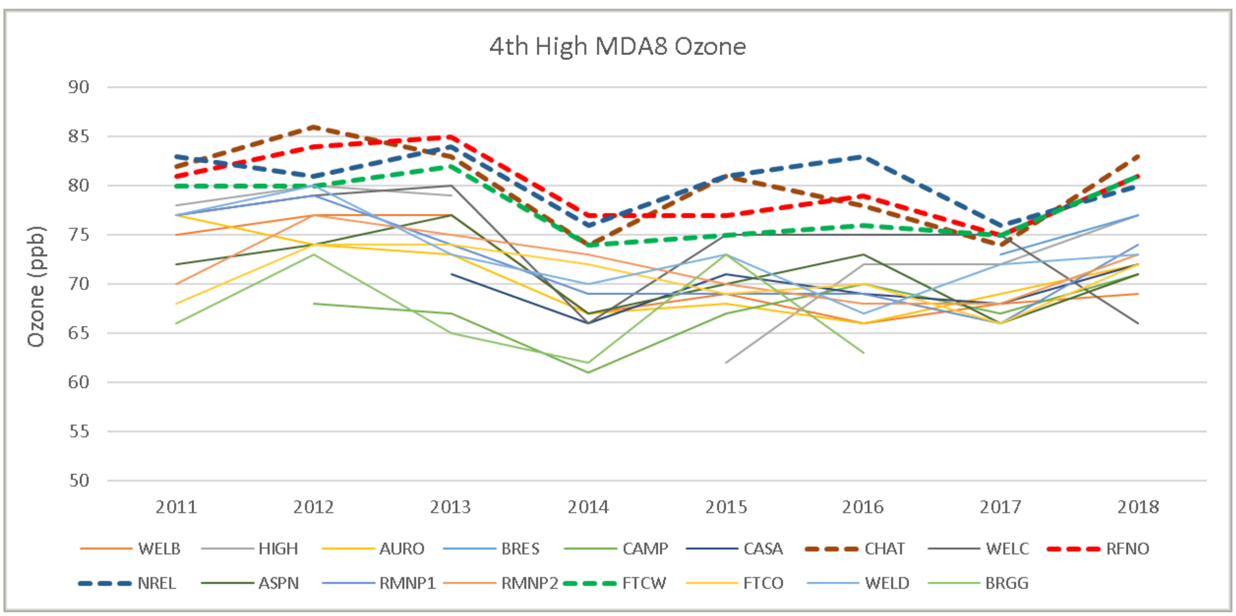



**Figure 3-1. 2011-2018 4th highest MDA8 ozone concentrations at monitoring sites in the DM/NFR NAA.**

### *3.1.3 Trends in Ozone and Meteorological Conditions Conducive to High Ozone in the DM/MFR NAA*

Reddy and Pfister (2016) and CDPHE and RAQC (2016c) analyzed meteorological factors that contributed to the interannual variability in midsummer ozone concentrations focusing mainly on Utah and Colorado. They analyzed ozone and meteorology for July during 1995-2013 and found several meteorological variables that were able to explain the years with higher ozone formation conditions. The most powerful meteorological variable for describing high ozone formation potential conditions (i.e. ozone conducive conditions) was the height of the 500 hPa[32] pressure level.

#### 3.1.3.1 Trends in Summer-Average Ozone and Meteorological Conditions 1995-2018

We extended the analysis of meteorology conducive to ozone formation and observed ozone trends analysis of Reddy and Pfister (2016) and CDPHE and RAQC (2016c) to include the most recent years (through 2018) and for summer-average conditions. Details on this analysis is contained in Appendix A. Figure 3-2 shows the relationship between summer-average 500 hPa heights and summer-average ozone at the RFNO monitoring site and the years 1995-2018, results for the other sites are similar (see Appendix A). Both of the candidate base years have higher than typical summer-average ozone formation conducive conditions as measured by the 500 hPa heights with 2016 having higher 500 hPa heights and ozone than 2017. Although 2016 has some of the highest summer-average 500 hPa heights, it is not atypically high and actually lower than the most recent year (2018) as well as 2012 and just a little bit higher than 2006. Thus, 2016 had meteorological conditions more conducive to ozone formation than 2017 as well as higher summer-average ozone levels at most sites.

[32] hPa is100 Pa where Pa is short for Pascal that is a unit of pressure where 500 hPa = 500 mb.

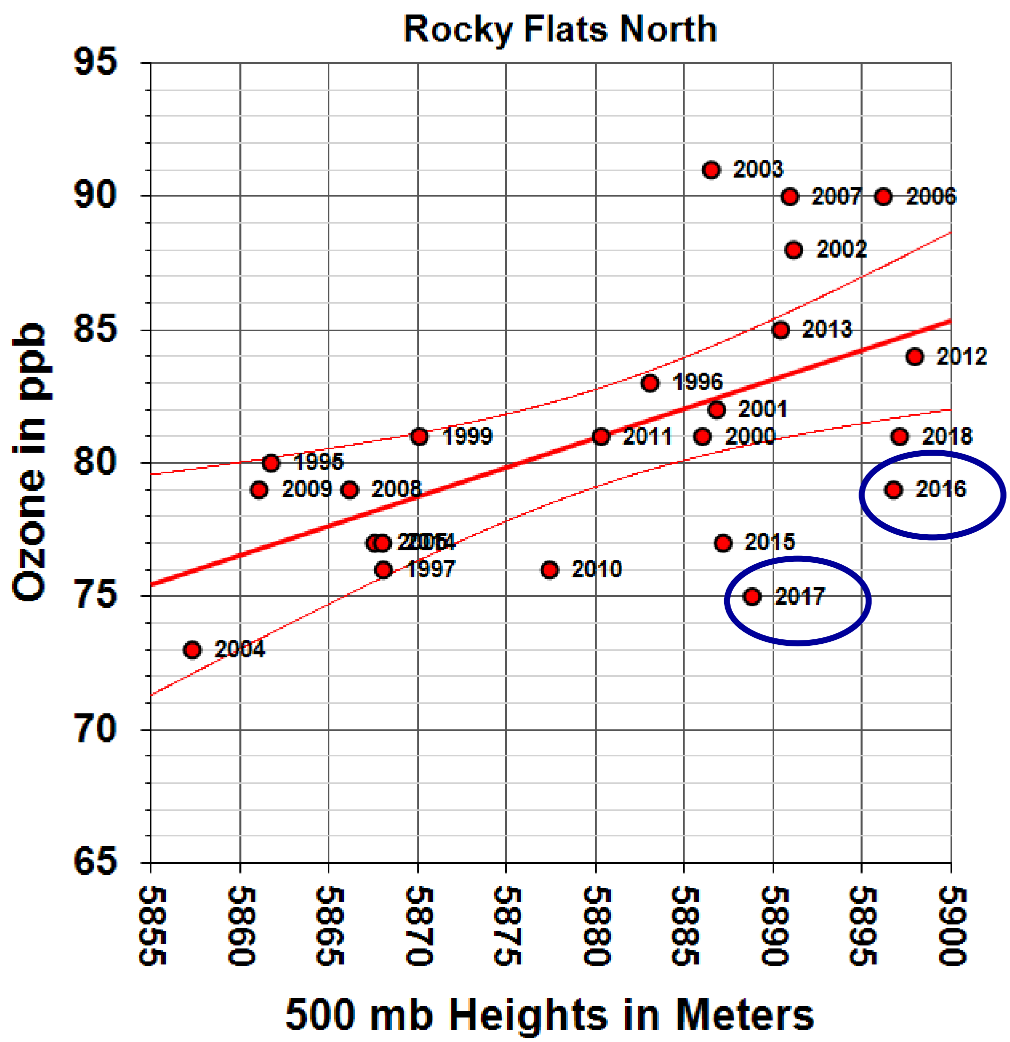



**Figure 3-2. Linear regression of the annual 4th highest MDA8 ozone concentrations and mean July through August NCEP/NCAR Reanalysis 500 hPa (or 500 mb) heights for the DM/NFR region at the Rocky Flats North (RFNO) monitoring site for the years 1995 to 2018.**

#### 3.1.3.2 Trends in Meteorology and Ozone for Days with Highest Ozone during 1995-2018

Appendix A also has details of the analysis of ozone and meteorology for the 20-highest observed MDA8 ozone days at key monitoring sites in the DM/BFR NAA for the years 1995-2018. Figure 3-3 reproduced from Appendix A shows the 500 hPa height versus MDA* ozone concentrations averaged across the 20-highest ozone days at RFNO. The highest 500 hPa height data in this analysis at RFNO occurred in 2003 and 2018, with the lowest values in 1999 and 2004. Although 2004 and 2018 had the same ozone formation conducive meteorological conditions as measured by the 500 hPa height, 2018 has much lower ozone as the emissions were much lower. The two candidate base years have nearly identical 500 hPa heights and ozone for the 20 highest MDA8 ozone that with the 500 hPa heights being higher than average over 1995-2018. Results at NREL and CHAT are similar with 2016 and 2017 having similar 55 hPa heights with 2016 slightly higher ozone for the 20 highest observed MDA8 ozone days (Appendix A). The 2016 500 hPa heights averaged across the 20-highest MDA8 ozone days at FTCW at FTCW are higher than those for 2017, although the average ozone is very similar (Appendix A).

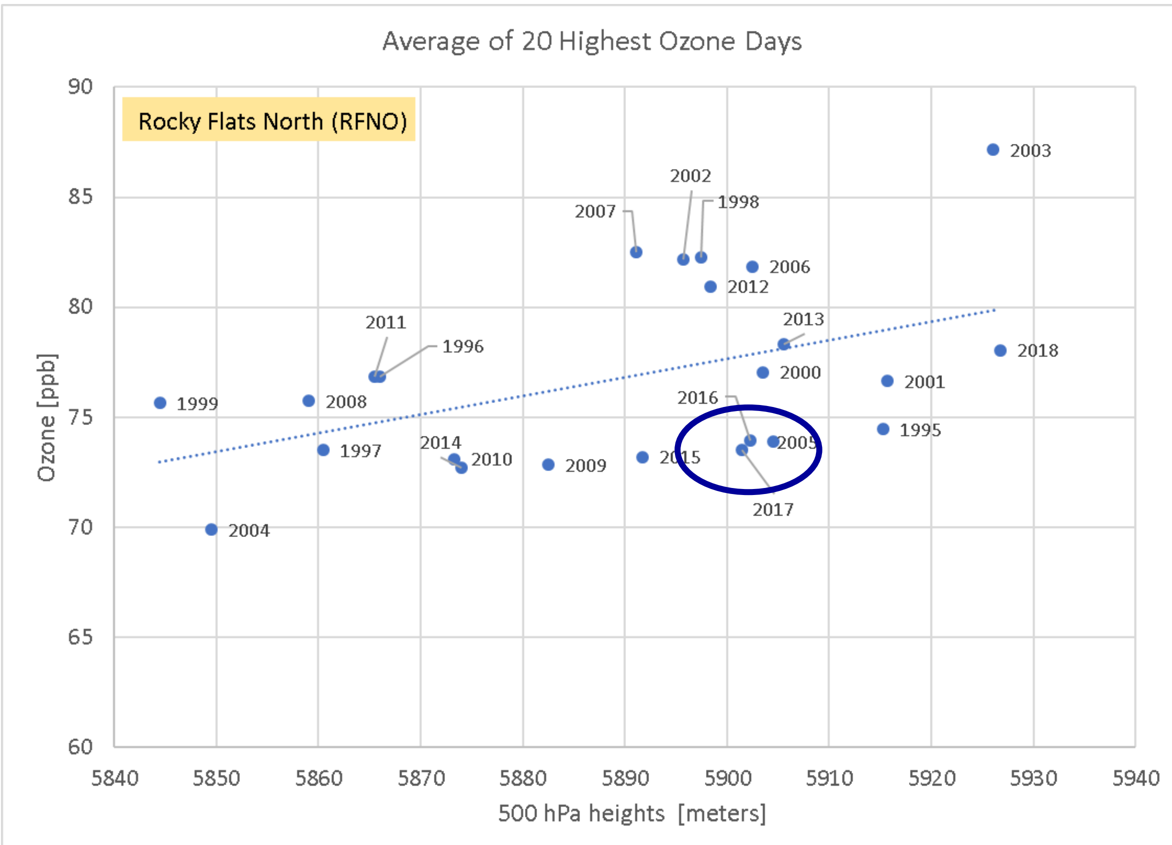



**Figure 3-3. Linear regression of the mean MDA8 ozone concentrations and Denver sounding 500 hPa heights for the 20 highest MDA8 ozone concentrations days at Rocky Flats North (RFNO) monitoring site for the years 1995 to 2018.**

### *3.1.4 Surface Temperatures, Precipitation, Drought and Fires*

Appendix A presents maps and trends of precipitation, surface temperature, drought and fires in the western states with focus on Colorado over 2011-2018. 2016 was not found to be anomalous compared to other years with regard to those parameters. Colorado state-wide precipitation was near average for the 12 months ending in August 2016, whereas for the 12-month period ending in August 2017 precipitation was slightly above average in Colorado. The Colorado June-August average temperatures in 2016 were in the 90$^{th}$ percentile (13$^{th}$ hottest summer in 122 years), but it is in the mid-range of summer temperatures over the 2011-2018 as summers tend to be hotter in more recent years.  Summer of 2017 in Colorado was a little bit cooler but still hotter than average coming in at the 85$^{th}$ percentile over 123 years.  In 2016, June (98$^{th}$ percentile) and July (86$^{th}$ percentile) were much hotter than normal, but August was much cooler (30$^{th}$ percentile), which explains the lower ozone in August 2016.  2016 had approximately half the amount of wildfires in the western U.S. than 2017.

## 3.2 EPA Episode Selection Criteria

EPA's 8-hour ozone SIP modeling guidance (EPA, 2018d) identifies specific criteria to consider when selecting one or more episodes for use in demonstrating attainment of the 8-hour ozone NAAQS.  This guidance builds off the 1-hour ozone modeling guidance (EPA, 1991) and the original (EPA, 2007) and revised draft (EPA, 2014d) 8-hour ozone modeling guidance that recommends selecting multiple episodes representing diverse meteorological conditions that lead to exceedances of the ozone NAAQS in the region under study.

As has been done in previous DM/NFR NAA ozone SIPs (e.g., 2003, 2008 and 2016), an entire summer ozone season will be modeled to capture a wide range of different types of meteorological and emission conditions that lead to observed ozone exceedances at monitoring sites in the DM/NFR NAA.

One EPA criteria, as listed below, is to model a more recent period so that it is representative of current conditions and minimizes the number of years between the base year and the future attainment year.  For the purposes of this discussion we are just considering modeling summer periods from either 2016 or 2017 as specified in the RAQC RFP, unless both years are deemed unrepresentative and inappropriate for use. The 2016 and 2017 years include the 3-year period (2015-2017) for the 8-hour ozone Design Value that failed to attain the 2008 ozone NAAQS as required for a Moderate NAA.  The observed 2014-2016 ozone DVs were used to designate the DM/NFR area as a Marginal NAA under the 2015 ozone NAAQS.  The ozone levels in 2018 are also important as they were too high to grant the DM/NFR another one-year extension to attain the 2008 ozone NAAQS.  Thus, it is relevant to compare the ozone levels in the 2016 and 2017 candidate modeling periods to the 2014-2016, 2015-2017 and 2016-2018 ozone DVs to determine which candidate modeling period is more representative of the ozone DV concentrations levels.

Below we address each of EPA's episode selection criteria (EPA, 2018a, pp. 19) and the justification for using the summer 2016 modeling period over summer of 2017 for the DM/NFR NAA 2020/2023 ozone attainment demonstration modeling.

### *3.2.1 Model a Time Period that Corresponds to a Year with an Available National Emissions Inventory (NEI) and has Air Quality and Meteorological Data Available*

Both the 2016 and 2017 candidate modeling periods have all the routine air quality and meteorological data, available so neither year is preferred over the other based on data availability.

NEI's are prepared every three years. The most recent currently available NEIs are for the 2011 and 2014 years. The 2017 NEI is in preparation and version 1 is currently schedule for release in March 2020, which is too late for this study. Thus, the 2014NEI is the latest NEI available. However, as discussed above, and in more detail below, 2014 had lower ozone than typical in the DM/NFR NAA so would be a poor baseline year choice for ozone attainment demonstration. In fact, 2014 ozone was lower than typical throughout the U.S., which is why EPA decided it was an inappropriate baseline year for addressing national ozone or $PM_{2.5}$ issues. However, 2014 has an advantage that it had special field study database from the FRAPPE study and 2014 is being modeled by WRAP to support Regional Haze SIP modeling.

The EPA and MJOs have embarked on a joint effort to develop a 2016 emissions inventory[33] that includes an update of the 2014NEIv2 to 2016. Current schedule is to release the 2016 Beta emissions inventory and modeling platform in early 2019, which would be in time for use in this study. Thus, the 2016 modeling year has all the same emission data available as an NEI year and will be available in time for this study. Although 2017 is an actual NEI year, the 2017 NEIv1 emissions will be available too late for use in this study (March 2020).

### *3.2.2* Model Time Periods in which Observed Ozone Concentrations are Close to the Appropriate Base Year Ozone Design Values.

Table 3-1 compares the 4th highest MDA8 ozone concentrations during 2016, 2017 and 2018 with the 2014-2016, 2015-2017 and 2016-2018 ozone DVs at the four key monitoring sites in the DM/NFR NAA. The 2017 4th highest MDA8 ozone concentrations are below the 2014-2016, 2015-2017 and 2016-2018 ozone DVs at all sites, except for FTCW, by on average -3% to -4%. The 4th highest MDA8 ozone in 2018 are always above the 2014-2016, 2015-2017 and 2016-2018 ozone DVs (except for NREL and 2014-2016 ozone DV) by on average by +5% and +6%. The 2016 4th highest MDA8 ozone provides the best match with the 2014-2016, 2015-2017 and 2014-2016 ozone DVs, albeit with a high bias that results in average values that match within, respectively +2% to +3%. Thus, the 2016 modeling year is preferred over 2017 that has 4th high MDA8 ozone lower than the DVs. Although an argument could be made to use the 2018 modeling year as it has worst case ozone levels and more meteorological conditions conducive to ozone formation to be conservative, it's conditions could be anomalous, and data availability for such a current year could be an issue.

[33]http://views.cira.colostate.edu/wiki/wiki/9169

**Table 3-1. Comparison of observed 2014-2016, 2015-2017 and 2016-2018 ozone DVs with observed 4th highest MDA8 ozone concentrations in 2016, 2017 and 2018 at the Chatfield (CHAT), NREL. Rocky Flats North (RFNO) and Fort Collins West (FTCW) monitoring sites.**

| Monitoring Site = | CHAT | NREL | RFNO | FTCW | Avg |
|---|---|---|---|---|---|
| **Design Value** | | | | | |
| 2014-2016 | 77 | 80 | 77 | 75 | 77.3 |
| 2015-2017 | 77 | 79 | 77 | 75 | 77.0 |
| 2016-2018 | 78 | 78 | 78 | 77 | 77.8 |
| **4th High MDA8 O3** | | | | | |
| 2016 Ozone | 78 | 83 | 79 | 76 | 79.0 |
| Percent Difference from 2016 Ozone | | | | | |
| %2014-2016 DV | 1.3% | 3.8% | 2.6% | 1.3% | 2.3% |
| %2015-2017 DV | 1.3% | 5.1% | 2.6% | 1.3% | 2.6% |
| %2016-2018 DV | 0.0% | 6.4% | 1.3% | -1.3% | 1.6% |
| 2017 Ozone | 74 | 74 | 75 | 75 | 74.5 |
| Percent Difference from 2017 Ozone | | | | | |
| %2014-2016 DV | -3.9% | -7.5% | -2.6% | 0.0% | -3.6% |
| %2015-2017 DV | -3.9% | -6.3% | -2.6% | 0.0% | -3.2% |
| %2016-2018 DV | -5.1% | -5.1% | -3.8% | -2.6% | -4.2% |
| 2018 Ozone | 83 | 80 | 81 | 81 | 81.3 |
| Percent Difference from 2018 Ozone | | | | | |
| %2014-2016 DV | 7.8% | 0.0% | 5.2% | 8.0% | 5.2% |
| %2015-2017 DV | 7.8% | 1.3% | 5.2% | 8.0% | 5.5% |
| %2016-2018 DV | 6.4% | 2.6% | 3.8% | 5.2% | 4.5% |

## 3.3 Episode Selection Conclusions

Based on an examination of over 20 years of observed meteorological and ozone air quality conditions with particular emphasis on 2011-2018, and an examination of other factors including data availability (e.g., emissions) and the occurrence of fires, the summer ozone season of 2016 is the most appropriate baseline year for conducting 2020 and 2023 DM/NFR NAA attainment demonstration modeling.

Tables 3-2 through 3-6 displays the highest MDA8 ozone concentrations that occurred anywhere in the DM/NFR NAA during each day of May-September and the years 2011-2018. MDA8 ozone concentrations above the 2008 and 2015 ozone NAAQS are shaded, respectively, red and orange, and those in the 65-70 ppb range are shaded yellow. Each year exhibits its own distribution of high ozone days during the ozone season. 2011, 2012 and 2018 exhibit the highest ozone days with an ozone season that begin in May. The highest ozone days occurred during June-August, with 2012, 2013, 2017 and 2018 having high ozone extending into early September, although the two days on September 2 and 4, 2017 that exceeded the 75 ppb 2008 ozone NAAQS were classified as Exceptional Event days due to influences from wildfire emissions.  2016 was characterized by a more compact ozone season than the other years with ozone exceedance days of the 2008 and 2015 ozone NAAQS starting in mid-June and ending in mid-August.  Even with this more compact ozone season in 2016, the ozone levels were still higher and more representative of recent ozone DVs that 2017 (see Table 3-1).  Based on Table 3-2, it is sufficient to model just the June-August 2016 period to capture all the ozone exceedance days in the DM/NFR NAA.

## Table 3-2. 2011-2018 highest MDA8 ozone concentrations in the DM/NFR NAA during May.

| Year | 5/1 | 5/2 | 5/3 | 5/4 | 5/5 | 5/6 | 5/7 | 5/8 | 5/9 | 5/10 | 5/11 | 5/12 | 5/13 | 5/14 | 5/15 | 5/16 | 5/17 | 5/18 | 5/19 | 5/20 | 5/21 | 5/22 | 5/23 | 5/24 | 5/25 | 5/26 | 5/27 | 5/28 | 5/29 | 5/30 | 5/31 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2011 | 55 | 61 | 63 | 72 | 65 | 61 | 71 | 73 | 72 | 77 | 50 | 62 | 64 | 50 | 46 | 55 | 51 | 53 | 51 | 65 | 56 | 56 | 57 | 64 | 57 | 62 | 63 | 62 | 69 | 72 | 77 |
| 2012 | 61 | 64 | 69 | 68 | 70 | 62 | 52 | 67 | 66 | 60 | 55 | 53 | 60 | 71 | 76 | 66 | 73 | 72 | 53 | 65 | 65 | 70 | 63 | 71 | 63 | 79 | 75 | 77 | 78 | 68 | 73 |
| 2013 | 53 | 61 | 61 | 56 | 51 | 61 | 61 | 55 | 55 | 61 | 60 | 66 | 62 | 59 | 61 | 66 | 71 | 66 | 62 | 61 | 60 | 66 | 52 | 73 | 72 | 61 | 67 | 66 | 62 | 64 | 73 |
| 2014 | 59 | 56 | 66 | 68 | 63 | 61 | 58 | 58 | 59 | 60 | 44 | 49 | 53 | 57 | 54 | 50 | 60 | 65 | 65 | 65 | 59 | 59 | 60 | 54 | 67 | 65 | 60 | 69 | 78 | 54 | 61 |
| 2015 | 51 | 61 | 62 | 51 | 44 | 48 | 52 | 39 | 58 | 56 | 61 | 62 | 57 | 62 | 51 | 55 | 53 | 41 | 44 | 40 | 52 | 47 | 62 | 64 | 59 | 52 | 62 | 58 | 59 | 60 | 60 |
| **2016** | **57** | **61** | **64** | **63** | **69** | **64** | **62** | **56** | **58** | **61** | **56** | **61** | **51** | **35** | **47** | **33** | **38** | **51** | **58** | **61** | **67** | **56** | **64** | **59** | **66** | **59** | **51** | **54** | **57** | **60** | **57** |
| 2017 | 54 | 49 | 56 | 65 | 66 | 66 | 59 | 48 | 49 | 43 | 60 | 66 | 67 | 65 | 65 | 59 | 59 | 34 | 46 | 54 | 59 | 57 | 55 | 56 | 54 | 56 | 53 | 58 | 56 | 67 | 71 |
| 2018 | 59 | 47 | 49 | 65 | 62 | 71 | 61 | 70 | 68 | 62 | 61 | 34 | 36 | 55 | 70 | 65 | 72 | 57 | 43 | 52 | 66 | 71 | 68 | 71 | 73 | 77 | 61 | 57 | 66 | 67 | 66 |

## Table 3-3. 2011-2018 highest MDA8 ozone concentrations in the DM/NFR NAA during June.

| Year | 6/1 | 6/2 | 6/3 | 6/4 | 6/5 | 6/6 | 6/7 | 6/8 | 6/9 | 6/10 | 6/11 | 6/12 | 6/13 | 6/14 | 6/15 | 6/16 | 6/17 | 6/18 | 6/19 | 6/20 | 6/21 | 6/22 | 6/23 | 6/24 | 6/25 | 6/26 | 6/27 | 6/28 | 6/29 | 6/30 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2011 | 65 | 58 | 73 | 74 | 66 | 70 | 84 | 56 | 77 | 74 | 65 | 70 | 70 | 74 | 80 | 71 | 69 | 66 | 61 | 50 | 65 | 82 | 70 | 104 | 72 | 64 | 70 | 79 | 65 | 72 |
| 2012 | 64 | 54 | 61 | 67 | 65 | 78 | 71 | 73 | 56 | 74 | 74 | 66 | 72 | 81 | 65 | 68 | 80 | 75 | 74 | 70 | 90 | 101 | 64 | 74 | 76 | 70 | 60 | 61 | 64 | 64 |
| 2013 | 59 | 72 | 62 | 62 | 48 | 69 | 69 | 61 | 81 | 59 | 66 | 82 | 80 | 66 | 72 | 59 | 71 | 73 | 71 | 74 | 71 | 72 | 67 | 66 | 60 | 69 | 71 | 85 | 68 | 64 |
| 2014 | 59 | 74 | 64 | 73 | 71 | 62 | 57 | 52 | 58 | 63 | 59 | 60 | 69 | 60 | 55 | 62 | 58 | 52 | 72 | 79 | 64 | 55 | 69 | 71 | 70 | 82 | 56 | 65 | 74 | 67 |
| 2015 | 61 | 67 | 60 | 71 | 51 | 54 | 68 | 76 | 74 | 62 | 61 | 63 | 61 | 62 | 58 | 53 | 76 | 69 | 71 | 81 | 93 | 68 | 91 | 67 | 81 | 66 | 68 | 77 | 71 | 70 |
| **2016** | **57** | **67** | **62** | **62** | **60** | **62** | **58** | **63** | **67** | **64** | **58** | **59** | **57** | **62** | **77** | **86** | **74** | **80** | **76** | **61** | **74** | **63** | **64** | **66** | **60** | **75** | **83** | **76** | **66** | **60** |
| 2017 | 70 | 59 | 67 | 73 | 62 | 70 | 74 | 76 | 70 | 58 | 63 | 60 | 65 | 64 | 73 | 60 | 51 | 67 | 67 | 59 | 64 | 57 | 54 | 71 | 63 | 71 | 63 | 65 | 64 | 70 |
| 2018 | 65 | 73 | 66 | 65 | 66 | 87 | 67 | 61 | 68 | 69 | 93 | 73 | 86 | 57 | 67 | 67 | 42 | 59 | 56 | 70 | 74 | 56 | 67 | 59 | 71 | 71 | 74 | 64 | 67 | 58 |

## Table 3-4. 2011-2018 highest MDA8 ozone concentrations in the DM/NFR NAA during July.

| Year | 7/1 | 7/2 | 7/3 | 7/4 | 7/5 | 7/6 | 7/7 | 7/8 | 7/9 | 7/10 | 7/11 | 7/12 | 7/13 | 7/14 | 7/15 | 7/16 | 7/17 | 7/18 | 7/19 | 7/20 | 7/21 | 7/22 | 7/23 | 7/24 | 7/25 | 7/26 | 7/27 | 7/28 | 7/29 | 7/30 | 7/31 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2011 | 74 | 78 | 61 | 68 | 73 | 74 | 72 | 67 | 75 | 65 | 67 | 71 | 66 | 65 | 88 | 89 | 77 | 86 | 80 | 61 | 64 | 69 | 73 | 83 | 86 | 75 | 65 | 66 | 77 | 78 | 83 |
| 2012 | 73 | 86 | 75 | 96 | 88 | 73 | 72 | 66 | 69 | 77 | 90 | 75 | 86 | 76 | 74 | 76 | 74 | 67 | 75 | 75 | 77 | 72 | 79 | 78 | 67 | 78 | 69 | 69 | 67 | 64 | 69 |
| 2013 | 65 | 71 | 80 | 58 | 65 | 66 | 72 | 75 | 76 | 87 | 86 | 74 | 70 | 61 | 66 | 80 | 93 | 83 | 75 | 75 | 83 | 79 | 75 | 64 | 51 | 68 | 65 | 49 | 45 | 65 | 71 |
| 2014 | 67 | 76 | 74 | 61 | 61 | 61 | 74 | 74 | 77 | 74 | 68 | 60 | 68 | 70 | 61 | 62 | 74 | 59 | 74 | 65 | 60 | 82 | 62 | 61 | 60 | 66 | 60 | 73 | 65 | 54 | 63 |
| 2015 | 67 | 70 | 85 | 70 | 61 | 46 | 53 | 52 | 65 | 60 | 53 | 58 | 51 | 52 | 56 | 61 | 61 | 65 | 62 | 62 | 54 | 61 | 56 | 52 | 58 | 60 | 65 | 65 | 73 | 78 | 71 |
| **2016** | **52** | **59** | **59** | **60** | **58** | **61** | **80** | **67** | **58** | **63** | **65** | **73** | **71** | **81** | **69** | **79** | **71** | **67** | **75** | **64** | **68** | **72** | **59** | **67** | **89** | **65** | **88** | **75** | **77** | **76** | **58** |
| 2017 | 75 | 74 | 69 | 66 | 78 | 76 | 78 | 74 | 65 | 74 | 72 | 58 | 72 | 75 | 67 | 71 | 71 | 70 | 69 | 76 | 69 | 73 | 77 | 78 | 57 | 71 | 81 | 66 | 57 | 66 | 69 |
| 2018 | 71 | 65 | 69 | 74 | 65 | 88 | 88 | 67 | 77 | 89 | 75 | 71 | 76 | 83 | 44 | 86 | 78 | 79 | 77 | 69 | 73 | 69 | 53 | 78 | 69 | 68 | 65 | 60 | 65 | 70 | 76 |

## Table 3-5. 2011-2018 highest MDA8 ozone concentrations in the DM/NFR NAA during August.

| Year | 8/1 | 8/2 | 8/3 | 8/4 | 8/5 | 8/6 | 8/7 | 8/8 | 8/9 | 8/10 | 8/11 | 8/12 | 8/13 | 8/14 | 8/15 | 8/16 | 8/17 | 8/18 | 8/19 | 8/20 | 8/21 | 8/22 | 8/23 | 8/24 | 8/25 | 8/26 | 8/27 | 8/28 | 8/29 | 8/30 | 8/31 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2011 | 72 | 66 | 71 | 68 | 65 | 67 | 65 | 64 | 79 | 71 | 66 | 82 | 84 | 60 | 63 | 52 | 73 | 65 | 59 | 83 | 69 | 75 | 75 | 73 | 78 | 74 | 80 | 70 | 72 | 68 | 71 |
| 2012 | 68 | 63 | 60 | 66 | 73 | 69 | 73 | 83 | 98 | 78 | 64 | 75 | 65 | 79 | 76 | 59 | 77 | 73 | 75 | 67 | 80 | 67 | 66 | 65 | 80 | 74 | 67 | 68 | 71 | 73 | 80 |
| 2013 | 66 | 68 | 62 | 69 | 70 | 65 | 56 | 58 | 58 | 62 | 62 | 66 | 59 | 62 | 74 | 79 | 87 | 64 | 74 | 76 | 76 | 70 | 70 | 69 | 67 | 60 | 63 | 75 | 86 | 69 | 60 |
| 2014 | 64 | 71 | 78 | 77 | 54 | 62 | 51 | 67 | 60 | 63 | 64 | 69 | 79 | 59 | 56 | 65 | 55 | 63 | 60 | 62 | 60 | 50 | 63 | 73 | 64 | 52 | 53 | 50 | 47 | 51 | 49 |
| 2015 | 79 | 70 | 54 | 58 | 65 | 55 | 77 | 70 | 65 | 66 | 69 | 72 | 60 | 65 | 64 | 65 | 63 | 63 | 64 | 75 | 81 | 61 | 72 | 79 | 78 | 71 | 56 | 63 | 71 | 59 | 50 |
| **2016** | **70** | **74** | **80** | **55** | **58** | **59** | **73** | **59** | **62** | **59** | **65** | **73** | **66** | **68** | **65** | **75** | **69** | **64** | **58** | **56** | **64** | **61** | **57** | **49** | **48** | **61** | **60** | **57** | **57** | **64** | **67** |
| 2017 | 69 | 68 | 49 | 78 | 71 | 58 | 48 | 49 | 68 | 58 | 69 | 58 | 58 | 62 | 59 | 65 | 67 | 77 | 63 | 62 | 63 | 74 | 63 | 56 | 67 | 65 | 71 | 73 | 74 | 76 | 62 |
| 2018 | 76 | 81 | 64 | 67 | 63 | 68 | 72 | 72 | 75 | 78 | 74 | 70 | 86 | 74 | 78 | 81 | 77 | 57 | 59 | 76 | 54 | 61 | 68 | 80 | 67 | 56 | 55 | 60 | 70 | 54 | 49 |

## Table 3-6. 2011-2018 highest MDA8 ozone concentrations in the DM/NFR NAA during September.

| Year | 9/1 | 9/2 | 9/3 | 9/4 | 9/5 | 9/6 | 9/7 | 9/8 | 9/9 | 9/10 | 9/11 | 9/12 | 9/13 | 9/14 | 9/15 | 9/16 | 9/17 | 9/18 | 9/19 | 9/20 | 9/21 | 9/22 | 9/23 | 9/24 | 9/25 | 9/26 | 9/27 | 9/28 | 9/29 | 9/30 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2011 | 68 | 61 | 54 | 59 | 64 | 50 | 56 | 61 | 66 | 64 | 58 | 59 | 53 | 42 | 43 | 56 | 56 | 54 | 52 | 49 | 48 | 55 | 54 | 55 | 55 | 57 | 58 | 59 | 51 | 57 |
| 2012 | 67 | 58 | 53 | 59 | 63 | 59 | 57 | 73 | 79 | 74 | 57 | 38 | 58 | 56 | 52 | 54 | 52 | 65 | 61 | 57 | 58 | 71 | 65 | 45 | 44 | 49 | 49 | 55 | 60 | 52 |
| 2013 | 60 | 73 | 64 | 65 | 68 | 71 | 78 | 81 | 58 | 55 | 42 | 38 | 41 | 46 | 39 | 46 | 59 | 49 | 50 | 58 | 65 | 48 | 50 | 59 | 60 | 54 | 46 | 49 | 49 | 45 |
| 2014 | 65 | 71 | 57 | 58 | 36 | 54 | 48 | 47 | 37 | 49 | 21 | 46 | 59 | 53 | 54 | 63 | 59 | 62 | 73 | 67 | 49 | 44 | 46 | 59 | 68 | 79 | 66 | 52 | 53 | 53 |
| 2015 | 59 | 58 | 46 | 54 | 57 | 51 | 46 | 63 | 68 | 64 | 64 | 64 | 63 | 62 | 39 | 46 | 53 | 56 | 64 | 69 | 64 | 59 | 65 | 60 | 67 | 76 | 63 | 55 | 51 | 51 |
| **2016** | **66** | **51** | **55** | **52** | **54** | **56** | **54** | **59** | **49** | **67** | **54** | **52** | **28** | **40** | **50** | **57** | **59** | **47** | **53** | **54** | **50** | **55** | **60** | **47** | **48** | **53** | **49** | **59** | **59** | **41** |
| 2017 | 62 | 76 | 64 | 78 | 51 | 75 | 71 | 68 | 62 | 64 | 65 | 72 | 62 | 54 | 66 | 59 | 55 | 64 | 63 | 61 | 60 | 51 | 33 | 33 | 30 | 42 | 40 | 39 | 37 | 50 |
| 2018 | 55 | 68 | 62 | 70 | 49 | 50 | 60 | 78 | 58 | 61 | 51 | 58 | 49 | 52 | 60 | 57 | 56 | 63 | 58 | 57 | 68 | 59 | 61 | 50 | 51 | 54 | 60 | 38 | 44 | 0 |

# 4. MODELING DOMAIN SELECTION AND DATA AVAILABILITY

This Chapter summarizes the definition of the horizontal modeling domains for the PGM 2020/2023 ozone attainment demonstration modeling. This includes the map projection, domain coverage, grid resolution and grid nesting for the DM/NFR NAA 8-hour ozone modeling. As the vertical structure of the PGM model will be defined by the vertical structure of the WRF meteorological model, it is discussed in Chapter 5. This Chapter also discusses emissions, aerometric and other data available for use in model input preparation and performance testing.

## 4.1 Horizontal Domain

The DM/NFR NAA 2020/2023 attainment demonstration modeling will use the same 36-km 36US3 and 12-km 12US2 domains as used in the EPA 2016 modeling platform (see Figure 1-1). A 4-km Colorado domain will be added to the 36/12-km domain structure using the same 4-km Colorado domain as used in the DM/NFR NAA 2017 ozone SIP. Figure 4-1 displays the 36/12/4-km domain structure with Figure 4-2 showing the 4-km Colorado domain. New WRF 2016 36/12/4-km meteorological modeling will need to be conducted to generate finer scale 4-km meteorological conditions for the Colorado domain and consistent meteorology among the 36/12/4-km domains.

CAMx will be run using the 36/12/4-km domain structure shown in Figure 4-1 using two-way interactive grid nesting. Note that for the 2017 ozone SIP, CAMx was run using one-way grid nesting between the 36/12-km and 4-km domains so that local controls within the 4-km Colorado domain could be evaluated without the additional computational burden of carrying the 36/12-km domains in the same simulation. However, when examining the contributions of ozone transport from outside Colorado, the CAMx 36/12-km and 4-km domain simulations provided different contributions that were difficult to reconcile. Thus, in this study all CAMx modeling will be performed using two-way grid nesting using all three 36/12/4-km nested domains whether examining the effects of local controls or interstate or international transport. As CMAQ does not support two-way grid nesting, it will be run using a stand-alone 4-km Colorado domain using BCs from a 12-km 12US2 domain CAMx simulation.

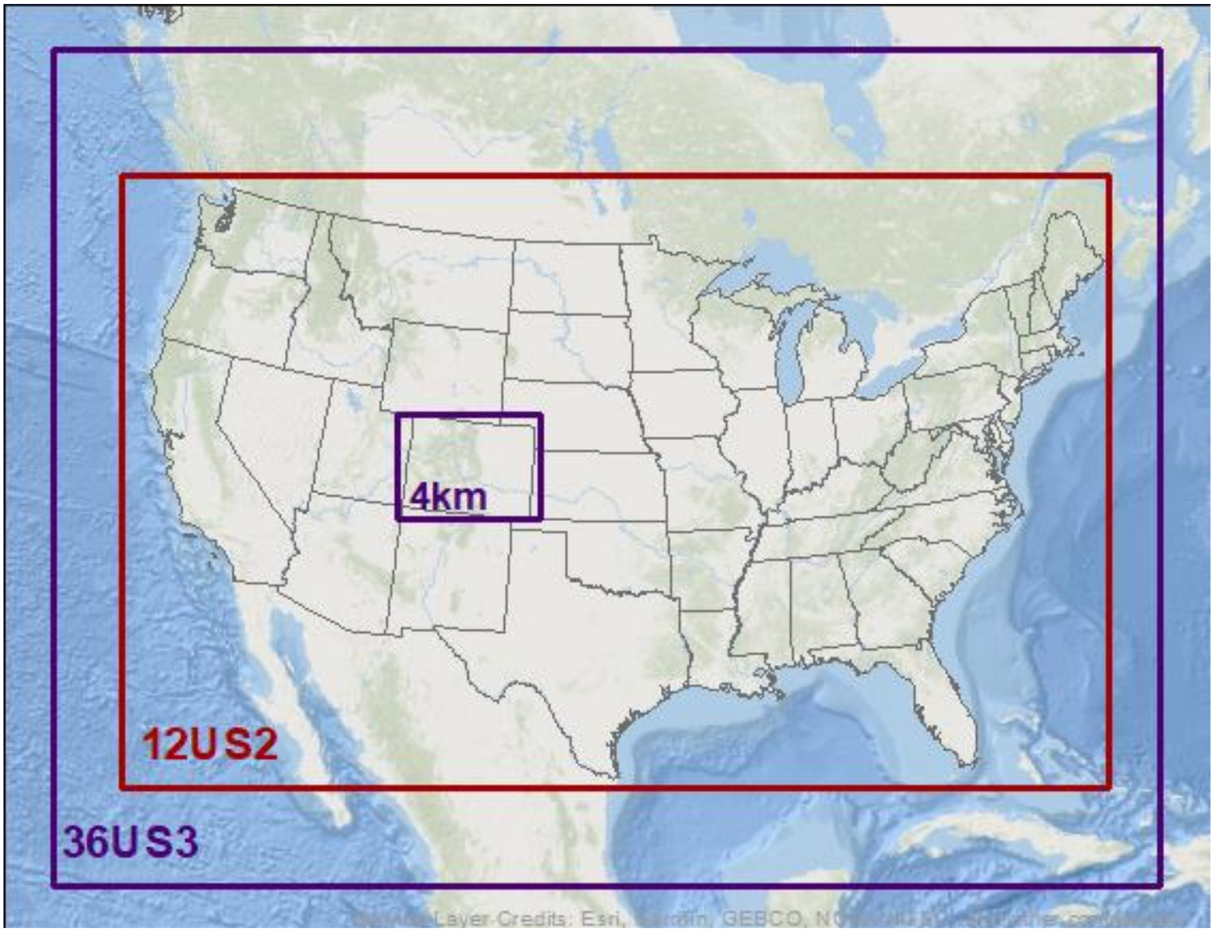



**Figure 4-1. DM/NFR NAA 2020/2023 attainment demonstrations modeling 2016 36/12/4-km PGM and emissions modeling domains.**

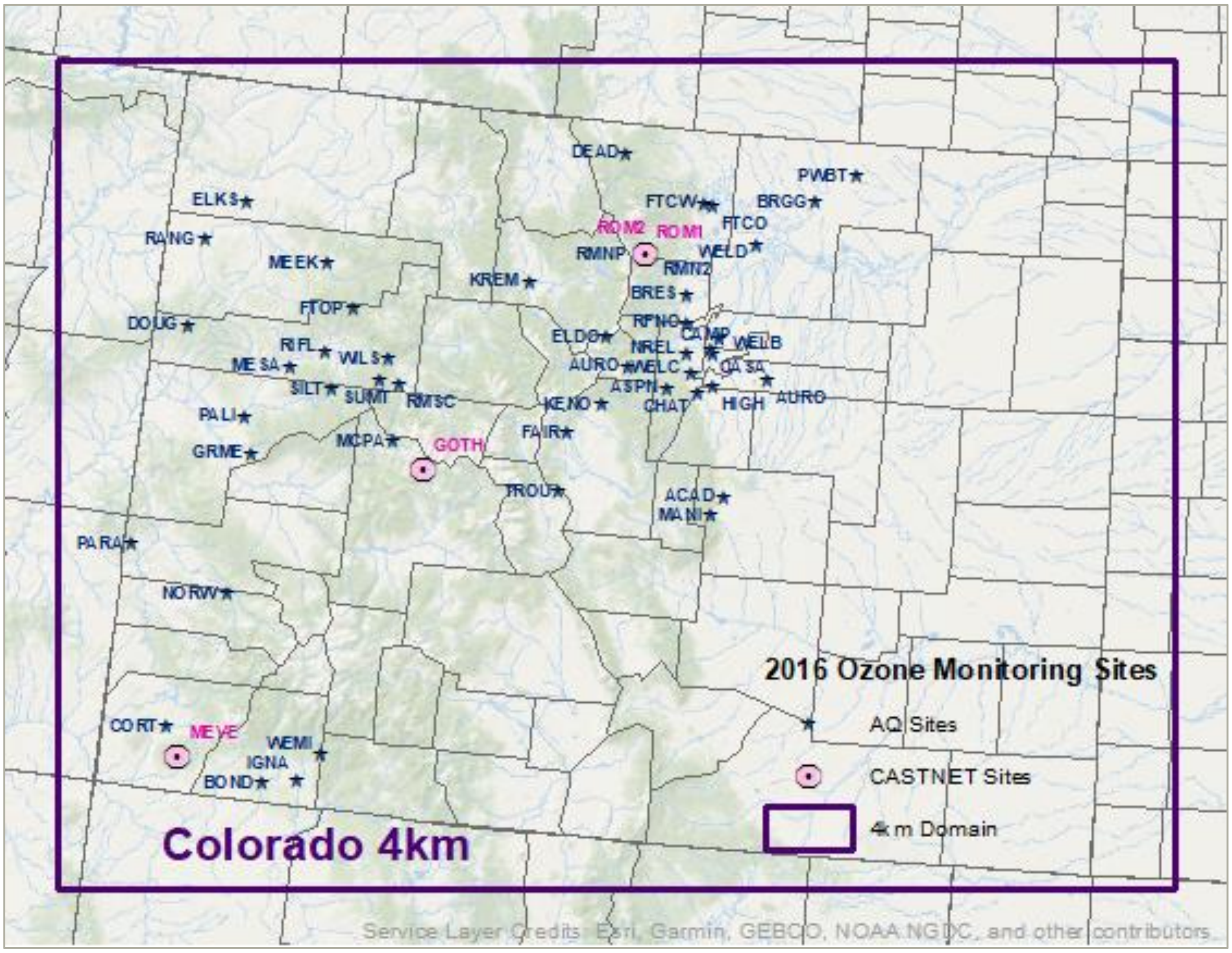



**Figure 4-2. DM/NFR NAA 2020/2023 attainment demonstrations modeling 4-km Colorado domain for PGM and emissions modeling, with locations of ozone monitors that were operating during some portion of 2016.**

**Table 4-1. Projection parameters for the Denver 36/12/4 modeling domains.**

| Parameter | Value |
|---|---|
| Projection | Lambert-Conformal |
| 1st True Latitude | 33 degrees N |
| 2nd True Latitude | 45 degrees N |
| Central Longitude | -97 degrees W |
| Central Latitude | 40 degrees N |

**Table 4-2. Grid definitions for CAMx DM/NFR NAA 2016 36/12/4-km modeling domains.**

| Grid | Origin (SW) (km) | Extent (NE) (km) | NX | NY |
|---|---|---|---|---|
| 36 km | (-2952, -2772) | (3240, 2556) | 172 | 148 |
| 12 km* | (-2412, -1620) | (2340, 1332) | 396 | 246 |
| 4 km* | (-1084, -328) | (-392, 184) | 173 | 128 |

## 4.2 Data Availability

The CAMx and CMAQ PGM modeling systems requires emissions, meteorology, surface characteristics, initial and boundary conditions (IC/BC), and ozone column data for defining the inputs.

### *4.2.1 Emissions Data*

Except for on-road mobile source emissions, the 2016 base year anthropogenic emissions inventory for Colorado will be based on emissions provided by the CDPHE/APCD. For states outside of Colorado, we will use the 2016 inventory developed as part of the EPA/MJO joint 2016 emissions collaborative development effort.[34]

- Major point source $SO_2$ and $NO_x$ emissions will be based off measured Continuous Emissions Monitor (CEM) data that are available online from the EPA Clean Air Markets Division (CAMD[35]) website. These data are hour-specific for $SO_2$, $NO_x$, and heat input. The temporal variability of other pollutant emissions (e.g., PM) from the CEM sources will be simulated using the hourly CEM heat input data using the annual emissions from the 2016 EPA/MJO emissions inventory.
- For 2016 emissions from oil and gas (O&G) production and exploration sources in Colorado, we will use data provided by the CDPHE. Outside of Colorado we will use the EPA/MJO 2016 O&G emission estimates.
- On-road mobile sources will be based on the EPA's MOVES2014 on-road emissions model (EPA, 2014a,b,c). Different procedures will be used for generating on-road mobile source emission inputs within Colorado and outside Colorado as follows.
  - Within Colorado, SMOKE-MOVES would be used with MOVES2014 emission factor (EF) tables using Colorado-specific fleet data, county-level vehicle activity data, hourly 4-km WRF meteorology and spatial surrogates.
    - Within the DM/NFR NAA we will evaluate the use of SMOKE-MOVES/OTIS that uses link-based TDM activity data to determine whether the improved on-road mobile source emissions using link-based activity is worth the additional effort.
  - Outside of Colorado, the EPA 2016 modeling platform on-road mobile source emission inputs will be used for the 36/12-km domains.

[34] http://views.cira.colostate.edu/wiki/wiki/9169
[35] http://www.epa.gov/AIRMARKETS/

- The 2016 fire emissions developed for the EPA/MJO 2016 emissions and/or EPA 2016 modeling platform will be used. If fire emissions for Canada and Mexico are not included in the EPA/MJO 2016 emissions or EPA 2016 platform, the FINN fires will be used for Canada and Mexico.
- 2016 biogenic emissions will be generated for the 36/12/4-km domains using version 3 of the Model of Emissions of Gases and Aerosols in Nature (MEGAN[36]) that was updated by WRAP[37] to include western U.S. plant types.
- Mexico and Canada emissions will be based on the EPA/MJO 2016 modeling platform.

### *4.2.2 Air Quality Data*

Data from ambient air quality monitoring networks for gaseous species are used in the model performance evaluation. Table 4-3 summarizes routine ambient gaseous and PM monitoring networks available in the U.S. Figure 4-2 displays the locations of the routine ozone monitoring sites within Colorado operating during 2016.

36 http://acd.ucar.edu/~guenther/MEGAN/MEGAN.htm

37 http://www.wrapair2.org/pdf/WGA_BiogEmisInv_FinalReport_March20_2012.pdf

## Table 4-3. Overview of routine ambient data monitoring networks.

| Monitoring Network | Chemical Species Measured | Sampling Period | Data Availability/Source |
|---|---|---|---|
| The Interagency Monitoring of Protected Visual Environments (IMPROVE) | Speciated PM25 and PM10 (see species mappings) | 1 in 3 days; 24 hr average | http://vista.cira.colostate.edu/improve/Data/IMPROVE/improve_data.htm |
| Clean Air Status and Trends Network (CASTNET) | Speciated PM25, Ozone (see species mappings) | Approximately 1-week average | http://www.epa.gov/castnet/data.html |
| National Atmospheric Deposition Program (NADP) | Wet deposition (hydrogen (acidity as pH), sulfate, nitrate, ammonium, chloride, and base cations (such as calcium, magnesium, potassium and sodium)), Mercury | 1-week average | http://nadp.sws.uiuc.edu/ |
| Air Quality System (AQS) or Aerometric Information Retrieval System (AIRS) | CO, NO2, O3, SO2, PM25, PM10, Pb | Typically, hourly average | http://www.epa.gov/air/data/ |
| Chemical Speciation Network (CSN) | Speciated PM | 24-hour average | http://www.epa.gov/ttn/amtic/amticpm.html |
| Photochemical Assessment Monitoring Stations (PAMS) | Varies for each of 4 station types. | | http://www.epa.gov/ttn/amtic/pamsmain.html |
| National Park Service Gaseous Pollutant Monitoring Network | Acid deposition (Dry; SO4, NO3, HNO3, NH4, SO2), O3, meteorological data | Hourly | http://www2.nature.nps.gov/ard/gas/netdata1.htm |

### 4.2.3 Ozone Column Data

Additional data used in the air quality modeling include ozone column data from the Ozone Monitoring Instrument (OMI) which continues the Total Ozone Mapping Spectrometer (TOMS) record for total ozone and other atmospheric parameters related to ozone chemistry (OMI officially replaced the TOMS ozone column satellite data on January 1, 2006). OMI data are available every 24-hours and are obtained from the TOMS ftp site.[38] The CAMx o3map program reads the OMI ozone column txt file data and interpolates to fill gaps and generated gridded daily ozone column input data. The OMI data are used in the CAMx (TUV) radiation models to calculate photolysis rates. The CAMx o3map processor also allows for the use of episode and monthly average data, although in this study daily data are used. Note that a new ozone column satellite product is available (OMPS) that may be used if appropriate.

### 4.2.4 Meteorological Data

Meteorological data for PGM modeling will be obtained from the WRF meteorological model as described in Chapter 5.

### 4.2.5 Initial and Boundary Conditions Data

Boundary conditions (BCs) for the PGM 36-km 36US3 domain for both the base and future years will be derived from the output from a 2016 simulation of the GEOS-Chem global chemistry model.

[38] ftp://toms.gsfc.nasa.gov/pub/omi/data/

# 5. WRF METEOROLOGICAL MODELING

This chapter describes how the Weather Research Forecasting (WRF) meteorological model will be used to generate 2016 36/12/4-km meteorological inputs for photochemical grid model (PGM) modeling. The WRF model contains separate modules to compute different physical processes, such as surface energy budgets and soil interactions, turbulence, cloud microphysics, and atmospheric radiation. Within WRF, the user has many options for selecting the different schemes for each type of physical process. The WRF Pre-processing System (WPS) generates the initial and boundary conditions used by WRF, based on topographic datasets, land use information, and larger-scale atmospheric and oceanic models.

## 5.1 Description of WRF

WRF's research and operational application ensures state-of-the-science physics and adaptability to a wide range of environments, through a broad selection of physics options, allowing us to develop the best-performing configuration for simulating meteorology in the region.

The non-hydrostatic version of the Advanced Research version of the Weather Research and Forecast (WRF-ARW) model (Skamarock et al., 2008) is a three-dimensional, limited-area, primitive equation, prognostic model that has been used widely in regional air quality model applications. WRF is a next-generation mesoscale prognostic meteorological model routinely used in urban- and regional-scale photochemical, fine particulate and regional haze regulatory modeling studies. Developed jointly by the National Center for Atmospheric Research (NCAR) and NCEP, WRF is maintained and supported as a community model by researchers and practitioners around the globe. It is suitable for use in a broad spectrum of applications across scales ranging from hundreds of meters to thousands of kilometers.

## 5.2 WRF Model Domain

The PGM (CAMx and CMAQ) 2016 36/12/4-km modeling domains were shown in Figure 4-1 in the previous Chapter. The WRF 2016 36/12/4-km modeling domains will be defined slightly larger than the PGM 36/12/4-km domains so that any modeling artifacts that occur near the WRF boundaries as the BCs come into dynamic balance with the WRF numerical algorithms are not present in the PGM meteorological inputs.

## 5.3 WRF Model Configuration

Below we summarized the proposed WRF configuration and input to be used to generate 2016 36/12/4-km meteorological inputs for the PGM 2020/2023 attainment demonstration modeling. WPS and WRF version 4.0.3 are used for this modeling analysis. Previous Denver ozone SIP modeling, as well as other studies such as the WRAP WestJumpAQMS, WAQS, Southern New Mexico Ozone Study (SNMOS) and EPA modeling platform development, have evaluated different configurations of WRF. Table 5-1 below summarizes the WRF/PGM configurations used in the WAQS 2014 and EPA 2014/2015 WRF modeling. If it is appropriate, it is desirable to match the DM/NFR NAA WRF/PGM grid configuration (e.g., horizontal domains and vertical layer structure) with

EPA's 2016 WRF/PGM grid configuration in order the facilitate the use of data between the two studies. The documentation for the EPA 2016 WRF modeling is not yet available, but we suspect that the EPA 2016 WRF configuration is similar to what EPA used for their 2014 and 2015 WRF modeling. The following paragraphs describe the proposed WRF configuration for the DM/NFR NAA 2020/2023 attainment demonstration modeling.

### *5.3.1 Model Vertical Resolution*

The WAQS WRF modeling that was used in the 2017 Denver ozone SIP modeling used 37 vertical levels from the surface to a 50 mb (hPa) height (approximately 19-km above sea level). The EPA 2014 and 2015 WRF modeling used 36 vertical layers also up to a 50 mb height. Although EPA has released documentation for their 2014[39] and 2015[40] WRF modeling, similar document for their 2016 WRF modeling has not yet been released. It would be advantageous to use the same WRF vertical resolution in the DM/NFR NAA 2016 WRF modeling as used by EPA in their 2016 WRF modeling especially given that it was similar to that used by WAQS in the previous Denver SIP modeling. Figure 5-1 displays the 36-vertical level structure used in EPA's 2014/2015 WRF modeling that is likely the same as used in EPA's 2016 WRF modeling and will be the layer structure proposed for our WRF 2016 36/12/4-km modeling.

[39] https://www3.epa.gov/ttn/scram/reports/WRF_MPE_12km_CONUS_2014_FINAL.pdf

[40] https://www3.epa.gov/ttn/scram/reports/WRF_MPE_12km_CONUS_2015_FINAL.pdf

| WRF Meteorological Model | | | | |
|---|---|---|---|---|
| WRF Layer | Sigma | Pressure (mb) | Height (m) | Thickness (m) |
| 36 | 0.0000 | 50.00 | 19313 | 3423 |
| 35 | 0.0500 | 98.15 | 15890 | 2243 |
| 34 | 0.1000 | 146.30 | 13648 | 1706 |
| 33 | 0.1500 | 194.45 | 11942 | 1392 |
| 32 | 0.2000 | 242.60 | 10551 | 1183 |
| 31 | 0.2500 | 290.75 | 9367 | 1034 |
| 30 | 0.3000 | 338.90 | 8333 | 921 |
| 29 | 0.3500 | 387.05 | 7412 | 832 |
| 28 | 0.4000 | 435.20 | 6580 | 761 |
| 27 | 0.4500 | 483.35 | 5820 | 702 |
| 26 | 0.5000 | 531.50 | 5117 | 652 |
| 25 | 0.5500 | 579.65 | 4465 | 610 |
| 24 | 0.6000 | 627.80 | 3856 | 573 |
| 23 | 0.6500 | 675.95 | 3283 | 541 |
| 22 | 0.7000 | 724.10 | 2742 | 412 |
| 21 | 0.7400 | 762.62 | 2330 | 298 |
| 20 | 0.7700 | 791.51 | 2032 | 289 |
| 19 | 0.8000 | 820.40 | 1742 | 188 |
| 18 | 0.8200 | 839.66 | 1554 | 185 |
| 17 | 0.8400 | 858.92 | 1369 | 182 |
| 16 | 0.8600 | 878.18 | 1188 | 178 |
| 15 | 0.8800 | 897.44 | 1010 | 175 |
| 14 | 0.9000 | 916.70 | 834 | 87 |
| 13 | 0.9100 | 926.33 | 748 | 86 |
| 12 | 0.9200 | 935.96 | 662 | 85 |
| 11 | 0.9300 | 945.59 | 577 | 84 |
| 10 | 0.9400 | 955.22 | 492 | 84 |
| 9 | 0.9500 | 964.85 | 409 | 83 |
| 8 | 0.9600 | 974.48 | 325 | 83 |
| 7 | 0.9700 | 984.11 | 243 | 82 |
| 6 | 0.9800 | 993.74 | 162 | 41 |
| 5 | 0.9850 | 998.56 | 121 | 40 |
| 4 | 0.9900 | 1003.37 | 80 | 40 |
| 3 | 0.9950 | 1008.19 | 40 | 20 |
| 2 | 0.9975 | 1010.59 | 20 | 20 |
| 1 | 1.0000 | 1013 | 0 | |

**Figure 5-1. WRF 36 level vertical layers structure used in EPA's 2014 and 2015 WRF modeling. We would likely use a similar WRF layer structure for the DM/NFR NAA 2016 36/12/4-km WRF modeling.**

### 5.3.2 Topographic Inputs

Topographic information for WRF will be based on a combination of the standard WRF terrain databases and high-resolution terrain. The 36-km 36US3 domain will use the 10-minute global data, the 12-km e 12US2 domain will use the 2-minute data, and the 4-km Colorado domain will use the 30 second data.

### 5.3.3 Vegetation Type and Land Use Inputs

Vegetation type and land use information will use the United States Geological Survey (USGS) land use databases from the most recently released WRF databases provided with the WRF distribution. Standard WRF surface characteristics corresponding to each land use category were employed.

### 5.3.4 Atmospheric Data Inputs

WRF relies on other model or re-analysis output meteorological fields to provide initial and boundary conditions (IC/BC) and fields for the four-dimensional data assimilation (FDDA). FDDA refers to the nudging of the WRF meteorological fields to observed analysis fields so that the WRF meteorological fields better represent what was observed and prevent the model from drifting away from the observed meteorology. As seen in Table 5-1, both the WAQS 2014 and EPA 2014/2015 WRF modeling used the 12-km resolution North American (NAM) analysis fields for IC/BC and analysis nudging. However, the NAM 12-km analysis fields do not extend far enough north for use with the 36-km 36US3 domain. Thus, we propose to use the ~70 km European Center for Medium-Range Weather Forecasting (ECMWF) Re-Analysis (ERA[41])-Interim or ERA5 dataset analysis fields for IC/BC and FDDA. We have found from previous work that the ERA-Interim dataset has lower humidity near the surface and higher humidity aloft, leading to lower convective available potential energy (CAPE), which lowers overall precipitation rates, especially during the summer Monsoon season that is vitally important to the Denver ozone modeling. Many WRF simulations of the southwest U.S. summer Monsoon have featured an over-prediction of summertime (convective) precipitation when the NAM analysis fields are used. The Southern New Mexico Ozone Study (SNMOS) conducted PGM ozone sensitivity modeling using meteorological fields based on WRF simulations using the NAM and ERA analysis fields and found that the PGM ozone performance using the WRF/ERA meteorological inputs produced superior ozone performance than when WRF/NAM inputs were used.[42]

The ERA5 is a fairly new analysis fields product that has not been used in WRF modeling as extensively as the ERA fields. We will conduct WRF and PGM sensitivity modeling using the ERA and ERA5 analysis fields to determine which configuration provides the best meteorological inputs and potentially resultant ozone model performance. The ERA/ERA5 fields will be objectively re-analyzed using meteorological observational data to the higher resolution for the 36-km and 12-km grid domains using the OBSGRID program. These fields are used both to initialize the model and used with analysis nudging (on selected domains) to guide the model to best match the

[41] https://www.ecmwf.int/en/forecasts/datasets/archive-datasets/reanalysis-datasets/era5

[42] https://www.wrapair2.org/SNMOS.aspx

observations. The initialization dataset with the best WRF performance will be chosen for the final configuration.

### 5.3.5 Time Integration

Third-order Runge-Kutta integration will be used (rk_ord = 3). The maximum time step, defined for the outer-most domain (36 km) only, should be set by evaluating the following equation:

$$dt = \frac{6dx}{F_{map}}$$

Where dx is the grid cell size in km, Fmap is the maximum map factor (which can be found in the output from REAL.EXE), and dt is the resulting time-step in seconds. For the case of the 36 km RPO domain, dx = 36 and Fmap = 1.08, so *dt* should be taken to be less than 200 seconds. Longer time steps risk CFL errors, associated with large values of vertical velocity, which tend to occur in areas of steep terrain (especially during stable conditions typical of winter). For this WRF run, adaptive time-stepping will be used with a maximum timestep of 180s.

### 5.3.6 Diffusion Options

Horizontal Smagorinsky first-order closure (km_opt=4) with sixth-order numerical diffusion and suppressed up-gradient diffusion (diff_$6^{th}$_opt=2) will be used.

### 5.3.7 Lateral Boundary Conditions

Lateral boundary conditions will be specified from the initialization dataset on the 36-km 36US3 WRF domain with continuous updates nested from each "parent" domain to its "child" domain, using one-way nesting (feedback=0).

### 5.3.8 Top and Bottom Boundary Conditions

The implicit Rayleigh dampening for the vertical velocity will be used for the top boundary conditions. Consistent with the model application for non-idealized cases, the bottom boundary condition was selected as physical, not free-slip.

### 5.3.9 Sea Surface Temperature Inputs

The water temperature data for the refined WRF configurations will be taken from either the Fleet Numerical Meteorology and Oceanography Center (FNMOC)[43] or the NASA Global 1-km Sea Surface Temperature (G1SST)[44]. The FNMOC product has horizontal resolution of about 9-km in the mid-latitudes but is produced *four* times per day using AVHRR satellite sensors and in-situ observations. The G1 dataset has a 1-km resolution but is only produced once per day.

### 5.3.10 FDDA Data Assimilation

Analysis nudging will be used for winds, temperature, and humidity on the 36-km and 12-km domains. Both surface and aloft nudging will be used but nudging for

[43] http://www.usgodae.org/cgi-bin/datalist.pl?summary=Go&dset=fnmoc_ghrsst
[44] http://podaac.jpl.nasa.gov/dataset/JPL_OUROCEAN-L4UHfnd-GLOB-G1SST

temperature and mixing ratio will not be not performed within the boundary layer. Observation nudging within the 4-km Colorado domain will be performed for winds, temperature, and humidity, but no analysis nudging will be performed within the 4-km domain. Observation nudging will be performed using the Meteorological Assimilation Data Ingest System (MADIS) observation archive, using both near-surface and profiler subsets.

### *5.3.11 New Lightning Data Assimilation*

More recently, the assimilation of lightning data in WRF simulations has been shown to improve the locations and amounts of convective precipitation. The use of lighting detection networks, such as the National Lightning Detection Network (NLDN) have been used in WRF simulations and used to force deep convection (thunderstorms) when lightning is observed and only allow shallow convection when lightning is not present. The use of the new lightning assimilation approach has been demonstrated to improve both WRF convective precipitation as well as PGM concentration and deposition performance (Heath et al., 2016). We will investigate the use of lightning data assimilation in WRF and if data are available and it is easy to implement will conduct a sensitivity test on its use and use it in final WRF 2016 36/12/4-km simulations if appropriate.

### *5.3.12 PBL and LSM Physics Options*

The YSU Planetary Boundary Layer (PBL) and Noah Land Surface Model (LSM) physics options will be used in the DM/NFR NAA WRF 2016 36/12/4-km modeling. Previous WRF sensitivity modeling for the IMW region, including the DM/NFR NAA, found the YSU/Noah PBL/LSM schemes produces the most realistic meteorological fields. Note that EPA’s 2014 and 2015 (and presumably 2016) WRF modeling uses the ACM2 PBL and Pleim-Xiu (PX) LSM schemes (Table 5-1). The WAQS tried to evaluate WRF using the ACM2/PX PBL/LSM and found it more difficult to implement and didn’t always run so that annual fields could not be generated. Furthermore, the PX LSM scheme requires each run segment of a WRF run soil moisture inputs to be initialized using the previous WRF run segment PX output so that an annual WRF simulations must be run in series. This contrasts with the Noah LSM scheme that initializes soil moisture based on observations with some spin-up time (typically 12-hours) that allows annual WRF runs to be performed using parallel run segments (e.g., 5.5 day run segments). Thus, annual WRF simulations using the YSU/NOAH PBL/LSM physics options can be completed much faster than when ACM2/PX is used.

### *5.3.13 Remaining WRF Physics Options*

Table 5-1 lists the remaining WRF physics options for the DM/NFR NAA 2016 36/12/4-km WRF application. These are standard WRF physics options and consistent with the WRF options used in the WAQS 2014 and EPA 2014/2015 WRF modeling.

**Table 5-1. Proposed DM/NFR NAA 2016 WRF model configuration and comparison with the WRF configuration used in the WAQS 2014 and EPA 2014/2015 WRF modeling.**

| WRF Option | Proposed 2016 DM/NFR | 2014 WAQS | 2014/2015 EPA |
|---|---|---|---|
| Domains run | 36/12/4-km | 36/12/4-km | 12-km |
| Microphysics | Thompson | Thompson | Morrison 2 |
| LW Radiation | RRTMG | RRTMG | RRTMG |
| SW Radiation | RRTMG | RRTMG | RRTMG |
| Sfc Layer Physics | MM5 similarity | MM5 similarity | MM5 similarity |
| LSM | Noah | Noah | Pleim-Xiu |
| PBL scheme | Yonsei University (YSU) | YSU | ACM2 |
| Cumulus | 36/12-km Kain Fritsch; 4-km None | 36/12-km Multi-scale_Kain Fritsch; 4-km None | Kain-Fritsch |
| BC, IC Analysis Nudging Source | GFS | 12-km NAM | 12-km NAM |
| Analysis Nudging Grids | 36/12-km | 36/12-km | 12-km |
| Obs Nudging | 4-km | 4-km | None |
| Sea Sfc Temp | RTG | FNMOC | FNMOC |

### *5.3.14 Application Methodology*

The WRF model will be executed in 5.5-day blocks initialized at 12Z every five days. Model results will be output every 60 minutes, split at twelve (12) hour intervals. Twelve (12) hours of spin-up is included in each 5-day block before the data is used in the subsequent evaluation and PGM meteorological inputs.

## 5.4 WRF Model Evaluation

Quantitative and qualitative evaluations of the DM/NFR NAA WRF simulations will be conducted. The quantitative evaluations compare integrated surface hourly meteorological observations with WRF predictions matched by time and location. The qualitative evaluations compared time series plots of modeled wind speed and wind direction to the observations at specific sites. The evaluation is conducted for meteorological observation sites across the western U.S. with particular focus on sites within the 4-km Colorado domain and the DM/NFR NAA.

### *5.4.1 Quantitative Evaluation Using METSTAT*

A quantitative model performance evaluation of the DM/NFR NAA 2016 WRF modeling will be performed using the publicly-available METSTAT software (Ramboll Environ,

2015) evaluation tool. Output from meteorological models will be compared against meteorological observations from the various networks operating in the study area. This is carried out both graphically and statistically to evaluate model performance for surface winds, temperatures, humidity, and the placement, intensity, and evolution of key weather phenomena. The purpose of these evaluations is to establish a first-order acceptance/rejection of the simulation in adequately replicating the weather phenomena in the study area. Thus, this approach screens for obvious model flaws and errors.

#### 5.4.1.1 Quantitative Statistics

The quantitative analysis will be conducted using METSTAT. Statistical measures calculated by METSTAT include observation and prediction means, prediction bias, and prediction error that are given as follows.

Mean observation ($M_o$) is calculated using values from all sites for a given time period by Eq. **(5-1)**:

$$M_o = \frac{1}{IJ}\sum_{j=1}^{J}\sum_{i=1}^{I} O_j^i \qquad (5\text{-}1)$$

where $O^i_j$ is the individual observed quantity at site *i* and time *j*, and the summations are over all sites ($I$) and over time periods ($J$).

Mean Prediction ($M_p$) is calculated from simulation results that are interpolated to each observation used to calculate the mean observation for a given time period by Eq. **(5-2)**:

$$M_p = \frac{1}{IJ}\sum_{j=1}^{J}\sum_{i=1}^{I} P_j^i \qquad (5\text{-}2)$$

where $P^i_j$ is the individual predicted quantity at site *i* and time *j*. Note the predicted mean wind speed and mean resultant direction are derived from the vector-average (for east-west component *u* and north-south component *v*), from which the

Bias (B) is calculated as the mean difference in prediction-observation pairings with valid data within a given analysis region and for a given time period by Eq. **(5-3)**:

$$B = \frac{1}{IJ}\sum_{j=1}^{J}\sum_{i=1}^{I}\left(P_j^i - O_j^i\right) \qquad (5\text{-}3)$$

Gross Error (E) is calculated as the mean *absolute* difference in prediction-observation pairings with valid data within a given analysis region and for a given time period by Eq. **(5-4)**:

$$E = \frac{1}{IJ}\sum_{j=1}^{J}\sum_{i=1}^{I}\left|P_j^i - O_j^i\right| \tag{5-4}$$

Note that the bias and gross error for winds are calculated from the predicted-observed residuals in speed and direction (not from vector components *u* and *v*). The direction error for a given prediction-observation pairing is limited to range from 0 to ±180°.

Root Mean Square Error (RMSE) is calculated as the square root of the mean squared difference in prediction-observation pairings with valid data within a given analysis region and for a given time period by Eq **(5-5)**:

$$RMSE = \left[\frac{1}{IJ}\sum_{j=1}^{J}\sum_{i=1}^{I}\left(P_j^i - O_j^i\right)^2\right]^{\frac{1}{2}} \tag{5-5}$$

The RMSE, as with the gross error, is a good overall measure of model performance. However, since large errors are weighted heavily (due to squaring), large errors in a small sub-region may produce a large RMSE even though the errors may be small and quite acceptable elsewhere.

#### 5.4.1.2 METSTAT Processing

METSTAT was developed to calculate and graphically present statistics associated with temporally paired meteorological model predictions and observations. The horizontal analysis range can be given for an entire output grid, by a coordinate box, or as a list of specific site identifiers (such as WBAN or AIRS numbers), as labeled on the observational file. This allows for an evaluation at a single site, a subset of specific sites (e.g., within a state) or over an entire regional domain. The program then proceeds to calculate statistics for each hour and for each day of the time window.

The process involves statistical comparisons of model data from the WRF grid cells to observational measurements located with each grid cell. METSTAT evaluates wind speed and direction, air temperature, and air humidity using both bias-like and error-like statistics. METSTAT has been widely applied to WRF runs for many years, across many modeling domains. Using a consistent definition of the statistical quantities to be calculated and a consistent methodology for pairing observations in time, METSTAT allows for more straightforward comparisons between model applications in widely different regions and time periods.

### *5.4.2 Statistical Benchmarks*

METSTAT calculates statistical performance metrics for bias, error and correlation for surface winds, temperature, and mixing ratio (i.e., water vapor or humidity). To evaluate the performance of a meteorological model simulation for air quality model applications, a number of performance benchmarks for comparison are typically used. Tale 5-2 lists the meteorological model performance benchmarks for simple (Emery et al., 2001) and complex (Kemball-Cook et al., 2005) situations. The simple benchmarks were developed by analyzing well-performing meteorological model evaluation results for simple, mostly flat terrain conditions and simple meteorological conditions (e.g., stationary high pressure) that were mostly conducted to support air quality modeling studies (e.g., ozone SIP modeling). The complex benchmarks were developed during the Western Regional Air Partnership (WRAP) regional haze modeling and are performance benchmarks for more complex conditions, such as the complex terrain of the Rocky Mountains and Alaska (Kemball-Cook et al., 2005). McNally (2009) analyzed multiple annual runs that included complex terrain conditions and suggested an alternative set of benchmarks for temperature under more complex conditions. The purpose of the benchmarks is to understand how good or poor the results are relative to other model applications run for the United States.

The DM/NFR NAA 2016 WRF application will compare the WRF meteorological variables to the benchmarks as an indication of WRF model performance. These benchmarks include bias and error in temperature, wind direction and mixing ratio as well as the wind speed bias and Root Mean Squared Error (RMSE) between the models and databases.

**Table 5-2. Meteorological model performance benchmarks for simple and complex conditions.**

| Parameter | Emery et al. (2001) | Kemball-Cook et al. (2005) | McNally (2009) | Resulting Criteria |
|---|---|---|---|---|
| Conditions | Simple | Complex | Complex | Complex |
| Temperature Bias | ≤ ±0.5 K | ≤ ±2.0 K | ≤ ±1.0 K | ≤ ±1.0 K |
| Temperature Error | ≤ 2.0 K | ≤ 3.5 K | ≤ 3.0 K | ≤ 3.0 K |
| Temperature IOA | ≥ 0.8 | (not addressed) | (not addressed) | ≥ 0.8 |
| Humidity Bias | ≤ ±1.0 g/kg | ≤ ±0.8 g/kg | ≤ ±1.0 g/kg | ≤ ±1.0 g/kg |
| Humidity Error | ≤ 2.0 g/kg | ≤ 2.0 g/kg | ≤ 2.0 g/kg | ≤ 2.0 g/kg |
| Humidity IOA | ≥ 0.6 | (not addressed) | (not addressed) | ≥ 0.6 |
| Wind Speed Bias | ≤ ±0.5 m/s | ≤ ±1.5 m/s | (not addressed) | ≤ ±1.5 m/s |
| Wind Speed RMSE | ≤ 2.0 m/s | ≤ 2.5 m/s | (not addressed) | ≤ 2.5 m/s |
| Wind Speed IOA | ≥ 0.6 | (not addressed) | (not addressed) | ≥ 0.6 |
| Wind Dir. Bias | ≤ ±10 degrees | (not addressed) | (not addressed) | ≤ ±10 degrees |
| Wind Dir. Error | ≤ 30 degrees | ≤ 55 degrees | (not addressed) | ≤ 55 degrees |

The output from the 2016 36/12/4-km WRF simulations will be compared against meteorological data obtained from the National Climate Data Center's (NCDC) global-scale, quality-controlled DS3505 integrated surface hourly observational (ISHO) data (NOAA-NCDC, 2015) as verification data. Global hourly and synoptic observations are compiled from numerous sources into a single common ASCII format and common data model. The DS3505 database contains records of most official surface meteorological stations from airports, military bases, reservoirs/dams, agricultural sites, and other sources dating from 1901 to the present.

A standard set of statistical metrics from the METSTAT package will be used. These metrics will be calculated on hourly, daily and monthly time frames for wind speed, wind direction, temperature, and humidity at the surface, using all available observational weather data. The WRF surface meteorological model performance metrics will be compared against the simple and complex model performance goals using "soccer plots." Soccer plots use two WRF performance metrics as X-axis and Y-axis values (e.g., temperature bias as X, and temperature error as Y) along with the performance benchmarks. The closer the symbols are to the zero origin, the better the model performance. It is also easy to see when the two WRF performance metrics fall within the benchmark lines. Figure 5-2 displays an example WRF monthly temperature soccer plot from the 2011 WRF simulations used in the 2017 Denver ozone SIP modeling.  We will present WRF 2016 monthly-averaged surface meteorological model performance from the 4-km Colorado domain with additional performance products produced for sites within the DM/NFR NAA.

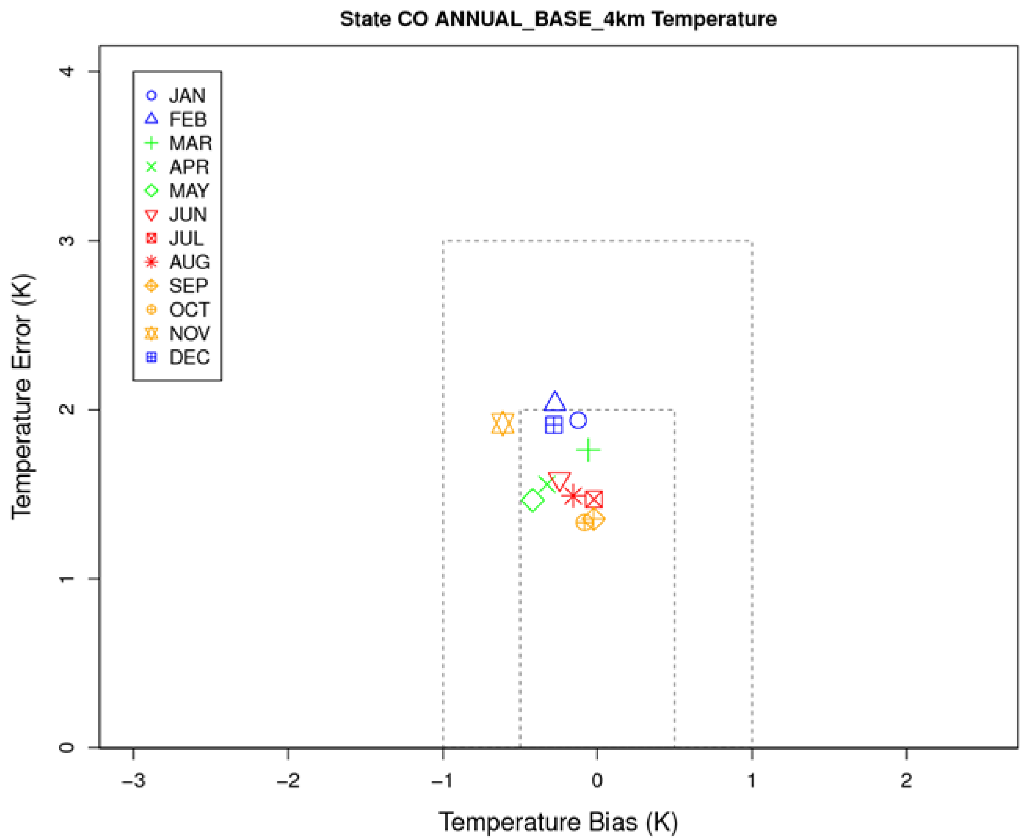



**Figure 5-2. Example Soccer plot of monthly temperature error and bias (K) for 4-km domain over Colorado for the 2011 WRF simulation used in the 2017 Denver ozone SIP.**

### *5.4.3 Qualitative Evaluations Using PRISM Data*

Oregon State University (OSU) publishes precipitation analysis fields based on observations that can be used to qualitatively evaluate the WRF precipitation fields. The Parameter-elevation Relationships on Independent Slopes Model (PRISM[45]) is used to generate the precipitation analysis fields (Daly et al., 2008). The PRISM interpolation method was used to develop data sets that reflected, as closely as possible, the current state of knowledge of spatial climate patterns in the United States. PRISM calculates a climate – elevation regression for each digital elevation model (DEM) grid cell, and stations entering the regression are assigned weights based primarily on the physiographic similarity of the station to the grid cell. Factors considered are location, elevation, coastal proximity, topographic facet orientation, vertical atmospheric layer, topographic position, and orographic effectiveness of the terrain.

[45] http://prism.oregonstate.edu/

Spatial plots of the WRF monthly precipitation fields will be compared with the PRISM spatial maps for the 12-km 12US2 and 4-km Colorado modeling domains in a qualitative model evaluation (note that PRISM does not include any analysis fields outside of the U.S.). Daily PRISM precipitation fields will be compared against the WRF daily spatial maps within the Colorado 4-km domain. The WRF performance for daily convective precipitations will be analyzed in particular as overstated summer convective precipitation can suppress ozone formation and its correct simulation is critically important for ozone modeling in the DM/NFR NAA. In the past WRF has had difficulty in accurately predicting the spatial extent and magnitude of the summer convective precipitation in the IMW region. Note that the PRISM precipitation interpolation scheme works better for synoptic weather systems than for convective showers that can be spotty and intermittent. So even though quantitative statistics can be calculated using the PRISM and WRF precipitation data, the evaluation will still be qualitative in nature as the PRISM interpolations scheme has greater uncertainties for convective precipitation.

# 6. PGM BASE YEAR INPUT PREPARATION PROCEDURES

This section summarizes the procedures to be used for developing the base case meteorological, emissions, and air quality inputs for the CAMx and CMAQ photochemical grid models (PGMs) for the summer 2016 modeling period. The modeling procedures used in the DM/NFR NAA modeling are consistent with almost 30 years of EPA ozone modeling guidance documents (e.g., EPA, 1991; 1999; 2005a; 2007; 2014d; 2018d), past Denver 8-hour ozone SIP modeling (Morris and Mansell, 2003a; Morris et al., 2004d; Morris et al., 2008a,b; Ramboll and Alpine, 2016a,b; 2017a; RAQC and CDPHE, 2017) and other recent air quality modeling studies conducted for various State and local agencies (see, for example, Morris et al., 2004a,b, 2005a,b; 2007; 2008a,b,c; Tesche et al., 2005a,b; Stoeckenius et al., 2009; ENVIRON, Alpine and UNC, 2013; Adelman, Shankar, Yang and Morris, 2014; 2016), as well as the methods used by EPA in support of their recent Transport analysis (EPA, 2010; 2015b, EPA, 2016c).

## 6.1 Meteorological Inputs

Procedures for WRF meteorological modeling for the DM/NFR NAA 2016 36/12/4-km applications were described in Chapter 5. The WRF meteorological model output data will be processed to provide inputs for the CAMx and CMAQ photochemical grid model.

### *6.1.1 WRFCAMx and MCIP Processing of 2016 WRF Output*

The WRFCAMx processor maps WRF meteorological fields to the format required by CAMx. It also calculates turbulent vertical exchange coefficients (Kz) that define the rate and depth of vertical mixing in CAMx. The MCIP processor performs a similar function for CMAQ. Steps in the WRFCAMx/MCIP processing include:

- Reading in meteorological model output files;
- Extracting meteorological data for PGM domain;
- Collapsing meteorological data if coarser vertical resolution data is requested in the PGMs than used in WRF;
- Computing vertical diffusivities (Kz); and
- Output the meteorological fields in the formats used by CAMx and CMAQ.

Several options are available to derive vertical turbulent exchange coefficient (also known as: Kv, Kz or vertical diffusivity) fields from WRF output in WRFCAMx. When TKE (turbulent kinetic energy) is not available from the WRF output (as is the case with the YSU PBL selected WRF physics options), Kv fields are diagnosed from wind, temperature, and Planetary Boundary Layer (PBL) parameters in WRFCAMx. For this application the CMAQ-like Kv profile option was selected in WRFCAMx. MCIP has less options than WRFCAMx and will be applied in a similar fashion.

### *6.1.2 Treatment of Minimum Kv*

The CMAQ MCIP processor has an option to set spatially varying minimum Kz near the surface to account for the effects of the urban heat island that can results in enhanced vertical mixing near the surface. The CMAQ minimum Kz value near the surface will vary from 0.1 to 2.0 $m^2/s$ depending on the amount of urban land use present (0.1 $m^2/s$ if no urban and 2.0 $m^2/s$ if 100% urban). For CAMx the Kv_patch program will be used to invoke a similar minimum Kv strategy the sets it to 0.1 to 1.0 $m^2/s$ depending on the amount urban land use category in grid cell in the lowest 100 m of the atmosphere.

## 6.2 Emission Inputs

### *6.2.1 Available Emissions Inventory Datasets*

The emissions inventories developed for the PGM 2016 36/2/4-km base case modeling will be based on several sources. Within the 36-km 36US3 North American and 12-km 12US2 continental U.S. domains, the 2016 base case emissions developed by the joint EPA/MJO 2016 inventory collaborative effort[46] will be used.

For the 4-km Colorado domain, 2016 emissions provided by the CDPHE/APCD will be used, with the exception of on-road mobile sources that will be based on MOVES2014 model, 2016 activity data and day-specific hourly gridded 2016 WRF meteorology.

### *6.2.2 Development of CAMx and CMAQ Emission Inputs*

CAMx and CMAQ emission inputs will be generated mainly by the SMOKE and MEGAN emissions models. CAMx requires two emission input files for each day: (1) low level gridded emissions that are emitted directly into the first layer of the model from sources whose emissions are released at the surface with little or no plume rise; and (2) elevated point sources (stacks) with plume rise calculated from stack parameters and meteorological conditions. CMAQ has similar emission inputs, only you can also provide emission inputs by source sector without merging them all together if desired. CAMx and CMAQ will be operated using version 6 revision 2 of the Carbon Bond chemical mechanism with halogen chemistry (CB6r2h) (Yarwood et al., 2010).

A 2016 base case 4-km Colorado domain emission inputs for CAMx and the June to August 2016 modeling period will be based on 2016 emissions provided by the CDPHE/APCD for Colorado that will be processed by the Sparse Matrix Operator Kernel Emissions (SMOKE) modeling system (UNC, 2015). The same version of SMOKE as is used in the EPA/MJO 2016 emissions development will be used. The current version is 4.6 of SMOKE released in September 2018[47], but the EPA/MJO effort may use an earlier version and the files may not be directly compatible with the later version. For sliver of other states within the 4 km domain, the EPA/MJO joint 2016 emission inventory collaborative emissions that are based on projections of the 2014NEIv2 will be used.

#### 6.2.2.1 Day-Specific On-Road Mobile Source Emissions

The on-road mobile source emission inputs for the 4-km Colorado domain will be generated using the SMOKE-MOVES emissions model. SMOKE-MOVES will use mobile source emission factor (EF) lookup table generated by the Motor Vehicle Emission Simulator (MOVES2014[48]) model (EPA, 2014a,b,c). SMOKE-MOVES will use vehicle

[46] http://views.cira.colostate.edu/wiki/wiki/9169

[47] https://www.cmascenter.org/smoke/smoke_release_notes.html

[48] http://www.epa.gov/oms/models/moves/#user

activity specific for Colorado provided by CDPHE/APCD, rather than use of MOVES2014 default vehicle activity data. SMOKE-MOVES uses the EF lookup table, hourly gridded meteorological data from WRF and activity data (e.g., vehicle miles travelled [VMT], speed, etc.) to generate day-specific hourly gridded on-road mobile source emission inputs for CAMx. For the DM/NFR NAA SMOKE-MOVES will be applied using two different sets of activity data: (1) use of link-based activity from Traffic Demand Models (TDMs) within the DM/NFR NAA; and (2) use of county-level activity data in Colorado outside of the DMA/NFR NAA.

#### 6.2.2.2 Colorado-Specific Vehicle Activity Data

The CDPHE/APCD will provide 2016 vehicle fleet characteristics, fuel, I/M program and activity data specific to Colorado that will be used with MOVES2014 to produce the EF lookup table to be used with SMOKE-MOVES. The MOVES2014 default vehicle activity data for Colorado may not account for the unique aspects of the fleet age distribution in Colorado.

#### 6.2.2.3 SMOKE On-Road Mobile Emissions for 4-km Colorado Domain

The SMOKE-MOVES emissions model would be used to generate on-road mobile source emissions for the 4 km Colorado domain using the 2016 county-level VMT data, 2016 MOVES2014 EF lookup table for Colorado representative counties (using CDPHE/APCD vehicle distribution data), hourly gridded 2016 4-km WRF meteorology and spatial surrogate distributions.

#### 6.2.2.4 On-Road Emissions for the DM/NFR NAA

The use of link-based activity data for generating on-road mobile source emission inputs will be evaluated for the DM/NFR NAA. The CDPCD/APCD has developed an Open Data Base Connectivity (ODBC) Transportation Inventory System (OTIS) tool that can grid the DRCOG and NFRMPO link-based activity data from their TDM modeling to the 4-km grids within a region that roughly covers the DM/NFR NAA portion of the 4-km Colorado domain. The Denver Regional Council of Governments (DRCOG) and North Front Range Metropolitan Planning Organization (NFRMPO) will provide TransCAD TDM output for the DMA and NFR regions, respectively, that will be interpolated to the 2016 baseline year. These data include link-specific capacities, volumes, and speeds for a typical weekday for 10-time periods in each day in the TransCAD model (3 morning peak, 3 afternoon peak, and 4 off-peak time).

The OTIS model is a MS Access database application that links MOVES2014 emissions rate lookup tables using the ODBC connection. ODBC is a standard programming language middleware Application Program Interface (API) for accessing database management systems, which is aimed to make it independent of database systems and operating systems. OTIS uses Weekday, Saturday and Sunday-specific link-level volume and speed data by time period from the TDM model and VMT mix to calculate hourly gridded VMT by vehicle type. The lookup tables are queried to retrieve appropriate emissions factors and combined with gridded hourly VMT estimate emissions. OTIS, as used by CDPHE/APCD for calculating mobile source conformity emission budgets, uses constant temperature so does not consider the day-to-day or spatial variations of meteorological data on emissions rates as needed for photochemical modeling.

The link-level TDM gridding capability of OTIS will be used with DRCOG/NFRMPO link-based activity data to generate 4-km gridded vehicle activity data representing all links that intersect with a 4-km grid cell. The OTIS model calculates hourly gridded VMT using the link-level volume, speed and vehicle mix data for each combination of following fields:

- Grid cell
- Hour (corresponding to 10 periods in the TDM)
- Speed Class
- Vehicle Type
- Road Type

The hourly gridded VMT data will be provided to the SMOKE-MOVES2014 integration tool. SMOKE-MOVES is typically applied using county-level VMT, vehicle population and speeds that are allocated to grid cells using an appropriate spatial surrogate and then applies MOVES emission factors from a lookup table using hourly gridded meteorological data (temperature and humidity). In order to use the OTIS gridded link-based data from the TDM models, we will "trick" SMOKE-MOVES and treat each 4 km grid cell and speed class as a pseudo-county. The spatial surrogate will be one-to-one mapping of a pseudo-county to the respective 4-km grid cell. We will provide daily grid cell level VMT to SMOKE calculated from the OTIS model. If there is more than one speed class for a given grid cell, vehicle type, and road type, we will treat them as separate pseudo-counties so that we can use the correct average speed. We will develop a diurnal temporal profile for each pseudo-county (i.e. grid cell intersecting the network) using the OTIS data and apply them on a pseudo-county basis in the temporal processing using the day-specific hourly gridded WRF meteorological data to select the appropriate MOVES2014 emissions factors from the MOVES2014 lookup table. SMOKE-MOVES tool will do the speciation and emissions calculation. Figure 6-1 shows the steps involved in preparing model-ready emissions with this approach. We will have to do separate SMOKE-MOVES runs for each modeling day using hourly gridded WRF meteorological data for that day and Weekday, Saturday and Sunday activity data from OTIS. The off-network emissions will be spatially allocated using surrogates developed from trip starts (start exhaust) and trip ends (for evaporative processes) by Traffic Analysis Zone (TAZ). These surrogates will be used in SMOKE-MOVES "rate per vehicle" and "rate per profile" processing. We will use this approach for the DRCOG and NFR networks to generate day-specific gridded hourly on-road mobile source PGM emission inputs for the DMA/NFR region.

The Colorado state-wide on-road mobile source emissions for the entire 4-km domain and the on-road mobile source emissions for the portion of the 4 km domain covered by the link-based activity data in the DMA/NFR region will be combined by first zeroing out emissions in the grid cells in the state-wide inventory in the portion covered by the link-based data and then merging them with the on-road mobile emissions based on the link-based data for the DMA/NFR NAA.

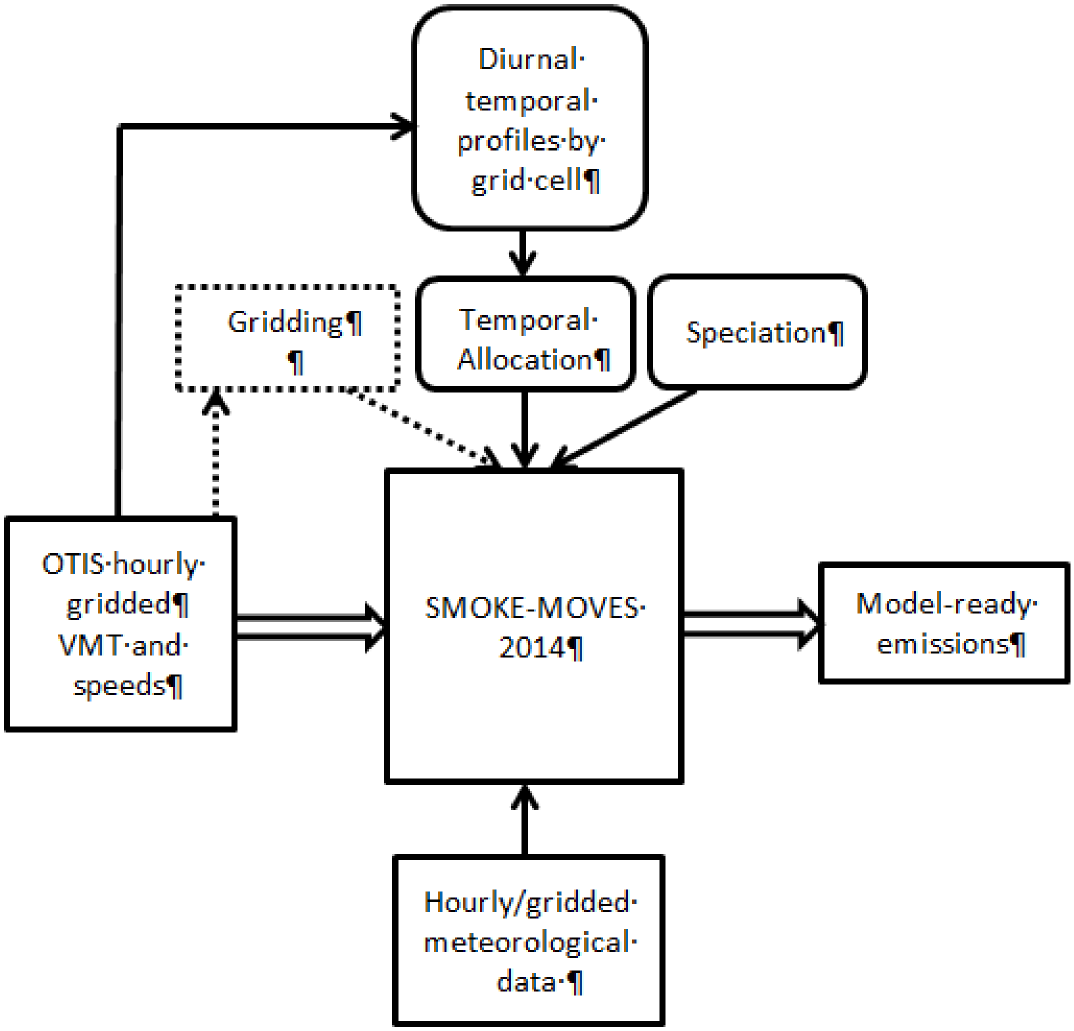



**Figure 6-1. Steps involved in preparing model-ready emissions interfacing the OTIS model with SMOKE-MOVES2014.**

#### 6.2.2.5 Testing of the Link-Based On-Road Mobile Source Emissions

As seen in the discussion above, the use of SMOKE-MOVES/OTIS to generate link-based on-road mobile source emissions for the DM/NFR NAA is considerable additional work. Although conducting such detailed link-based on-road mobile source emissions modeling may have been needed in the 2002 and 2006 baseline years used in the, respectively, 2003 EAC and 2008 Denver ozone SIPs, with the reduction in mobile NOx emissions in more recent years such detailed treatment may not be needed given emission uncertainties and the additional costs of the link-based emissions modeling effort. Furthermore, the OTIS tool is a non-standard tool with few people have experience in its use. Thus, the SMOKE-MOVES vs. SMOVE-MOVES/OTIS tools will both be used to generate on-road mobile sources in the DM/NFR NAA and evaluated. If SMOKE-MOVES/OTIS is deemed necessary to use in the 2016 base case modeling, then it also must be used for the future year (2020 and 2023 modeling) and any control strategies or updates to on-road mobile sources resulting in significant additional resources.

#### 6.2.2.6 Point Source Emissions

2016 point source emissions for Colorado will be provided by CDPHE/APCD. Point sources will be developed in two categories: (1) major point sources with Continuous Emissions Monitoring (CEM) devices; and (2) point sources without CEMs. For point sources with continuous emissions monitoring (CEM) data, day-specific hourly $NO_X$ and $SO_2$ emissions will be used for the 2016 base case emissions scenario. The VOC, CO and PM emissions for point sources with CEM data will be based on the annual data provided by the CDPHE/APCD temporally allocated to each hour of the year using the CEM hourly heat input. The hourly CEM data available in the Acid Rain database on the EPA CAMD website fills hours with missing CEM data with maximum potential to emit (PTE) emission rates and flags the data. This is because the purpose of the Acid Rain database is to assure that the source is not emitting higher emissions than its cap. Thus, a data filling program is used that uses the missing data flags to identify hours when the PTE emissions occur, and they are replaced with typical emission rates. The locations of the point sources will be converted to the LCP coordinate system used in the modeling. Point sources will be processed by SMOKE to generate the temporally varying (i.e., day-of-week and hour-of-day) speciated emissions needed by CAMx/CMAQ. The Colorado 2016 point source emissions provided by the CDPHE/APCD for sources without CEM data will be processed using SMOKE with the default temporal (e.g., monthly, day-of-week and hourly) and speciation profiles.

#### 6.2.2.7 Area and Non-Road Source Emissions

CDPHE/APCD will provide 2016 area and non-road emissions for Colorado. Area and non-road emissions for portions of the 4-km domain not covered by Colorado will be based on the EPA/MJO 2016 inventory collaborative study.

The area and non-road sources will be spatially allocated to the grid using an appropriate surrogate distribution (e.g., population for home heating, etc.). The area sources will be temporally allocated by month and by hour of day using the SMOKE source-specific temporal allocation factors. The SMOKE source-specific CB6r2h speciation allocation profiles will also be used.

#### 6.2.2.8 Episodic Biogenic Source Emissions

Biogenic emissions will be generated using Version 3 of the MEGAN biogenic emissions model. MEGAN uses high resolution GIS data on plant types and biomass loadings and the WRF surface temperature fields, and solar radiation (modeled or satellite-derived) to develop hourly emissions for biogenic species on the 36/12/4-km grids. MEGAN generates gridded, speciated, temporally allocated emission files. The MEGAN biogenic emissions will be used for the 36-km 36US3 and 12-km 12US2 modeling domains to replace the BEIS biogenic emissions used by EPA in the 2016 platform development.

#### 6.2.2.9 Wildfires, Prescribed Burns, Agricultural Burns

2016 emissions from open-land burning including wildfires, prescribed burns and agricultural burning will come from the EPA/MJO joint 2016 emissions collaborative effort.[49] The 2016 emissions use the Bluesky/SMARTFIRE approach for fire emissions in the U.S. In the past fire emissions provided with the NEI have not included Canada and Mexico where the Fire Inventory from NCAR (FINN[50]) would be used in that case.

#### 6.2.2.10 Other Natural Emissions

Lightning $NO_x$ (LNOx), ocean sea salt and dimethyl sulphide (DMS) and windblown dust (WBD) emissions will be generate using special CAMx processors and WRF 2016 meteorological data. CMAQ generates emissions for these source categories in-line.

#### 6.2.2.11 QA/QC and Emissions Merging

The emissions for the 4-km Colorado domain will be processed by major source category in several different "streams", including area sources, on-road mobile sources, non-road mobile sources, biogenic sources, non-CEM point sources, CEM point sources using day-specific hourly emissions, and emissions from fires. Separate Quality Assurance (QA) and Quality Control (QC) will be performed for each stream of emissions processing and in each step following the procedures developed by WRAP (Adelman, 2004). SMOKE includes advanced quality assurance features that include error logs when emissions are dropped or added. In addition, we will generate visual displays that include:

- Spatial plots of the hourly emissions for each major species (e.g., $NO_X$, VOC, some speciated VOC, $SO_2$, $NH_3$, PM and CO).
- Summary tables of emissions for major species for each grid and by major source category.
- This QA information will be examined against the original point and area source data and summarized in an overall QA/QC assessment.

Scripts to perform the emissions merging of the appropriate biogenic, on-road, non-road, area and low-level point sources (i.e., point sources with little or no plume rise so they are released into the first layer of the PGM) emission files will be written to generate the CAMx-ready two-dimensional day and domain-specific hourly speciated gridded emission inputs. The point source and fire, emissions would be processed into the day-specific hourly speciated emissions in the CAMx-ready point source format.

For the 36/12-km domains we plan on using the model-ready emissions from the EPA 2016 modeling platform, with the exception of biogenic where we would replace the BEIS biogenic emissions with those from MEGAN.

[49] http://views.cira.colostate.edu/wiki/wiki/9175
[50] https://www2.acom.ucar.edu/modeling/finn-fire-inventory-ncar

The resultant CAMx model-ready emissions will be subjected to a final QA using spatial maps to: (1) assure that the emissions were merged properly and CAMx inputs contain the same total emissions; and (2) provide additional QA/QC information.

#### 6.2.2.12 Use of the Plume-in-Grid (PiG) Subgrid-Scale Plume Treatment

CAMx includes a Plume-in-Grid (PiG) sub-model treats the early plume chemistry and dynamics of emissions from point sources and then releases the emissions into the grid model farther downwind at such time that the plume is adequately resolved by the grid. Large $NO_X$ emissions point sources will be selected for treatment by the subgrid-scale PiG module. The selection of which sources to be treated by the PiG module will be made after a review of the inventory. Two point source $NO_X$ emission thresholds will be selected in order for the point source to be treated by the PiG module, a lower threshold for point sources in the DM/NFR NAA and a higher threshold for the remainder of Colorado.

#### 6.2.2.13 Products of the Emissions Inventory Development Process

In addition to the CAMx-ready and CMAQ-ready emission input files generated for each hour of all days modeled in the June-August 2016 modeling period, a number of quality assurance (QA) files will be prepared and used to check for gross errors in the emissions inputs. Importing the model-ready emissions into PAVE or VERDI and examine both the spatial and temporal distribution of the emission to investigate the quality and accuracy of the emissions inputs.

- Visualizing the model-ready emissions with the scale of the plots set to a very low value, we can determine whether there are areas omitted from the raw inventory or if emissions sources are erroneously located in water cells;
- Spot-checking the holiday emissions files to confirm that they are temporally allocated like Sundays;
- Producing pie charts emission summaries that highlight the contribution of each emissions source component (e.g. non-road mobile);
- Normalizing the emissions by population for each state will illustrate where the inventories may be deficient and provide a reality check of the inventories.

State inventory summaries prepared prior to the emissions processing will be used to compare against SMOKE output report totals generated after each major step of the emissions generation process. To check the chemical speciation of the emissions to CB6 species, we will compare reports generated with SMOKE to target these specific areas of the processing. For speciation, the inventory state import totals will be compared against the same state totals with the speciation matrix applied.

The quantitative QA analyses often reveal significant deficiencies in the input data or the model setup. It may become necessary to tailor these procedures to track down the source of each major problem. As such, one can only outline the basic quantitative QA steps that we will perform in an attempt to reveal the underlying problems with the inventories or processing.

#### 6.2.2.14 Baseline Emissions for 2016, 2020 and 2023 Years

A challenge in applying the photochemical models is the development of representative platform, and then attempting to compare the ozone results from this platform with observed ozone concentrations. The modeling period is selected based on the representativeness of ozone conducive conditions and for valid comparison with observations, the modeling must include the most time resolved emissions possible. However, the emissions during the modeling period may not be representative of other periods. For instance, a significant point source may be shut-down during a high ozone period, or period has fires impacts. Since the base and future year modeling results are used in a relative fashion to project ozone Design Values that are averaged over 3 to 5 years, then having a source shut-down or large fire impacts in one-year may not be representative of other years.

The Ramboll 2020/2023 attainment demonstration modeling Proposal identified an Optional Task L-1 to generate more representative baseline emissions for EGUs and Fires (Ramboll, 2018b). In this task a Baseline (sometimes called "typical") inventory will be developed much like the approach used by the WRAP for the first round of regional haze modeling and by the Texas Commission on Environmental Quality (TCEQ) for SIP modeling in Texas. In this approach new emissions will be developed where the Electric Generation Units (EGU) emissions will be temporally disaggregated based on long-term operating conditions based on the Continuous Emissions Monitor (CEM) data. The longer-term CEM data will be used to define EGU-specific typical diurnal, daily, and monthly distribution of emissions for while the EGU was operating. These temporal factors will be applied for both the base year, making "baseline" emissions, and the future year emissions.

Another potential change will be the removal of the fires from the baseline and future year emissions. Fires are problematic since the timing and placement are uncertain in the future year. Traditional modeling holds the fires constant in the base and future years. This is a poor assumption since if a fire burned and area in the base year, it is unlikely that an area will have sufficient biomass to burn again in the future year. In addition, the base year ozone Design Values may not have the influence of some fires if the ozone values they contributed were removed as part of an Exceptional Events demonstration. In the first round of regional haze modeling, WRAP developed typical fire emissions to replace the 2002 actual fire emissions in the base and future years when making projections, which is another approach that could be used.

Note that currently the Optional Task to develop typical EGU and fire emissions for use in making future year ozone projections is not funded and the current plan is to use actual 2016 fire emissions in the base and future years and the same actual EGU emissions 2016 temporal variations from 2016 in the base and future years.

## 6.3 Photochemical Model Inputs

### *6.3.1 PGM Science Configuration and Input Configuration*

This section describes the CAMx and CMAQ PGM configuration and science options to be used in the DM/NFR NAA 2020/2023 attainment demonstration modeling. Table 6-1 summarizes the CAMx and CMAQ configuration to be used, with more details provided below.

#### 6.3.1.1 PGM Model Versions

The latest version 6.5 (v6.5) of CAMx released in April 2018 will be used in the DM/NFR NAA modeling unless a newer version becomes available at the time the modeling starts and is judged to be more appropriate. The model will be configured to predict both ozone and PM species.

Currently the latest version of CMAQ available on the CMAS Center is version 5.2.1 released in April 2018.[51] EPA has released a beta version of CMAQ v5.3 on a GitHub website[52] that is undergoing testing and evaluation and expect to release a final version in mid-2019. At this time, we propose to use CMAQ v5.2.1 unless a fully tested version of CMAQ v5.3 is released before our CMAQ modeling starts and it is compatible with the CMAQ databases we have developed.

#### 6.3.1.2 PGM Grid Nesting Strategy

CAMx will be operated using the 36/12/4-km nested grid structure using two-way grid nesting for all simulations. CMAQ does not support two-way grid nesting so we plan to operate CMAQ just on the 4-km Colorado using one-way nesting with Boundary Conditions (BCs) from the CAMx 12-km domain output.

#### 6.3.1.3 Initial and Boundary Conditions

Boundary Conditions for the CAMx most outer 36-km 36US3 modeling domain will be based on output from a 2016 simulation of the GEOS-Chem global chemistry. EPA is currently evaluating and comparing BCs for their 2016 platform based on GEOS-Chem and the Hemispheric version of CMAQ (CMAQ-HEMI). Depending on EPA’s results and the availability of the CMAQ-HEMI model and results, we may consider using the CMAQ-HEMI output for BCs. If the CMAQ-HEMI results are available, we will consider conducing a BC sensitivity test to determine how they affect ozone performance in the DM/NFR NAA.

BCs for the CMAQ 4-km Colorado domain will be based on three-dimensional output from the CAMx 12-km 12US2 domain.

The initialization strategy is to run CAMx on the 36/12-km domains for the May 20-31 period to initialize the CAMx 36/12/4-km configuration and CMAQ 4-km configuration on June 1, 2016, which is 14 days before the first observed ozone exceedance day of the summer 2016 modeling period (June 15, 2016).

#### 6.3.1.4 Other PGM Model Options

The CAMx and CMAQ model options and setup are defined in Table 6-1. The PPM advection solver (Colella and Woodward, 1984) will be used for horizontal transport for both models along with the spatially varying (Smagorinsky) horizontal diffusion

[51] https://www.cmascenter.org/download/release_calendar.cfm
[52] https://github.com/USEPA/CMAQ/blob/5.3.b2/DOCS/Release_Notes/v5.3/README.md

approach. K-theory will be used for vertical diffusion. The CB6r4 gas-phase chemical mechanism is selected for CAMx because it includes the very latest chemical kinetic rates with halogen chemistry that affects ozone levels over the ocean. The latest aerosol mechanisms will be used in the two PGMs along with the standard wet and dry deposition schemes. The Plume-in-Grid module will be used to treat the near-source chemistry and dispersion of major $NO_X$ emissions sources in the Colorado 4-km domain and the CAMx simulations. The Colorado NOX point sources will be selected for plume-in-grid treatment after an examination of the 2016 base case emissions, 10-20 sources will be selected to minimize the computational burden. For the future year modeling the same point sources will be selected for the plume-in-grid treatment, if they are still operating. The latest versions of CMAQ do not include a plume-in-grid treatment.

## Table 6-1. CAMx (Version 6.5) and CMAQ v5.2.1 model configurations.

| Science Options | CAMx | CMAQ | Comment |
|---|---|---|---|
| Model Codes | CAMx V6.5 - Apr 2018 | CMAQ v5.2.1 – Apr 2018 | Newer version of CAMx or CMAQ may be used if available at time of modeling |
| Horizontal Grid Mesh | 36/12/4-km | 36/12/4-km | CMAQ may be just run on 4-km domain |
| 36 km grid | 172 x 148 cells | 172 x 148 cells | 36/12/4 two-way grid nesting |
| 12 km grid | 396 x 246 cells | 396 x 246 cells | 36/12 km domains match the WAQS |
| 4 km grid | 173 x 128 cells | 173 x 128 cells | Also set up 4 km domain as a one-way nest |
| Vertical Grid Mesh | 25 vertical layers, defined by WRF | 25 vertical layers, defined by WRF | Layer 1 thickness 20 m. Model top at ~19 km AGL |
| Grid Interaction | 36/12/4 km two-way nesting | One-way grid nesting | CMAQ does not support two-way grid nesting so will just run for 4-km Colorado domain |
| Initial Conditions | 10-day spin-up on 36/12-km domains before June 1, 2016 | Initialize off of CAMx 12-km data | Start 4-km domain on Jun=e 1, 2016 that is 14 days before first ozone exceedance day (June 15) |
| Boundary Conditions | 2016 GEOS-Chem for 36US3 domain; Two-way nesting for 12/4-km domains | CAMx 12-km data processed for 4-km Colorado domain | EPA CMAQ-Hemi 2-16 BCs may be investigated |
| Emissions | | | |
| Baseline Emissions Processing | SMOKE, SMOKE-MOVES2014, MEGAN | SMOKE, SMOKE-MOVES2014, MEGAN | 2011 NEI plus CDPHE/APCD for Colorado |
| Sub-grid-scale Plumes | Plume-in-Grid for major $NO_X$ sources | No Plume-in-Grid | CMAQ does not have a Plume-in-Grid module |
| Chemistry | | | |
| Gas Phase Chemistry | CB6r4 | CB6r2h | Latest chemical reactions and kinetic rates with halogen chemistry (Yarwood et al., 2010) |
| Meteorological Processor | WRFCAMx | MCIP | Compatible with CAMx V5.3 and CMAQ V4.7.1 |
| Horizontal Diffusion | Spatially varying | Spatially varying | K-theory with Kh grid size dependence |
| Vertical Diffusion | CMAQ-like Kv | MCIP | Minimum Kv 0.1 to 1.0 $m^2/s$ |
| Diffusivity Lower Limit | Kz-min = 0.1 to 1.0 $m^2/s$ or 2.0 $m^2/s$ | Kz-min = 0.1 to 1.0 $m^2/s$ or 2.0 $m^2/s$ | Depends on urban land use fraction |

| Science Options | CAMx | CMAQ | Comment |
|---|---|---|---|
| Deposition Schemes | | | |
| Dry Deposition | Zhang dry deposition scheme | CMAQ formulation | (Zhang et. al, 2001; 2003) |
| Wet Deposition | CAMx -specific formulation | CMAQ formulation | rain/snow/graupel |
| Numerics | | | |
| Gas Phase Chemistry Solver | Euler Backward Iterative(EBI) | EBI | EBI fast and accurate solver |
| Vertical Advection Scheme | Implicit scheme w/ vertical velocity update | CMAQ | Emery et al., (2009a,b; 2011) |
| Horizontal Advection Scheme | Piecewise Parabolic Method (PPM) scheme | PPM | Colella and Woodward (1984) |
| Integration Time Step | Wind speed dependent | Wind speed dependent | ~0.5-1 min (4-km), 1-5 min (12-km), 5-15 min (36-km) |

# 7. 2016 BASE CASE MODELING AND MODEL PERFORMANCE EVALUATION

This Chapter describes the CAMx and CMAQ photochemical grid model (PGM) 2016 base case simulations and procedures for model performance evaluation (MPE). One of the main purposes of the MPE is to establish the reliability of the PGM 2016 base case modeling for predicting maximum daily average 8-hour (MDA8) ozone and related concentrations to have confidence that the modeled ozone responses to changes in emissions within the DM/NFR NAA are accurate. The CAMx and CMAQ 2016 base case model estimates are compared against the observed ambient ozone and other concentrations to establish that the model is capable of reproducing the current year observed concentrations, so it is likely a reliable tool for estimating future year ozone levels. The model performance evaluation will include many types of graphical and statistical comparisons of the predicted and observed ozone concentrations including spatial plots, scatter plots and time series analysis.

## 7.1 2016 Base Case Modeling

A CAMx 2016 June-August 36/12/4-km (with ~10 days of initialization) base case simulation will be performed following the procedures outlined in the previous Chapters. A CMAQ 4-km Colorado domain June-August 2016 simulation would then be conducted. The two 2016 base case simulations will then be subjected to a model performance evaluation following the procedures outlined in this Chapter.

## 7.2 EPA Model Performance Evaluation Recommendations

### *7.2.1 Overview of EPA Model Performance Evaluation Recommendations*

EPA's ozone modeling guidance (EPA, 2018d) describes a MPE framework that has four components:

- Operation Evaluation: The Operation Evaluation compares the modeled concentration estimates against concurrent observations using statistical and graphical analysis aimed at determining how well the model simulates the base year observed concentrations (i.e., does the model get the right answer).
- Diagnostic Evaluation: The Diagnostic Evaluation evaluates various components of the modeling system. It focuses on process-oriented evaluation and whether the model simulates the important processes for the air quality problem being studied (i.e., does the model get the right answer for the right reason).
- Dynamic Evaluation: The ability of the model's air quality predictions to correctly respond to changes in emissions and meteorology is part of the Dynamic Evaluation. This can include running the model for historical years to see whether the model's predictions match the changes in observations; comparison of model performance on weekdays versus weekend days can also help elucidate whether the model response to changes in emissions correctly.
- Probabilistic Evaluation: The Probabilistic Evaluation assess the level of confidence in the model predictions and estimates model uncertainty through techniques such as ensemble model simulations.

EPA's guidance recommends that "At a minimum, a model used for air quality planning should include a complete operational MPE using all available ambient monitoring data for the base case model simulations period" (EPA, 2018d, pg. 68). And goes on to say, "Where practical, the MPE should also include some level of diagnostic evaluation." EPA notes that there is no single definite test for evaluation model performance, but instead there are a series of statistical and graphical MPE elements to examine model performance in as many ways as possible while building a "weight of evidence" (WOE) that the model is performing sufficiently well for the air quality problem being studied.

#### *7.2.2 EPA Companion Model Performance Evaluation*

EPA is developing a 2016 PGM modeling platform that will likely include a MPE. If available, it would be useful to carry the MPE of the EPA 2016 PGM platform results with those being performed for the DM/NFR NAA attainment demonstration modeling study to help in the interpretation of the MPE and put it into context.

### 7.3 Overview of Evaluation of CAMx and CMAQ 2016 Base Case Procedures

This section describes the procedures for evaluating the performance of the CAMx model focusing on ozone and related species in the DMA/NFR NAA.

#### *7.3.1 Photochemical Model Evaluation Methodology*

The CAMx performance evaluations will follow the procedures recommended in the EPA photochemical modeling guidance documents (EPA, 1991; 1999; 2005a; 2007; 2014d; 2018d), EPA MPE Checklist (EPA, 2015a,b), procedures discussed by Boylan and Russell (2006), Simon, Baker and Phillips (2012), Emery and co-workers (2016) as well as procedures used in previous Denver ozone SIP modeling (e.g., Morris and Mansell, 2003a; Morris et al., 2004d; Morris et al., 2008a,b; Ramboll and Alpine, 2016a,b; 2017a; RAQC and CDPHE, 2017). The DM/NFR NAA 2016 PGM MPE will be conducted in a series of levels with each level diving more deeply into the MPE. An initial performance would focus on ozone performance in the DM/NFR NAA as an inability to adequately predict many of the observed high ozone concentrations at key monitors in the DM/NFR NAA would be a fatal flaw and require immediate corrective action. The MPE would then be expanded to ozone and ozone precursors across Colorado and ozone aloft (e.g., Boulder ozonesondes). Finally, a broad-brush evaluation would be conducted across the western U.S. for ozone, precursor and $PM_{2.5}$ mass and species.

#### *7.3.2 Model Performance Goals and Benchmarks*

EPA first proposed the use of ozone model performance goals in their 1991 ozone modeling guidance (EPA, 1991) with goals for bias (≤±15%) and error (≤35%). Since then, EPA has de-emphasized the use model performance goals as some users were focusing on achieving the model performance goals not on whether the model was accurately simulating the atmosphere. However, model performance goals are still useful for interpreting model performance and putting the performance into context. Since the EPA 1991 ozone performance goals, Boylan and Russell (2006) extended the performance goals to PM species and visibility. Simon, Baker and Phillips (2012) summarized the model performance statistics from 69 PGM applications from 2006 to

2012 and found lots of variability but were able to isolate model performance statistical levels for the best performing models.

Emery et al., (2016) built off the work of Simon, Baker and Phillips (2012) adding additional PGM model applications and coming up with a set of PGM model performance goals and criteria based on the variability in the past PGM model performance. "Goals" indicate statistical values that about a third of the top performance past PGM applications have met and should be viewed as the best a model can be expected to achieve. "Criteria" indicates statistics values that about two thirds of past PGM applications have met and should be viewed as what a majority of the models have achieved. We will compare the CAMx and CMAQ 2016 base case simulations model performance statistics for normalized mean bias (NMB), normalized mean error (NME) and correlation coefficient (r) against the model performance goals and criteria summarized by Emery et al., (2016) that are given in Table 7-1.

**Table 7-1. Recommended benchmarks for photochemical model statistics (Source: Emery et al., 2016).**

| Species | NMB | | NME | | r | |
|---|---|---|---|---|---|---|
| | Goal | Criteria | Goal | Criteria | Goal | Criteria |
| 1-hr & MDA8 Ozone | <±5% | <±15% | <15% | <25% | >0.75 | >0.50 |
| 24-hr $PM_{2.5}$, $SO_4$, $NH_4$ | <±10% | <±30% | <35% | <50% | >0.70 | >0.40 |
| 24-hr $NO_3$ | <±15% | <±65% | <65% | <115% | NA | NA |
| 24-hr OC | <±15% | <±50% | <45% | <65% | NA | NA |
| 24-hr EC | <±20% | <±40% | <55% | <75% | NA | NA |

### 7.3.3 *Multi-Level PGM Model Performance Approach*

The MPE of the DM/NFR NAA 2016 base case simulation will consist of several components with each component delving deeper into the model evaluation:

1. In initial evaluation will focus on ozone model performance of the CAMx and CMAQ 4-km predictions within the DM/NFR NAA that would include spatial maps, time series, scatter plots and comparisons with performance goals. Comparisons against the EPA 2016 12-km performance will also be made if available. In particular, the ability of the model to reproduce the highest (e.g., 20-highest days) observed MDA8 ozone concentrations at key monitoring sites in the DM/NFR NAA (e.g., RFNO, CHAT, NREL and FTCW) will be made. This evaluation will also examine subregional evaluation (i.e. DM, NFR, Eastern Slope) since the model needs to have skill in all these areas to have confidence in the model in the DM/NFR. The results of the initial ozone MPE will be discussed with RAQC and CDPHE/APCD.

2. The second level of the evaluation will evaluate for ozone and ozone precursor (e.g., $NO_2$) and product (e.g., $NO_3$, $HNO_3$) species throughout the Colorado 4-km domain. Spatial maps of hourly ozone fields with superimposed observations would be generated so that they can be animated, and we can track the evolution of ozone formation and transport. Additional CAMx simulations would be made to obtained 3-D output files for the 4-km Colorado domain in order to compare with the Boulder ozonesonde

data and look at the transport of ozone in layers aloft that are not as heavily influenced by the night-time titration of ozone due to surface NOx emissions that makes it difficult to evaluate ozone transport patterns. Performance for PM species would also be evaluated across the Colorado domain.

3. The third level of MPE will focus on the CAMx regional ozone and PM model performance across the Colorado 4-km domain and across the western states within the 12-km 12US2 domain. Within Colorado we would identify any modeled ozone "hotspots" that may be of interest to the CDPHE/APCD. Within the western U.S. the focus would be on rural monitoring sites (e.g., CASTNet and IMPROVE) and the characterization of ozone transport.

### *7.3.4 Available Aerometric Data for the Evaluations*

There were over 50 ozone monitoring sites operating in Colorado during some portion of 2016 of which over 20 were operating within the DM/NFR NAA (see Figure 4-2). There were also a few sites collecting CO, $NO_2$, $SO_2$ $PM_{10}$ and $PM_{2.5}$.

The following monitoring networks were operating in 2016 so these data that can be used in the MPE.

EPA AQS Surface Air Quality Data: Data files containing hourly-averaged concentration measurements at a wide variety of state and EPA monitoring networks are available in the Air Quality System (AQS[53]) database throughout the U.S. These data sets will be reformatted for use in the model evaluation software and used in the regional evaluation of the modeling system across the western U.S. Typical surface measurements at the ground level routine AIRS monitoring stations include ozone, $NO_2$, $NO_X$ and CO.

IMPROVE Monitoring Network: The Interagency Monitoring of Protected Visual Environments (IMPROVE[54]) network collects 24-hour average $PM_{2.5}$ and $PM_{10}$ mass and speciated $PM_{2.5}$ concentrations at many sites across the U.S. on a 1:3 day sampling frequency, including most Class I areas. The closest IMPROVE monitor to the DMA/NFR region is at Rocky Mountain National Park (RMNP).

CSN Monitoring Network: The Chemical Speciation Network (CSN[55]) collects 24-hour average speciated $PM_{2.5}$ components on a 1:3 or 1:6-day sampling frequency. CSN monitoring sites tend to be urban oriented as compared to IMPROVE sites that are typically rural.

FRM Monitoring Network: 24-hour total $PM_{2.5}$ mass is collected using the federal Reference Method (FRM[56]) on a 1:3-day sampling schedule.

[53] http://www.epa.gov/ttn/airs/airsaqs/aqsweb/
[54] http://vista.cira.colostate.edu/IMPROVE/
[55] http://www.epa.gov/ttnamti1/speciepg.html
[56] http://www.epa.gov/ttn/airs/airsaqs/detaildata/downloadaqsdata.htm

CASTNet Monitoring Network: The Clean Air Status and Trends Network (CASTNet[57]) operates approximately 80 monitoring sites in mainly rural areas across the U.S. CASTNet sites typically collect hourly ozone and weekly speciated $PM_{2.5}$, including HNO3. The closest CASTNet sites to the DMA/NFR region are Rock Mountain National Park, Gothic in Gunnison County Colorado and Centennial in Wyoming near the Colorado border.

NADP Network: The National Acid Deposition Program (NADP[58]) collects weekly samples of $SO_4$, $NO_3$ and $NH_4$ in precipitation (wet deposition). There are also some sites that collect daily samples as well as mercury.

Special Monitoring Networks: Special study ambient air data in operation during 2011 include the following:

- NOAA launches ozonesondes that measured the vertical profile of ozone in the atmosphere from Boulder, Colorado. These data can be downloaded from: http://www.esrl.noaa.gov/gmd/ozwv/ozsondes/. There were 16 ozonesonde measurements during the June-August 2016 modeling period, several of which correspond with ozone exceedance days in the DM/NFR NAA.
- NOAA also operates the Boulder Atmospheric Observatory (BAO; http://www.esrl.noaa.gov/psd/technology/bao/) in Erie, Colorado that includes a 300 m tower with instruments at various levels (e.g., 10 and 300 m). At a minimum this tower typically provides winds, humidity, temperature and ozone data, although other air quality data are sometimes available. However, the last day of operation of the BAO Tower was July 27, 2016 so data will only be available for approximately the first two months of the June-August 2016 3-month modeling episode.
- Other special study data may also be available.

## 7.4 Operational Evaluation

As noted above, the Operational Evaluation compares the modeled concentrations with concurrent observations. Various tools and graphical displays and statistical methods are used as part of the Operational Evaluation as discussed below.

### *7.4.1 Atmospheric Model Evaluation Tool (AMET)*

The Atmospheric Model Evaluation Tool (AMET[59]) (Appel et al., 2011) is a suite of software designed to facilitate the analysis and evaluation of predictions from meteorological and air quality models. AMET matches the model output for grid cells with observations from monitoring site locations from one or more networks of monitors. AMET also does species mappings to map the modeled species to the corresponding observations. These pairings of values (model and observation) are then used to statistically and graphically analyze the model's performance using a variety of techniques, many of which will be used in the CAMx and CMAQ 2016 base case MPE. The latest version of AMET is version 1.4, but AMET website doesn't have any

[57] http://java.epa.gov/castnet/
[58] http://nadp.sws.uiuc.edu/NADP/
[59] https://www.cmascenter.org/amet/

information on its release date or documentation so we assume the documentation for AMET v1.3[60] is pertinent for AMET v1.4.

### *7.4.2 Example Operational Model Performance Evaluation Products*

Below we use the results from the 2016 Denver ozone SIP (RAQC and CDPHE, 2016) modeling MPE (Ramboll and Alpine, 2017) for the 2011 CAMx ozone modeling platform to illustrate the type of MPE products that will be produced. Summary tables of ozone statistical model performance metrics across sites in the DM/NFR NAA as well as at key monitoring sites will be produced. Such ozone performance statistics can be calculated with and without observed cut-off concentrations as illustrated in the next section. AMET comes pre-loaded with observation data from multiple networks that were described previously:

- Air Quality System (AQS) network
- Clean Air Status and Trends Network (CASTNET)
- Interagency Monitoring of PROtected Visual Environments (IMPROVE)
- Mercury Deposition Network (MDN)
- National Atmospheric Deposition Program (NADP)
- South-Eastern Aerosol Research and Characterization Study (SEARCH)
- Chemical Speciation Network (CSN; formerly STN)

AMET will be the primary MPE tool used in the CAMx and CMAQ 2016 base case simulations augmented by spatial visualization tools (e.g., PAVE and/or VERDI) and other MPE tools as necessary. Some example MPE displays are described in the following sections.

#### 7.4.2.1 Soccer Plots for Comparing Performance Statistics with Goals and Criteria

Soccer Plots display ozone (or other species) model performance statistics against model performance goals and/or criteria using a scatter plot, such as bias on the x-axis and error on the y-axis. When the statistics achieves the goal, it falls within the box outlined by the goals. For example, Figure 7-1 shows ozone monthly fractional bias and error (FB and FE) performance statistics against a 15% and 35% performance goal, respectively, for the 2011 CAMx base case from the 2016 Denver ozone SIP. The Soccer Plots are for hourly (right) and MDA8 (left) ozone using no (top) and a 60 ppb (bottom) cut-off concentration. Using Soccer Plots it is easy to determine when the performance statistics are achieving the goals and as the symbols approach the (0,0) origin that indicates better model performance. Although the example in Figure 7-1 is for monthly performance across all sites in the DM/NFR NAA, the different symbols could be for different monitoring sites, specific modeling days with ozone exceedance days, stratified by observed ozone concentrations or stratified by any other variable that provides insight into the MPE.

[60] https://www.cmascenter.org/help/documentation.cfm

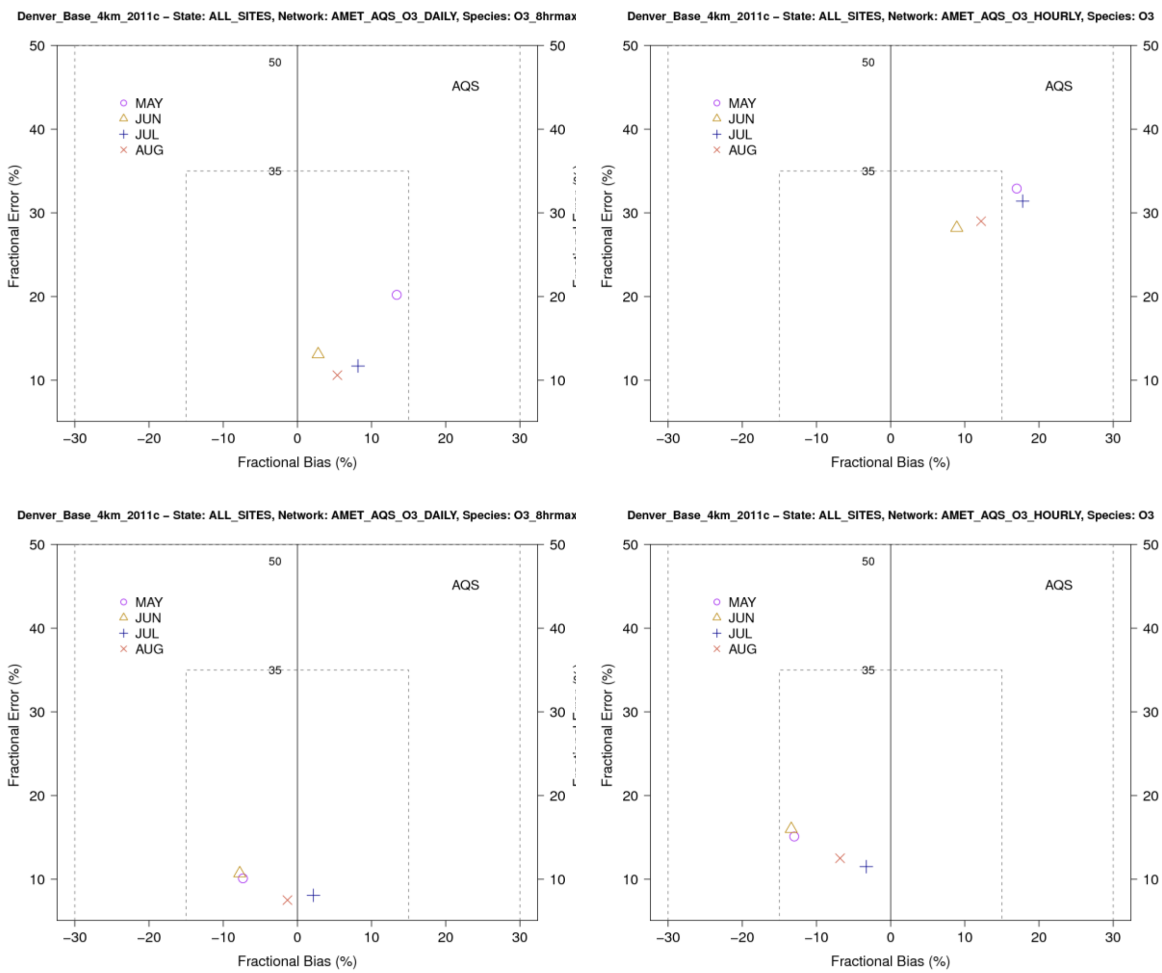



**Figure 7-1. Example Soccer Plots of MDA8 (left) and hourly (right) ozone bias (FB) and error (FE) performance across sites in the DM/NFR NAA using no (top) and 60 ppb (bottom) observed ozone cut-off concentration (Source: Ramboll and Alpine, 2017).**

### 7.4.2.2 Spatial Maps of Statistical Model Performance

AMET can generate spatial maps of different statistical performance metrics where the different colored symbols at the locations of monitoring sites allows an assessment of performance by geographic location. For example, Figure 7-2 displays the MDA8 ozone monthly bias (NMB) spatial plot from the CAMx 2011 base case simulation for sites in the DM/NFR NAA and shows an overestimation bias in May at many sites (yellow) with most of the sites achieving the <±15% performance goal for the other three months. The exception is the DMAS site in downtown Denver and the FTCO site in Fort Collins that are located close to mobile NOx emissions that titrate the ozone that is not reproduced by the model due to dilution of the local NOx emissions across a 4-km grid cell.

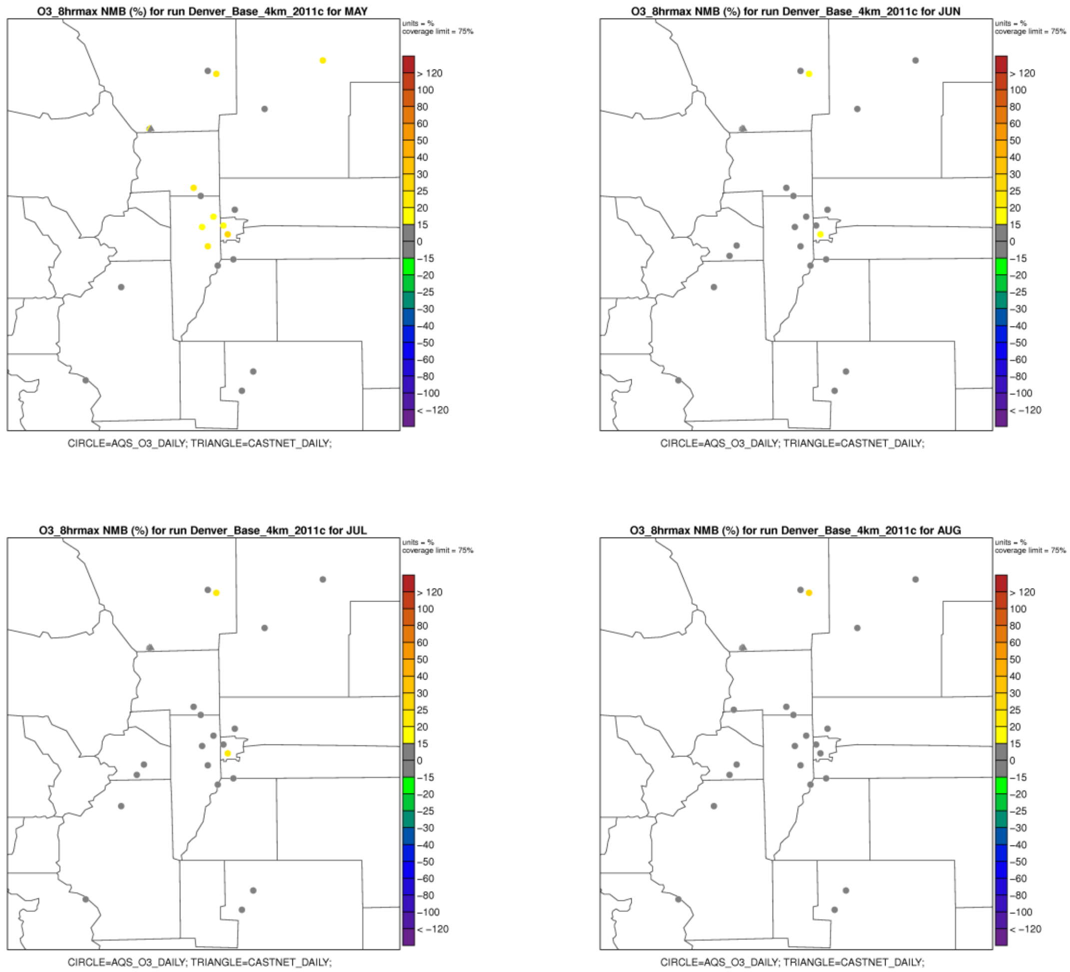



**Figure 7-2. Spatial statistics plot of MDA8 monthly ozone model performance for Normalized Mean Bias (NMB), AQS sites in the Denver Metro/NFR NAA using no observed ozone cut-off concentration and May (top left), June (top right), July (bottom left) and August (bottom right) (Source: Ramboll and Alpine, 2017).**

### *7.4.3 Scatter Plots of Model Performance*

Scatter Plots are a main stay of MPE as they allow you to directly see the point-by-point comparison of predicted and observed concentrations. Figure 7-3 shows example MDA8 (left) and hourly (right) ozone scatter plots for July and sites in the DM/NFR NAA without (top) and with a 60 ppb observed ozone cut-off concentration from the CAMx 2011 base case simulations. In this case ozone performance for two different CAMX base cases are shown (red and blue symbols) and summary performance statistics are also displayed. The model has difficulty in predicting the lowest observed hourly ozone concentrations (see comment above on DMAS and FTCO ozone over-prediction bias), which appears to have little effect on MDA8 ozone MPE or hourly ozone performance when a 60 ppb observed ozone cut-off is used.

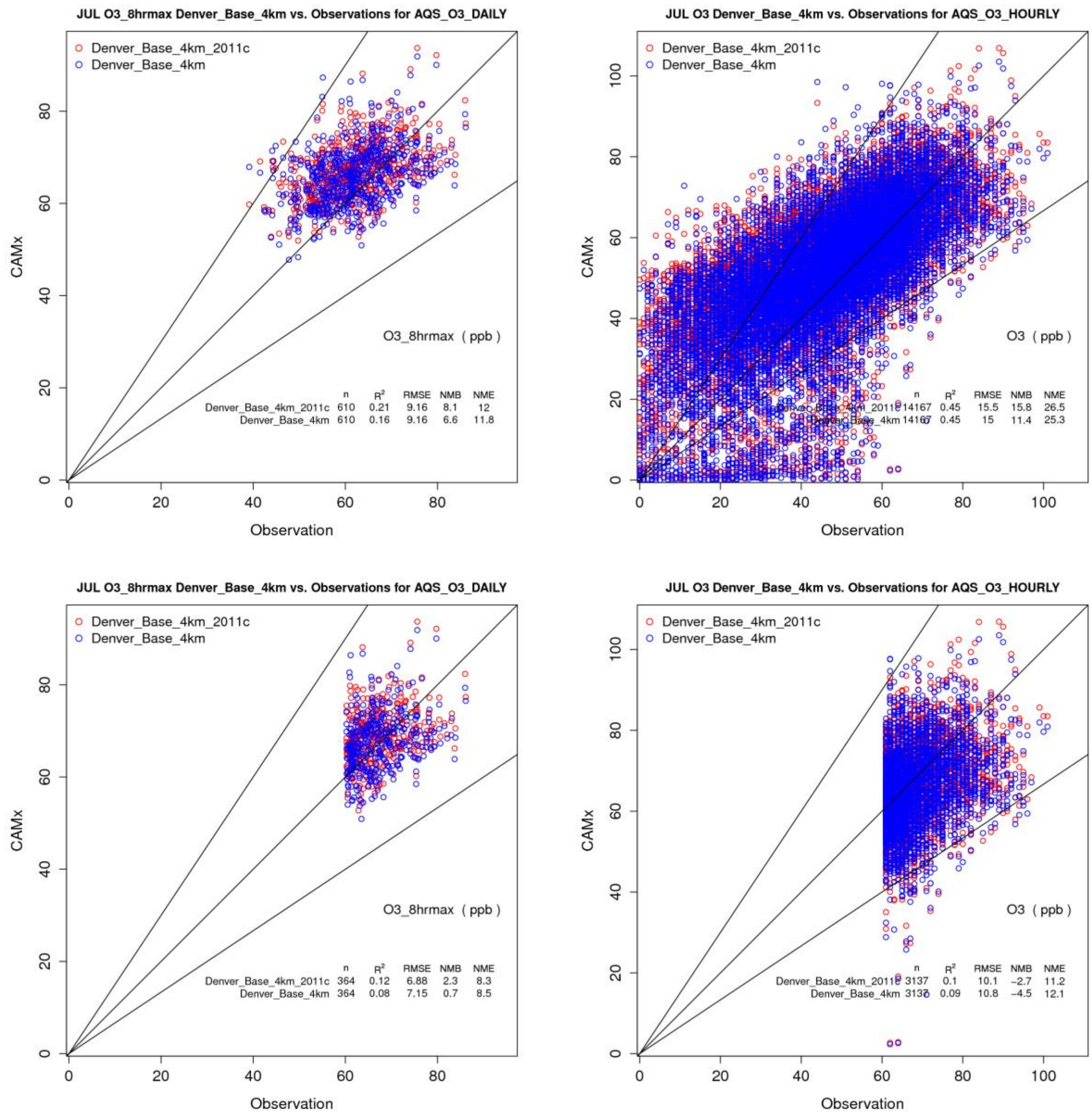



**Figure 7-3. Scatter plots and model performance statistics for MDA8 (left) and hourly (right) ozone concentrations using no (top) and 60 ppb (bottom) observed ozone cut-off concentrations during the month of July (Source: Ramboll and Alpine, 2017).**

### *7.4.4 Time Series of Predicted and Observed Concentrations*

Time series of predicted and observed concentrations is another main stay of a MPE and focuses of the temporal evaluation of model performance at particular sites. For example, Figure 7-4 displays time series of predicted and observed July and August MDA8 ozone concentrations at the RFNO monitoring site for two CAMx 2011 base case simulations. These displays not only include the MDA8 ozone concentrations levels but the daily bias (i.e., different in the predicted and observed MDA8 ozone.

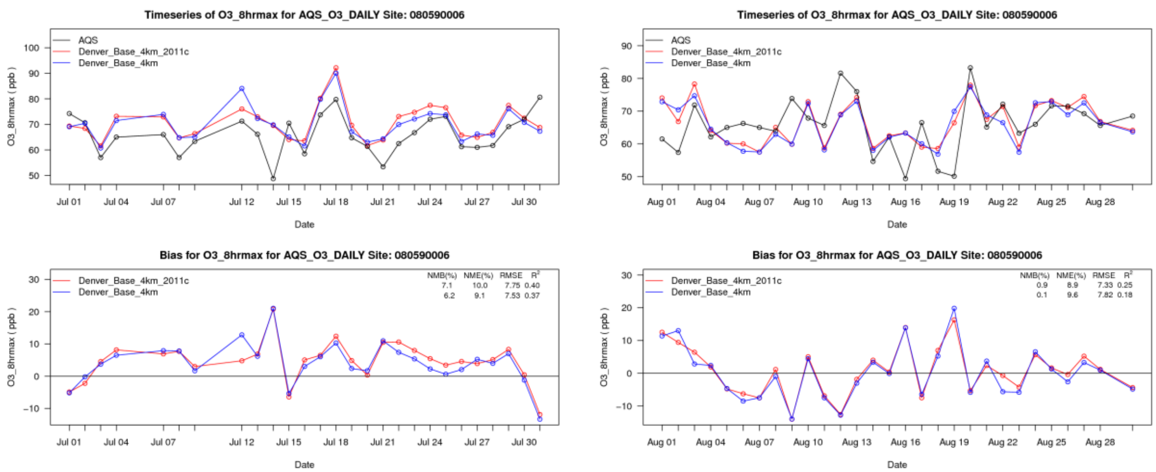



**Figure 7-4. Time series of predicted and observed (black) MDA8 ozone concentrations (top panel) and bias (bottom panel) at Rocky Flats North (RFNO) for the preliminary 2011b1 (blue) and final 2011c (red) CAMx 4 km base case simulations and the months of July (left) and August (right) (Source: Ramboll and Alpine, 2017).**

### *7.4.5 Visualization of Hourly and MDA8 Ozone Concentrations*

One powerful tool for interpreting model performance is visualizing the spatial variations of hourly and MDA8 ozone (and potentially other concentrations) with super imposed observations and generating animations of the results. This allows one to visualize the evolution of an ozone episode and assess the spatial distribution of ozone formation and transport and identify spatial and temporal misplacements of predicted and observed ozone concentrations. In the past we have used the PAVE[61] visualization tool to make such applications, but PAVE has not been updated in over a decade. The VERDI[62] visualization tool was developed as a replacement to PAVE but can be harder to use. Other options may be more efficient, such as using python scripts and NCL. The exact tool to be used for generating the spatial concentrations animations will be determined after a review of the potential tools. Figure 7-5 shows example displays of predicted and observed hourly ozone concentrations at 13:00 and 16:00 for August 20, 2011 for the CAMx 2011 base case. The observed hourly ozone concentrations are inside diamond symbols using the same color scheme is the spatial map of predicted

[61] https://www.cmascenter.org/pave/documentation/2.3/EntirePaveManual.html
[62] https://www.cmascenter.org/verdi/

values. When the observed colors blend into the predicted colored map, that indicates good hourly ozone model performance. For example, at 16:00 on August 20 (Figure 7-5, bottom) the model does a reasonably good job in predicted the observed ozone in the Denver area but overestimates the observed ozone in the Fort Collins area.

At a minimum we will generate spatial animation of predicted hourly and MDA8 ozone concentrations with superimposed observations for the June-August modeling period and the 4-km Colorado domain. Although example screen shot animations can be included in the MPE report, the real benefit is for the analyst to view them on their computer, so we will share these animations with RAQC, CDPHE/APCD and others designated by RAQC.

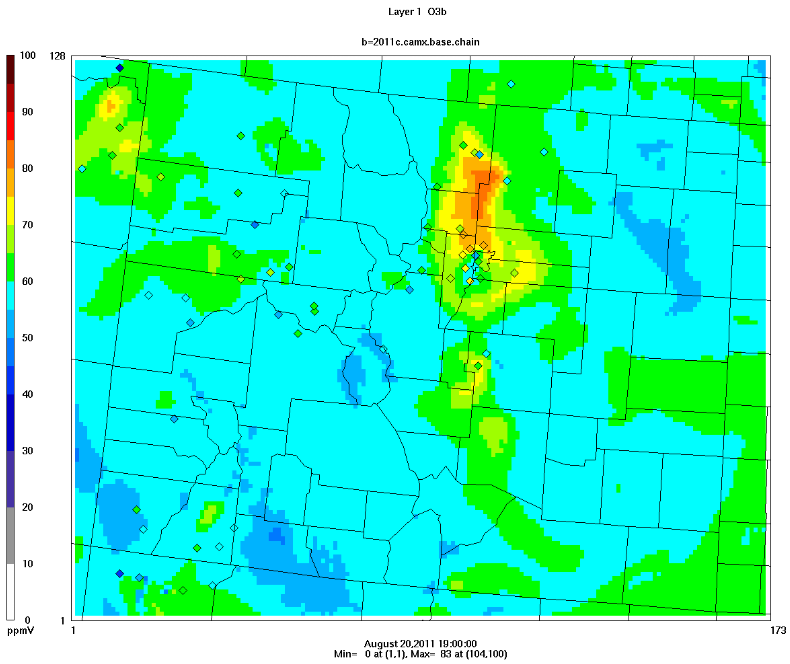



**Figure 7-5. Comparison of predicted hourly ozone concentrations at 13:00 (top) and 16:00 (bottom) MST on August 20, 2011 (Source: Ramboll and Alpine, 2017).**

### 7.4.6 Evaluation for the Highest Observed MDA8 Ozone Concentrations

An important component of a PGM MPE is to evaluate the model for how well it predicts the observed concentrations for the way the model is used to project future year ozone DVs. In this case, the model is run for a base and future year case and the relative change in the modeling results are used to project the current year observed ozone DVs to the future year. EPA's modeling guidance (EPA, 2018d) describes how to use the PGM modeling results to make the future year ozone DV projections with details presented in Chapter 8. The 10 highest base year modeled MDA8 ozone concentrations near a monitoring site are used to make the future year DV projections. It is desirable for the modeled MDA8 ozone concentrations on these 10 highest modeled base year ozone concentrations to match the observed MDA8 ozone concentrations on the same day reasonably well. Thus, the model performance for the days used in the future year ozone DV projections are evaluated. Table 7-2 compares the predicted and observed MDA8 ozone concentrations at the RFNO monitoring site from the CAMx 2011 base case modeling. The dates shaded in yellow are the 8-days used to make the future year projections (EPA guidance has changed slightly so now 10 days are always used). The observed ozone concentrations shaded in dark blue are part of the top 10 observed MDA8 ozone days in 2011 at RFNO and the observed ozone concentrations in slight blue are part of the 11-20 ranked observed MDA8 ozone concentrations in 2011. It is encouraging that 6 of the 8 highest modeled base case MDA8 ozone days overlap with the top 20 observed highest MDA8 ozone days.

**Table 7-2. Model performance for top 20 modeled MDA8 ozone days at RFNO using CAMx 2011c2 4 km base case modeling results Shaded dates are days used in 2017 ozone projections using 7x7 approach (Source: Ramboll and Alpine, 2017).**

| Date | Observed (ppb) | Modeled (ppb) | Bias (ppb) | Bias (%) |
|---|---|---|---|---|
| 7/18/2011 | 79.8 | 92.1 | 12.4 | 15.5% |
| 7/17/2011 | 73.8 | 80.2 | 6.5 | 8.8% |
| 8/3/2011 | 71.9 | 78.3 | 6.4 | 9.0% |
| 8/20/2011 | 83.3 | 77.9 | -5.3 | -6.4% |
| 7/24/2011 | 72.0 | 77.4 | 5.4 | 7.6% |
| 7/29/2011 | 69.1 | 77.4 | 8.3 | 12.0% |
| 7/25/2011 | 73.1 | 76.5 | 3.4 | 4.7% |
| 7/12/2011 | 71.3 | 76.0 | 4.8 | 6.7% |
| 6/24/2011 | 104.8 | 75.7 | -29.0 | -27.7% |
| 7/23/2011 | 66.8 | 74.7 | 8.0 | 12.0% |
| 8/27/2011 | 69.3 | 74.5 | 5.2 | 7.6% |
| 8/13/2011 | 76.0 | 74.2 | -1.8 | -2.4% |
| 8/1/2011 | 61.5 | 74.0 | 12.5 | 20.4% |
| 6/9/2011 | 37.1 | 74.0 | 36.9 | 99.3% |
| 8/25/2011 | 71.6 | 73.2 | 1.6 | 2.2% |
| 7/4/2011 | 65.0 | 73.2 | 8.2 | 12.6% |
| 7/22/2011 | 62.5 | 73.1 | 10.6 | 16.9% |
| 7/13/2011 | 66.1 | 73.0 | 6.8 | 10.3% |
| 8/10/2011 | 67.9 | 72.9 | 5.1 | 7.4% |
| 7/7/2011 | 66.0 | 72.9 | 6.9 | 10.5% |

## 7.5 Diagnostic Evaluation

The goal of the diagnostic evaluation is to assure that the model is simulating the correct physical and chemical processes that control the formation of ozone from the precursor emissions. Such processes include transport, dispersion, deposition and chemical transformation. The diagnostic evaluation investigates the processes that determine the ambient concentrations of ozone and related pollutants to develop confidence that the model's ozone response to changes in emissions will be accurate.

### *7.5.1 Base Year Base Case Diagnostic Sensitivity Tests*

When developing a PGM base year base case model configuration, diagnostic sensitivity tests are frequently used to evaluate the sensitivity of the model to alternative inputs or model options in an effort to obtain a better performing base year base case simulation. For example, if two WRF base year simulations are available, the PGM could be run with both sets of WRF meteorological inputs to determine which one produces better performing PGM simulations. However, care must be taken that compensatory errors are not introduced.[63] For the DM/NFR NAA 2020/2023 attainment demonstration 2016 base year PGM platform development, it is difficult to define what diagnostic sensitivity tests will need to be investigated to identify improvements to model performance without seeing the initial PGM 2016 base case MPE results, but the following are a few diagnostic sensitivity tests that could be explored if needed.

- Boundary Conditions (BC) Sensitivity: Use of 2016 CMAQ-HEMI BCs as an alternative to BCs from 2016 GEOS-Chem simulation.
- Vertical Mixing Sensitivity: Analyze alternative formulation of vertical mixing (Kz) formulations and the treatment of the minimum Kz near the surface.
- Other Meteorological Sensitivity: Use of 12-km WRF meteorological inputs, either from this study or from EPA, instead of the 4-km WRF data.
- Emissions Sensitivity: Increases or decreases in emissions (e.g., VOC and/or $NO_x$) from specific source categories or other emissions perturbation:
    - Top down studies have suggested oil and gas emissions may be under- or over-estimated.
    - Some studies have suggested MOVES mobile source NOx emissions may be overestimated, particularly in urban areas.
    - $NO_x$ emissions are almost always produced by combustion so typically are hotter than ambient air so have some buoyancy and plume rise even if emitted at the surface (e.g., mobile sources). By trapping them in the lowest layer (20-m in this case) it may overstate surface $NO_x$ emissions. Emitting some of the $NO_x$ in layer 2 may alleviate this condition, alternative the surface minimum Kz mixing parameter may also address this issue.
    - Biogenic and lightning $NO_x$ emissions are uncertain and the sensitivity to their estimates could be investigated.
- Other Sensitivity: In the development of the base case 2016 PGM modeling platform we may find inputs or parameterizations that are uncertain how to define so warrant further investigation.

When the initial results of the PGM 2016 base year base case MPE are obtained, they will be shared with RAQC, CDPHE/APCD and potential others and determine a path forward of additional sensitivity tests as needed and as time and resource constraints allow.

### 7.5.2 *Additional Diagnostic Evaluation Approaches*

Diagnostic Evaluation of a PGM can use several different techniques to diagnose features regarding model performance, such as evaluation of how the model responds to changes in inputs or simulates specific processes important for simulating the air quality issue being studied. The CAMx and CMAQ PGMs are instrumented with “probing tools” that can explore attributes of the model during a simulation, including ozone and particulate source apportionment (OSAT/PSAT), Decoupled Direct Method (DDM) sensitivity and Process Analysis. The most common type of diagnostic evaluation

[63] Compensatory errors can occur when two incorrect inputs compensate for each other so the PGM achieves seemingly good model performance, but for the wrong reason. For example, PGM modeling of Los Angeles in the late 1970s and early 1980s had a deficient VOC emissions inventory that was compensated for by overstated the Boundary Conditions.

involves using the Brute Force (BF) approach where a model base case and model perturbation case is performed, and the sensitivity of the model estimates are the differences in the output concentrations between the two BF runs.

The comparison of modeling results with observations for key indicator species can also be a useful diagnostic evaluation technique. Section 3.4.2 of EPA's PGM modeling guidance list several species indicator ratios that suggest whether the atmosphere and/or model ozone formation is more VOC-limited or $NO_x$-limited (EPA, 2018a, pp. 92-95). However, many of these indicator ratios involve species not routinely measured and may require more precision than typically obtained.

Although a comprehensive diagnostic sensitivity analysis may not be possible given resource and time constraints, some elements of a Diagnostic Evaluation is expected to occur.

## 7.6 Dynamic Evaluation

The Dynamic Evaluation evaluates a PGM for the way it is primary used in an ozone SIP as it evaluates how well the modeled ozone response to emissions changes with observed responses. The most comprehensive dynamic evaluation is to compare model responses to observed historical changes in ozone concentrations in a retrospective analysis. Because differences in meteorology between years can have as much or even more effect on observed ozone concentrations (this is especially true in the DM/NFR NAA, see Figure 1-1), such dynamic evaluation could include not only running with different historical years of emissions, but also running with different historical years of meteorology. Thus, this kind of retrospective analysis dynamic evaluation can be quite resource and time intensive. Since the 2020/2023 DM/NFR NAA attainment demonstration modeling study is using a very similar modeling system as the previous DM/NFR NAA ozone SIPs, a retrospective paper analysis could be cost-effectively performed analyzing how well the previous ozone SIPs did at predicting the observed changes in ozone concentrations in response to changes in emissions as part of a dynamic evaluation.

Another dynamic evaluation approach that is not as resource intensive as a retrospective modeling analysis is to stratify the operational model performance under varying conditions, such as day-of-week (e.g., weekday vs. weekend day), by season or by region. When the model shows the same ozone response as observed across these different chemical regimes, it supports the assertion that the modeled ozone concentrations would respond correctly to changes in emissions over time.

### *7.6.1 Probabilistic Evaluation*

The probabilistic evaluation attempts to assess the level of confidence in the model predictions through techniques such as ensemble of model simulations. At this time, there are no plans to incorporate the probabilistic evaluation as part of the DM/NFR NAA 2020/2023 attainment demonstration modeling.

# 8. FUTURE YEAR MODELING

This Chapter describes the future years to be modeled to address attainment of the 2008 and 2015 ozone NAAQS, the procedures for projecting emissions to the future years and the procedures for future year photochemical grid model (PGM) modeling.

## 8.1 Future Years to be Modeled

The DM/NFR NAA is expected to be reclassified as a Serious ozone NAA under the 2008 ozone NAAQS with an attainment date of July 2021.[64] This requires the 2018-2020 ozone DVs to achieve the 2008 ozone NAAQS resulting in a 2020 future attainment year. The DM/NFR NAA is currently classified as a Marginal NAA under the 2015 ozone NAAQS with an attainment date of August 2021,[65] which would require the 2018-2020 ozone DVs to comply with the 70 ppb 2015 ozone NAAQS. Given the high 4$^{th}$ highest MDA8 ozone concentrations in the DM/NFR NAA during 2018 (> 80 ppb), it seems unlikely that the 2018-2020 ozone DVs would attain the 2015 ozone NAAQS, we are anticipating that the DM/NFR NAA will be reclassified as a Moderate NAA under the 2015 ozone NAAQS with an attainment date of August 2024 so the 2021-2023 ozone DVs need to attain the 2015 ozone NAAQS. Thus, attainment demonstration modeling will be conducted for the 2023 future year to address attainment of the 2015 ozone NAAQS.

## 8.2 Future Year Emissions

Different sources will be used to obtain 2020 and 2023 future year anthropogenic emissions for inside versus outside of Colorado. The following natural emission sources will be assumed to remain unchanged from 2016 base year base case levels:

- Biogenic emissions.
- Lighting NOx emissions.
- Ocean Sea Salt and DMS emissions.
- Windblown Dust.
- Open Land Fires (Wildfires, Prescribed Burns and Agricultural Burning).

For Open Land Fires, no or typical levels of emissions may be used instead of actual 2016 fire emissions for a typical 2016 base case and future year modeling as discussed in Section 8.2.3.

### *8.2.1 Future Year Emissions Within Colorado*

With the exceptions of on-road mobile source emissions, within Colorado 2020 and 2023 future year anthropogenic emissions will be provided by the CDPHE/APCD. The future year anthropogenic emissions provided by CDPHE/APCD will be processed by SMOKE to generate the future year hourly gridded speciated PGM emission inputs.

[64] https://www.epa.gov/ground-level-ozone-pollution/ozone-naaqs-timelines
[65] ibid

For Electrical Generating Units (EGUs) the same 2016 base year hourly temporal profile will be used unless better information is available or typical emissions are used (see Section 8.2.3). This is the same approach as used in 2016 Denver ozone SIP.

For future year on-road mobile source emissions in Colorado, SMOKE-MOVES will be used with future year activity data, MOVES2014 future year emission factor (EF) look-up tables for Colorado representative counties and 2016 hourly 4-km gridded WRF meteorology. Depending on the testing in the 2016 base case simulations, future year on-road mobile source emissions may be based on link-based activity data within the DM/NFR NAA.

### *8.2.2 Future Year Emissions Outside of Colorado*

For the 36-km 36US3 and 12-km 12US2 domains outside of Colorado, emission from the joint EPA/MJO 2016 emissions inventory collaborative development study and EPA's 2016 modeling platform model-ready emissions will be used for the future year modeling. Currently the joint EPA/MJO 2016 emissions study plans to generate future year emissions that will feed into EPA's 2016 36/12-km domain modeling platform PGM model-ready emissions for the 2023 and 2028 future years. The 2023 36/12-km domain anthropogenic emissions from the joint EPA/MJO inventory collaborative study and EPA 2016 platform development will be used as-is and combined with this study's natural emissions.

For the 2020 future year, the joint EPA/MJO inventory collaborative study may provide 2020 emissions. However, if 2020 emissions are not provided we will interpolate between the 2023 and 2016 emissions to generate model-ready emissions for 2020 and the 36/12-km domains. At this time the joint EPA/MJO inventory collaborative study is considering running SMOKE-MOVES for the 36/12-km domains and the 2020 year that would be used instead of interpolating emissions if they become available.

### *8.2.3 Use of Typical EGU and Fire Baseline Emissions in Base and Future Years*

For the PGM 2016 base year base case and modeling performance evaluation, actual 2016 EGU and fire emissions will be used. 2016 EGU base case emissions are based on actual measured hourly emissions from CEMS and reported to EPA's CAMD website. To project future year ozone DVs the PGM modeling results are used in a relative fashion to project current year ozone DVs to the future. Thus, it is important that the base year and future year use consistent emission assumptions. If an EGU is assumed to be not operating during an important high ozone period in the base year base case, then it should be assumed to not be operating at the same time in the future year so that the relative changes in ozone between the base and future year are consistent. However, the presence of the EGU emissions are reflected in the observed ozone DVs than span 3-5 years when making projections so they should be included in the ozone DV projections even if an EGU happens to be down during important periods of 2016.

As an optional approach that is currently not funded, the Ramboll/Alpine team proposed to use "typical" EGU emissions for the 2016 base year and future years when making ozone projections. This would involve two 2016 base case simulations, one using actual measured 2016 EGU emission that are used in the model evaluation and another using 2016 typical EGU emissions that are used to make future year ozone projections. To obtain the 2016 typical EGU emissions, we would analyze long-term EGU CEM hourly data to determine what the typical operating conditions were while it was operating (e.g., monthly average diurnally varying) that would be used with the annual EGU emissions to define the 2016 baseline and future year hourly typical EGU emissions in a consistent fashion.

Actual Open Land Fires are also highly episodic in the 2016 base year. When Exceptional Event demonstrations are used, the presence of emissions from fires in the current year ozone DVs are removed. Thus, the use of no or more typical fire emissions in the 2016 typical base case future year modeling may also be considered if appropriate. However, one reason for selecting the 2016 baes year was ozone in the DM/NFR NAA was not as highly influenced by emissions from wildfires as some other years (e.g., 2017), so using typical fire emissions may not be necessary.

#### *8.2.4 Future Year Emissions Quality Assurance*

Similar QA/QC procedures (e.g., as described in Adelman, 2004; UNC, 2018; EPA, 2018a) will be performed on the future year model-ready emissions inventories as were utilized in checking the base year datasets described previously. Standard inventory assessment methods will be employed to generate the future year emissions data including, but not limited to: (a) visualizing the model-ready emissions graphically, (b) spot-checking the holiday emissions files to confirm that they are temporally allocated like Sundays, (c) producing pie charts emission summaries for each source category, and (d) normalizing the emissions by population for each state to reveal where the future year inventories may be suspect. Of particular importance will be the comparison of the 2016 base year and 2020 and 2023 future year emissions by source category and region to make sure the expected changes occurred in the modeling inventories.

### 8.3 Future Year PGM Modeling

The future year PGM base case modeling will be performed the same way that the base year base case modeling was performed only using the future year emissions. The CAMx PGM will be applied on the 36/12/4-km nested grid domain structure using two-way grid nesting. If there are appropriate future year GEOS-Chem runs consistent with the 2016 GEOS-Chem run used for the 2016 base case Boundary Conditions (BCs) around the outer 36-km 36US3 domain, they may be used for the future year BCs in the CAMx future year 36/12/4-km simulations. CMAQ future year 4-km Colorado domain simulations will be performed using the future year emissions and BCs based on the CAMx 12-km future year output.

Future year ozone DV projections will be made using the 2016 base case and future year PGM simulation outputs following the procedures given in Chapter 9 that use EPA's latest 8-hour ozone modeling guidance (EPA, 2018d).

#### *8.3.1 Future Year Ozone Transport Source Apportionment Modeling*

The CAMx Anthropogenic Precursor Culpability Assessment (APCA) version of the Ozone Source Apportionment Technology (OSAT) will be used to estimate the future year contributions of anthropogenic emissions in upwind states on ozone concentrations in Colorado and, in particular, the DM/NFR NAA. The future year state-specific anthropogenic ozone source apportionment simulations would also estimate the contributions of anthropogenic emissions from Colorado on ozone concentrations. A future year CAMx 36/12/4-km nested grid simulations will be conducted using geographic source regions defined by state boundaries and separating anthropogenic sources from natural sources. Fires would also be treated as a separate source category. The CAMx future year ozone source apportionment modeling will be used to estimate each western state's anthropogenic emissions contribution to ozone DVs throughout the U.S. At this time, the future year ozone transport analysis is planned to be just conducted for the 2023 future year.

### *8.3.2 Future Year Colorado Ozone Source Apportionment Modeling*

A future year CAMx 36/12/4-km APCA ozone source apportionment simulation will be conducted focusing on source regions and categories within Colorado. The exact definition of the source regions and categories to be analyzed will be defined based on discussion and approval from the RAQC and CDPHE/APCD.

### *8.3.3 Future Year Sensitivity and Control Strategy Simulations*

Future year sensitivity and control strategy simulations will be conducted as needed based on emissions for Colorado provided by the CDPHE/APCD and processed in the same way the future year base case emissions were processed. The future year PGM simulations will also be performed the same way as the future year base case PGM simulations. The future year sensitivity and control strategy modeling, if any, will be defined by the RAQC and CDPHE/APCD at a later date.

# 9. OZONE ATTAINMENT DEMONSTRATION

EPA's latest ozone State Implementation Plan (SIP) modeling guidance (EPA, 2018d) contains detailed procedures for how to use base year and future year photochemical grid model (PGM) modeling results to make future year ozone Design Value (DV) projections. The EPA-recommended ozone attainment demonstration includes a model attainment test for projecting base year ozone DVs to the future year and a weight of evidence (WOE) analysis used to confirm and corroborate the modeled attainment demonstration test. EPA has developed the Modeled Attainment Test Software (MATS[66]; Abt, 2014) and Speciated Modeled Attainment Test (SMAT[67]) tools that includes the recommended procedures for projecting ozone DVFs.

## 9.1 Modeled Attainment Demonstration Test

The procedures for making future year ozone DV projections are outlined in Chapter 4 of EPA's latest ozone modeling guidance (EPA, 2018d, pp. 99-110). EPA recommends using the PGM modeling results in a relative fashion the scale base year ozone DV (DVB) to estimate the future year ozone DV (DVF). The model derived scaling factors are called Relative Response Factors (RRF) and are the ratio of future to base year ozone modeling results.

$$DVF = DVB \times RRF$$

Below we highlight the key elements in EPA's recommended ozone DV projection approach, more details and justification for the approach are provided in EPA's modeling guidance (EPA, 2018d).

### *9.1.1 Base Year Ozone Design Value (DVB)*

The DVB is defined as the average of three-years of ozone DVs centered on the base modeling year. As an ozone DV is defined as the three-year average of the 4$^{th}$ highest MDA8 ozone concentrations at a monitor, the DVB is based on 5 years of 4$^{th}$ highest MDA8 ozone concentrations centered on the base year so the highest weight (3x) is on the 4$^{th}$ highest MDA8 ozone for the base year with less weights in the 2 years before and after the base year (i.e., weighting factors of 1, 2, 3, 2, 1).

For the DM/NFR NAA 2020/2023 attainment demonstration modeling, the base year is 2016 so that the DVB at each site will be defined from three years of ozone DVs as follows:

$$DVB_{2016} = (DV_{2014\text{-}2016} + DV_{2015\text{-}2017} + DV_{2016\text{-}2018}) / 3$$

[66] http://www.epa.gov/scram001/modelingapps_mats.htm

[67] https://www.epa.gov/scram/photochemical-modeling-tools

### *9.1.2 Calculation of Relative Response Factors (RRFs)*

The RRF is defined as the ratio of the average of the PGM future year (FY) to base year (BY) MDA8 ozone concentrations near the monitor for the 10 days with the -highest base year modeled MDA8 ozone concentrations near the monitoring site.

$$RRF = \sum MDA8\ Ozone_{FY} / \sum MDA8\ Ozone_{BY}$$

<u>Near the Monitor</u>: By near the monitor, the highest modeled base year MDA8 ozone is selected in a 3x3 array of grid cells centered on the monitor is used. For the future year, the future year MDA8 ozone is selected from the same grid cell in the 3x3 array centered on the monitor as used in the base year.

<u>10 Highest Base Year MDA8 Ozone Days</u>: The RRF is based on the 10 days with the 10 highest base year modeled ozone concentrations near the monitor, provided the base year MDA8 ozone is greater or equal to 60 ppb. If there are less than 10 days with base year MDA8 ≥ 60 ppb then just the days ≥ 60 ppb are used provided there are at least 5 days. If there are less than 5 days with base year MDA8 ozone ≥ 60 ppb EPA recommends that RRFs not be calculated for that site.

### *9.1.3 Flexibility in RRF Calculations*

EPA's modeling guidance includes the flexibility to modify the recommended ozone DV projection procedure. For example, there may be a reason that grid cells in the 3x3 array centered on the monitor may not be representative of conditions at the monitor. For example, if a grid cell is dominated by water so has different mixing characteristics or the monitor is in an area with sharp terrain gradients.

There may be also reasons that one of the highest 10 base year MDA8 ozone days should not be used in the RRF. For example, if the modeled base year MDA8 ozone is highly influenced by emissions from wildfires it could be excluded and then the next highest modeled MDA8 ozone included so that 10 modeled days are still used in the RRF.

There may be other reasons to modify EPA's recommended ozone DV projection approach. In the DM/NFR NAA 2020/2023 attainment demonstration approach, any deviations in the modeled attainment test from EPA's recommended procedures will be thoroughly documented and justified.

## 9.2 Unmonitored Area Analysis (UAA)

An unmonitored area analysis (UAA) will be conducted using the SMAT tool. The UAA will first interpolate the ozone DVB to each 4-km grid cell in the Colorado 4-km domain, which includes the DM/NFR NAA. The interpolation will be done with and without accounting for modeled concentration gradients. Once a gridded field of ozone DVB is obtained, the ozone DVB are projected to the future using the same procedures as used in the modeled attainment test only the modeling results at the grid cell containing the monitor is used and there is typically some relaxation of the requirement for MDA8 ozone to be above 60 ppb since the UAA is making projections in fairly clean ozone concentrations regions. The gridded future year ozone DVFs are then analyzed to determine locations with grid cells that exceed the ozone NAAQS. Note that estimate locations of ozone DVFs above the ozone NAAQS in the UAA does not necessarily imply a failure to demonstrate attainment. For example, when modeled concentration fields are used in the UAA ozone DVB interpolation frequently at locations of wildfires the ozone DVB and DVF are above the NAAQS. But any UAA ozone DVF exceedances of the NAAQS should be identified and explained in the analysis.

## 9.3 Weight of Evidence (WOE) Attainment Demonstration

The Weight of Evidence (WOE) is a necessary and critically important component of the ozone attainment demonstration. As stated in EPA's modeling guidance, "By definition, models are simplistic approximations of complex phenomena" (EPA, 2018a, pp. 169). EPA guidance recommends three types of supplemental analysis to support a modeled attainment demonstration:

1. Additional modeling analysis.

2. Analysis of trends in ambient concentrations and emissions.

3. Additional emission controls.

At this time, we cannot define what additional emission controls the RAQC and CDPHE/APCD will consider, but a few examples of the types of additional modeling and trends analysis to be used in the WOE to support the modeled attainment demonstration are given below.

### *9.3.1 Additional Modeling Analysis*

Additional modeling analysis and adjustments to the modeled attainment test to be used in the WOE could include the following:

- Use of CMAQ as an alternative model to conduct base and future year modeling and future year ozone DV projections to corroborate the CAMx ozone DV projections.

- Use of alternative base year DVs (DVB) from the recommended 5-years DVB, such as using DVBs based on the 2014-2016, 2015-2017 and 2016-2018 ozone DVs or eliminating ozone from days flagged as being influenced by wildfires from the DVB.

- Use of model performance screening for the 10 days used in the RRFs for making future year ozone DV projections. As was done in the 2017 ozone SIP, use only days in which the observed and modeled base year MDA8 ozone concentrations are within 20%, 15% and 10% of each other.

- Use of other alternative RRF future year projection approach, such as in the Coordinating Research Council's Project A-112 report that uses local sources RRFs with background ozone estimates (Ramboll, 2018c).

- Use alternative definitions of "near the monitor" such as at the monitor, within 5x5 and 7x7 grid cells of the monitor, in addition to the EPA-recommended 3x3 array of grid cells.

- Use of other modeling studies, such as EPA's 2023 modeling.

Although the recommended modeling ozone attainment demonstration uses the model in a relative sense, EPA's modeling guidance also recommends that the model absolute modeling results for the base and future years be used to support the recommended model attainment test. Some of the specific metrics based on absolute modeled concentrations are as follows (EPA, 2018d, pp. 172):

- Percent change in total amount of MDA8 ozone ≥ NAAQS within the DM/NFR NAA.

- Percent change in number of grid cells ≥ NAAQS within the DM/NFR NAA.

- Percent change in number of grid cells – hours (days) ≥ NAAQS within the DM/NFR NAA.

- Percent change in maximum modeled MDA8 ozone in the DM/NFR NAA.

### *9.3.2 Analysis of Air Quality and Emission Trends*

The use of meteorologically adjusted ozone trends may be particularly important for the DM/NFR NAA 2020/2023 ozone attainment demonstration modeling given the large year-to-year variations of ozone in the DM/NFR NAA. Such meteorological adjusted ozone trends analysis was an important component in the Denver 2017 ozone SIP (CDPHE and RAQC, 2016c). As discussed in the Chapter 3 and Appendix A episode selection, the meteorological conditions during 2018 in the DM/NFR NAA were highly conducive to ozone formation, possibly the worst year since 2003, 15 years ago. As 2018 observed ozone will influence the DVB as well as the 2018-2020 ozone DV used to determine whether the DM/NFR Serious NAA attains the 2008 ozone NAAQS, knowing how unusual or atypical ozone levels in 2018 are is important information. Ozone trends will be conducted using similar techniques as used in the 2017 ozone SIP (CDPHE and RAQC, 2016c).

Emission trends will also be examined. Trends based on emissions available from CDPHE/APCD and EPA (e.g., 2011NEI, 2024NEI, 2016 joint EPA/MJO inventory collaborative and 2023 and 2028 projections) will be used.

### *9.3.3 Commitment to Deliverables to Fully Document the Ozone SIP Attainment Demonstration Modeling*

The RAQC has funded the Ramboll/Alpine team to deliver several reports documenting the attainment demonstration that can be included in an ozone IP, along with several interim deliverables. The reports will include, but not be limited to, the following:

- Modeling Protocol (this document).

- 2016 WRF Meteorological Model Application and Evaluation Report.
- Base Year Base Case Modeling and Model Performance Evaluation.
- Future Year Modeling and Ozone Attainment Demonstration.
- Ozone SIP Air Quality Technical Support Document (AQTSD).

The AQTSD is designed to be a concise summary of all aspects of the ozone attainment demonstration modeling.

# 10. REFERENCES

Abt. 2014. Modeled Attainment Test Software – User's Manual. Abt Associates Inc., Bethesda, MD. April. (http://www.epa.gov/ttn/scram/guidance/guide/MATS_2-6-1_manual.pdf).

Adelman, Z. 2004. Quality Assurance Protocol – WRAP RMC Emissions Modeling with SMOKE, Prepared for the WRAP Modeling Forum by the WRAP Regional Modeling Center, Riverside, CA.

Adelman, Z. U. Shankar, D. Yang and R. Morris. 2014. Three-State Air Quality Modeling Study CAMX Photochemical Grid Model Draft Model Performance Evaluation Simulation Year 2011. University of North Carolina at Chapel Hill and ENVIRON International Corporation, Novato, CA. November 2014. (http://views.cira.colostate.edu/tsdw/Documents/).

Adelman, Z. U. Shankar, D. Yang and R. Morris. 2016. Three-State Air Quality Modeling Study CAMx Photochemical Grid Model Draft Model Performance Evaluation Simulation Year 2011. University of North Carolina at Chapel Hill and ENVIRON International Corporation, Novato, CA. January.

Adelman, Z. and B. Baek. 2015. Three-State Air Quality Modeling Study Emissions Modeling Report – Simulation Years 2008 and 2011. University of North Carolina at Chapel Hill. February 18. (http://vibe.cira.colostate.edu/wiki/Attachments/Emissions/3SAQS_Emissions_Modeling_Report_v18Feb2015.pdf).

Appel, W., R. Gilliam, N. Davis, A. Zubrow, and S. Howard. 2011. Overview of the atmospheric model evaluation tool (AMET) v1.1 for evaluating meteorological and air quality models. Environmental Modelling & Software. 26. 434-443. 10.1016/j.envsoft.2010.09.007.

Boylan, J. W. 2004. Calculating Statistics: Concentration Related Performance Goals, paper presented at the EPA PM Model Performance Workshop, Chapel Hill, NC. 11 February.

Boylan, J. W. and A. G. Russell. 2006. PM and light extinction model performance metrics, goals, and criteria for three-dimensional air quality models. *Atmos. Env.* Vol. 40, Issue 26, pp. 4946-4959. August. (https://www.sciencedirect.com/science/article/pii/S1352231006000690).

Carter, W.P.L. 1999. Documentation of the SAPRC-99 Chemical Mechanism for VOC Reactivity Assessment, Draft report to the California Air Resources Board, Contracts 92-329 and 95-308, 9/13/99.

CDPHE and RAQC. 2016a. Conceptual Model for the Ozone Nonattainment Area – Supporting the Denver Metro/North Front Range State Implementation Plan for the 2008 8-Hour Ozone National Ambient Air Quality Standard. Colorado Department of Health and Environment, Air Pollutions Control Division and Regional Air Quality Council. November 17. (https://raqc.egnyte.com/dl/FR2z7NBiZY/TSD_ConceptualModel.pdf_).

CDPHE and RAQC. 2016b. Analysis in Support of Exceptional Event Flagging and Exclusion for the Weight of Evidence Analysis – Supporting the Denver Metro/North Front Range State Implementation Plan for the 2008 8-Hour Ozone

National Ambient Air Quality Standard. Colorado Department of Health and Environment, Air Pollutions Control Division and Regional Air Quality Council. November 17. (https://raqc.egnyte.com/dl/223ntUeYf0/TSD_ExceptionalEventFlagging.pdf_).

CDPHE and RAQC. 2016c. Trends in Weather Corrected Ozone and Nitrogen Dioxide – Supporting the Denver Metro/North Front Range State Implementation Plan for the 2008 8-Hour Ozone National Ambient Air Quality Standard. Colorado Department of Health and Environment, Air Pollutions Control Division and Regional Air Quality Council. November 17. (https://raqc.egnyte.com/dl/H0xiX8ACR4/TSD_TrendsInWeatherCorrectedOzone.pdf_).

CDPHE. 2018. Exceptional Event Demonstration for Ozone on September 2 and 4, 2017. Colorado Department of Health and Environment, Air Pollution Control Division, Denver, CO. June 1. (https://www.colorado.gov/airquality/tech_doc_repository.aspx?action=open&file=TSD_Ozone_Sep_2_and_4_2017_20180405.pdf).

Coats, C.J. 1995. Sparse Matrix Operator Kernel Emissions (SMOKE) Modeling System, MCNC Environmental Programs, Research Triangle Park, NC.

Colella, P., and P.R. Woodward. 1984. The Piecewise Parabolic Method (PPM) for Gas-dynamical Simulations. *J. Comp. Phys.*, **54**, 174201.

Daley, C., M. Halbleib, J. Smith, W. Gibson, M. Doggett, G. Taylor, J. Curtis and P. Pasteris. 2008. Physiographically sensitive mapping of climatological temperature and precipitation across the conterminous United States. *Intl. J. Climate*. (http://prism.oregonstate.edu/documents/Daly2008_PhysiographicMapping_IntJnlClim.pdf).

Emery, C., E. Tai, and G. Yarwood. 2001. Enhanced Meteorological Modeling and Performance Evaluation for Two Texas Episodes, report to the Texas Natural Resources Conservation Commission, prepared by ENVIRON, International Corp, Novato, CA.

Emery, C.A., E. Tai, E., R. E. Morris, G. Yarwood. 2009a. Reducing Vertical Transport Over Complex Terrain in CMAQ and CAMx. AWMA Guideline on Air Quality Models Conference, Raleigh, NC, October 26-30, 2009.

Emery, C.A., E. Tai, R.E. Morris, G. Yarwood. 2009b. Reducing Vertical Transport Over Complex Terrain in Photochemical Grid Models. 8th Annual CMAS Conference, Chapel Hill, NC, October 19-21, 2009.

Emery, C., E. Tai, G. Yarwood and R. Morris. 2011. Investigation into approaches to reduce excessive vertical transport over complex terrain in a regional photochemical grid model. *Atmos. Env.*, Vol. 45, Issue 39, December 2011, pp. 7341-7351. (http://www.sciencedirect.com/science/article/pii/S1352231011007965).

Emery, C.E., Z. Liu, A.G. Russell, M.T. Odman, G. Yarwood and N. Kumar. 2016. Recommendations on statistics and benchmarks to assess photochemical model performance. J. of the Air and Waste Management Assoc., Vol. 67, Issue 5. DOI: 10.1080/10962247.2016.1265027. (https://www.tandfonline.com/doi/full/10.1080/10962247.2016.1265027).

ENVIRON and Alpine. 2005. CONCEPT Emissions Modeling User's Guide. ENVIRON International Corporation, Novato, CA. Alpine Geophysics, LLC, Arvada, CO. May 27. (http://www.ladco.org/reports/rpo/emissions/new_emissions_model_concept_introduction_alpine_environ.pdf).

ENVIRON. 2011. Western Regional Air Partnership (WRAP) West-wide Jump Start Air Quality Modeling Study (WestJumpAQMS) – Scope of Work. ENVIRON International Corporation, Novato, CA. February 23. (http://www.wrapair2.org/pdf/WestJumpAQMS_Project_Scope_of_Work_February23_2011.pdf).

ENVIRON and Alpine. 2012. Western Regional Air Partnership (WRAP) West-wide Jump-start Air Quality Modeling Study (WestJumpAQMS) WRF Application/Evaluation. ENVIRON International Corporation, Novato, CA and Alpine Geophysics, LLC, Arvada CO. February 29. (http://www.wrapair2.org/pdf/WestJumpAQMS_2008_Annual_WRF_Final_Report_February29_2012.pdf).

ENVIRON, Alpine, UNC. 2013. Western Regional Air Partnership (WRAP) West-wide Jump-start Air Quality Modeling Study (WestJumpAQMS) – Final Report. ENVIRON International Corporation, Novato, California. Alpine Geophysics, LLC. University of North Carolina. September 2013. (http://wrapair2.org/pdf/WestJumpAQMS_FinRpt_Finalv2.pdf).

EPA. 1991. Guidance for Regulatory Application of the Urban Airshed Model (UAM). Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency, Research Triangle Park, N.C.

EPA. 1999. Draft Guidance on the Use of Models and Other Analyses in Attainment Demonstrations for the 8-hr Ozone NAAQS". U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, N.C. May.

EPA. 2001. Guidance Demonstrating Attainment Air Quality Goals for PM2.5 and Regional Haze. Draft Final. U.S. Environmental Protection Agency, Atmospheric Sciences Modeling Division, Research Triangle Park, N.C.

EPA. 2003a. A Conceptual Model to Adjust Fugitive Dust Emissions to Account for Near Source Particle Removal in Grid Model Applications, prepared by Tom Pace, U.S. EPA, August. http://www.epa.gov/ttn/chief/emch/invent/statusfugdustemissions_082203.pdf.

EPA. 2003b. National Emission Inventory QA and Augmentation Memo, prepared by Anne Pope, U.S. EPA, June. http://www.epa.gov/ttn/chief/emch/invent/qaaugmementationmemo_99nei_60603.pdf

EPA. 2005a. Guidance on the Use of Models and Other Analyses in Attainment Demonstrations for the 8-hr Ozone NAAQS -- Final. U.S. Environmental Protection Agency, Atmospheric Sciences Modeling Division, Research Triangle Park, N.C. October.

EPA. 2005b. Technical Support Document for the Final Clean Air Interstate Rule – Air Quality Modeling. U.S. Environmental Protection Agency, Office of Air Quality and Planning Standards, Research Triangle Park, North Carolina, 27711. March.

EPA. 2005c. "Regional Haze Regulations and Guidelines for Best Available Technology (BART) Determinations". Fed. Reg./Vol. 70, No. 128/Wed. July, Rules and Regulations, pp. 39104-39172. 40 CFR Part 51, FRL-7925-9, RIN AJ31.

EPA. 2007. Guidance on the Use of Models and Other Analyses for Demonstrating Attainment of Air Quality Goals for Ozone, PM2.5 and Regional Haze. U.S. Environmental Protection Agency, Research Triangle Park, NC. EPA-454/B-07-002. April. (http://www.epa.gov/ttn/scram/guidance/guide/final-03-pm-rh-guidance.pdf).

EPA. 2010. Technical Support Document for the Transport Rule. Docket ID No. EPA-HQ-OAR-2009-0491. Air Quality Modeling. U.S. Environmental Protection Agency, Office of Pair Quality Planning and Standards, Air Quality Assessment Division, Research Triangle Park, NC. June.

EPA. 2014a. Motor Vehicle Emissions Simulator (MOVES) – User Guide for MOVES2014. Assessment and Standards Division, Office of Transportation and Air Quality, U.S. Environmental Protection Agency. (EPA-420-B-14-055). July. (http://www.epa.gov/oms/models/moves/documents/420b14055.pdf).

EPA. 2014b. Motor Vehicle Emissions Simulator (MOVES) –MOVES2014 User Interface Manual. Assessment and Standards Division, Office of Transportation and Air Quality, U.S. Environmental Protection Agency. (EPA-420-B-14-067). July. (http://www.epa.gov/oms/models/moves/documents/420b14057.pdf).

EPA. 2014c. Motor Vehicle Emissions Simulator (MOVES) –MOVES2014 Software Design Reference Manual. Assessment and Standards Division, Office of Transportation and Air Quality, U.S. Environmental Protection Agency. (EPA-420-B-14-058). December. (http://www.epa.gov/oms/models/moves/documents/420b14056.pdf).

EPA. 2014d. Draft Modeling Guidance for Demonstrating Attainment of Air Quality Goals for Ozone, PM2.5 and Regional Haze. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, RTP, NC. December 3. (http://www.epa.gov/ttn/scram/guidance/guide/Draft_O3-PM-RH_Modeling_Guidance-2014.pdf).

EPA. 2015a. Recommendations for Evaluating the Performance of the 3SAQS Photochemical Grid Model Platform. U.S. Environmental Protection Agency, Region 8. April 2. (http://vibe.cira.colostate.edu/wiki/Attachments/Modeling/DRAFT_EPAR8_Recommended_PGM_MPE_Analyses_3SAQS_04022015.pdf).

EPA. 2015b. Air Quality Modeling Technical Support Document for the 2008 Ozone NAAQS Transport Assessment. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards. January. (http://www.epa.gov/airtransport/O3TransportAQModelingTSD.pdf).

EPA. 2015c. Recommendations for Evaluating the Performance of the 3SAQS Photochemical Grid Model Platform. U.S. Environmental Protection Agency, Region 8. June 3.

EPA. 2016a. Implementation of the 2015 National Ambient Air Quality Standards for Ozone: Nonattainment Area Classifications and State Implementation Plan Requirements. Federal Register / Vol. 81, No. 243 / Monday, December 19, 2016 / Proposed Rules. 40 CFR Parts 50 and 51, [EPA–HQ–OAR–2016–0202;

FRL–9956–97–OAR]. (https://www.gpo.gov/fdsys/pkg/FR-2016-12-19/pdf/2016-30365.pdf).

EPA. 2016b. Guidance on the Use of Models for Assessing the Impacts of Emissions from Single Sources on the Secondarily Formed Pollutants: Ozone and $PM_{2.5}$. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Air Assessment Division. Research Triangle Park, NC. EPA-454/R-16-005. December. (https://www3.epa.gov/ttn/scram/appendix_w/2016/EPA-454_R-16-005.pdf).

EPA. 2016c. Air Quality Modeling Technical Support Document for the Final Cross State Air Pollution Rule Update. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards. Research Triangle Park, NC. August. (https://www.epa.gov/sites/production/files/2017-05/documents/aq_modeling_tsd_final_csapr_update.pdf).

EPA. 2017a. Revisions to the Guideline on Air Quality Models: Enhancements to the AERMOD Dispersion Modeling System and Incorporation of Approaches To Address Ozone and Fine Particulate Matter. 40 CFR Part 51 [EPA–HQ–OAR–2015–0310; FRL–9956–23– OAR]. Federal Register / Vol. 82, No. 10 / Tuesday, January 17, 2017 / Rules and Regulations. (https://www3.epa.gov/ttn/scram/appendix_w/2016/AppendixW_2017.pdf).

EPA. 2017b. Emissions Inventory Guidance for Implementation of Ozone and Particulate Matter National Ambient Air Quality Standards (NAAQS) and Regional Haze Regulations. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Air Assessment Division. Research Triangle Park, NC. EPA-454/B-17-003. July. (https://www.epa.gov/sites/production/files/2017-07/documents/ei_guidance_may_2017_final_rev.pdf).

EPA. 2017c. Use of Photochemical Grid Models for Single-Source Ozone and secondary PM2.s impacts for Permit Program Related Assessments and for NAAQS Attainment Demonstrations for Ozone, PM2.s and Regional Haze. Memorandum from Tyler Fox, Group Leader, Air Quality Modeling Group. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards. August 4. (https://www3.epa.gov/ttn/scram/guidance/clarification/20170804-Photochemical_Grid_Model_Clarification_Memo.pdf).

EPA. 2017d. Implementation of the 2015 National Ambient Air Quality Standards for Ozone: Nonattainment Area State Implementation Plan Requirements. Federal Register / Vol. 83, No. 234 / Thursday, December 6, 2018 / Rules and Regulations. 40 CFR Part 51, [EPA–HQ–OAR–2016–0202; FRL–9986–53–OAR]. (https://www.gpo.gov/fdsys/pkg/FR-2018-12-06/pdf/2018-25424.pdf).

EPA. 2017e. Emissions Inventory Guidance for Implementation of Ozone and Particulate Matter National Ambient Air Quality Standards (NAAQS) and Regional Haze Regulations. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Air Assessment Division. Research Triangle Park, NC. EPA-454/B-17-003. July. (https://www.epa.gov/sites/production/files/2017-07/documents/ei_guidance_may_2017_final_rev.pdf).

EPA. 2018a. Implementation of the 2015 National Ambient Air Quality Standards for Ozone: Nonattainment Area State Implementation Plan Requirements, Final Rule. 40 CFR Part 51, [EPA-HQ-OAR-2016-0202; FRL- -OAR] RIN 2060-AS82. U.S. Environmental Protection Agency. Signed November 7, 2018.

(https://www.epa.gov/sites/production/files/2018-11/documents/2015_ozone_srr_final_preamble_20181101.pdf).

EPA. 2018b. Additional Air Quality Designations for the 2015 Ozone National Ambient Air Quality Standards, Final Rule. U.S. Environmental Protection Agency. Federal Register / Vol. 83, No. 107 / Monday, June 4, 2018 / Rules and Regulations. 40 CFR Part 81; [EPA–HQ–OAR–2017–0548; FRL–9977–72–OAR]; RIN 2060–AT94. (https://www.govinfo.gov/content/pkg/FR-2018-06-04/pdf/2018-11838.pdf).

EPA. 2018c. Determinations of Attainment by the Attainment Date, Extensions of the Attainment Date, and Reclassification of Several Areas Classified as Moderate for the 2008 Ozone National Ambient Air Quality, Proposed Rule. U.S. Environmental Protection Agency. Federal Register /Vol. 83, No. 220 /Wednesday, November 14, 2018 / Proposed Rules. 40 CFR Parts 52 and 81; [EPA–HQ–OAR–2018–0226; FRL–9986–44–OAR]; RIN 2060–AT97. (https://www.govinfo.gov/content/pkg/FR-2018-11-14/pdf/2018-24816.pdf).

EPA. 2018d. Modeling Guidance for Demonstrating Air Quality Goals for Ozone, PM2.5, and Regional Haze. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Air Assessment Division. Research Triangle Park, NC. EPA 454/R-18-009. November 29. (https://www3.epa.gov/ttn/scram/guidance/guide/O3-PM-RH-Modeling_Guidance-2018.pdf).

EPA. 2018e. CMAQv5.2.1 Operational Guidance Document. U.S. Environmental Protection Agency, Office of Research and Development. (https://github.com/USEPA/CMAQ/blob/5.2.1/DOCS/User_Manual/README.md).

Guenther, A. and C. Wiedinmyer. 2004. User's Guide to the Model of Emissions of Gases and Aerosols from Nature (MEGAN). National Center for Atmospheric Research (NCAR), Boulder, Colorado (http://acd.ucar.edu/~christin/megan1.0_userguide.pdf).

Guenther, A., X. Jiang, T. Duhl, T. Sakulyanontvittaya, J. Johnson and X. Wang. 2014. MEGAN version 2.10 User's Guide. Washington State University, Pullman, WA. May 12. (http://lar.wsu.edu/megan/docs/MEGAN2.1_User_GuideWSU.pdf).

Heath, N., J. Pleim, R. Gillian, D. Kang, M. Woody, K. Foley and W. Appel. 2016. Impacts of WRF Lightning Assimilation on Offline CMAQ Simulations. Presented at 2016 CMAS Conference, Chapel Hill, NC. October 24-26. (https://cfpub.epa.gov/si/si_public_record_report.cfm?dirEntryId=335757&Lab=NERL).

Kalnay, E. et al. 1996. The NCEP/NCAR 40-Year Reanalysis Project. *Bull. Am. Meteorol. Soc.*, 77(3), 437-471. (https://rda.ucar.edu/datasets/ds090.0/docs/bams/bams1996mar/bams1996mar.pdf).

McNally, D., T.W. Tesche and R. Morris. 2003. Air Quality Modeling Analysis for the Denver Early Action Ozone Compact: Evaluation of MM5 Simulations of The Summer 2002 Denver Ozone Season and Embedded High 8-hr Ozone Episodes. Alpine Geophysics, LLC, Ft. Wright, Kentucky. July.

McNally, D., G. Schewe, J. Johnson and R. Morris. 2008a. "Evaluation of Preliminary MM5 Meteorological Model Simulation for the June-July 2006 Denver Ozone SIP

Modeling Period Focused on Colorado". Prepared by Alpine Geophysics, LLC and ENVIRON International Corporation. Prepared for Denver Regional Air Quality Council (RAQC). February. (http://www.ozoneaware.org/documents/MM5_Eval_DENSIP_Feb25_2008.pdf)

McNally, D., C. Loomis, R. Morris, T. Sakulyanontvittaya and E. Tai. 2008b. "2010 Ozone Projections for the 2010 Base Case and 2010 Sensitivity Tests and 2010 Ozone Source Apportionment Modeling for the Denver 8-Hour Ozone State Implementation Plan". Prepared for Denver Regional Air Quality Council, Denver, Colorado. Prepared by Alpine Geophysics, LLC, Arvada, CO and ENVIRON International Corporation, Novato, CA. November. (http://www.ozoneaware.org/documents/modeling/Exec_Sum1.pdf)

McNally, D., C. Loomis, R. Morris and T. Sakulyanontvittaya. 2009. "2020 Ozone Source Apportionment Modeling for the Denver Area". Prepared for Denver Regional Air Quality Council, Denver, Colorado. Prepared by Alpine Geophysics, LLC, Arvada, CO and ENVIRON International Corporation, Novato, CA. July 15. (http://www.ozoneaware.org/postfiles/documentsandpresentations/modeling/Draft%20Final%202020_OSAT_Report.pdf)

Michalakes, J., J. Dudhia, D. Gill, J. Klemp and W. Skamarock. 1998. Design of a Next-Generation Regional Weather Research and Forecast Model. Mesoscale and Microscale Meteorological Division, National Center for Atmospheric Research, Boulder, CO. (http://www.mcs.anl.gov/~michalak/ecmwf98/final.html).

Michalakes, J., S. Chen, J. Dudhia, L. Hart, J. Klemp, J. Middlecoff and W. Skamarock. 2001. Development of a Next-Generation Regional Weather Research and Forecast Model. Developments in Teracomputing: Proceedings of the 9th ECMWF Workshop on the Use of High Performance Computing in Meteorology. Eds. Walter Zwieflhofer and Norbet Kreitz. World Scientific, Singapore. Pp. 269-276. (http://www.mmm.ucar.edu/mm5/mpp/ecmwf01.htm).

Michalakes, J., J. Dudhia, D. Gill, T. Henderson, J. Klemp, W. Skamarock and W. Wang. 2004. The Weather Research and Forecast Model: Software Architecture and Performance. Proceedings of the 11th ECMWF Workshop on the Use of High Performance Computing in Meteorology. October 25-29, 2005, Reading UK. Ed. George Mozdzynski. (http://wrf-model.org/wrfadmin/docs/ecmwf_2004.pdf).

Moore, C.T. et al. 2011. "Deterministic and Empirical Assessment of Smoke's Contribution to Ozone – Final Report. Western Governors' Association, Denver, CO. (https://wraptools.org/pdf/11-1-6-6_final_report_DEASCO3_project.pdf)

Morris, R. E. and T. C. Myers. 1990. User's Guide for the Urban Airshed Model. Volume I: User's Manual for UAM (CB-IV) prepared for the U.S. Environmental Protection Agency (EPA-450/4-90-007a). Systems Applications International, San Rafael, CA.

Morris, R.E., G.E. Mansell, E. Tai, D.A. McNally and T.W. Tesche. 2004a. Air Quality Modeling Analysis for the Denver Early Action Compact: Preliminary Photochemical Base Case Modeling and Model Performance Evaluation for the Summer '02 Denver Ozone Season and Embedded High 8-Hour Ozone Episodes. Prepared for Denver Regional Air Quality Council, Denver, Colorado. Prepared by ENVIRON International Corporation, 101 Rowland Way, Novato, CA 94945. November.

Morris, R.E., G.E. Mansell, E. Tai, D.A. McNally and T.W. Tesche. 2004b. Air Quality Modeling Analysis for the Denver Early Action Compact: 2007 Base Case, Control Strategy and Sensitivity Analysis Modeling. Prepared for Denver Regional Air Quality Council, Denver, Colorado. Prepared by ENVIRON International Corporation, 101 Rowland Way, Novato, CA 94945. January.

Morris, R.E., G.E. Mansell, E. Tai, D.A. McNally and T.W. Tesche. 2004c. Air Quality Modeling Analysis for the Denver Early Action Compact: 2007 Emissions Reduction Sensitivity Modeling. Prepared for Colorado Department of Health and Environment and Denver Regional Air Quality Council, Denver, Colorado. Prepared by ENVIRON International Corporation, 101 Rowland Way, Novato, CA 94945. February.

Morris, R.E., G.E. Mansell, E. Tai, D.A. McNally and T.W. Tesche. 2004d. Air Quality Modeling Analysis for the Denver Early Action Compact: 2007 Control Strategy Modeling for the Denver EAC. Prepared for the Colorado Department of Health and Environment and Denver Regional Air Quality Council, Denver, Colorado. Prepared by ENVIRON International Corporation, 101 Rowland Way, Novato, CA 94945. February.

Morris, R., B. Wang, E. Tai, D. McNally, C. Loomis, G. Stella and T.W. Tesche. 2007. Modeling Protocol for the Denver 8-Hour Ozone Attainment Demonstration Modeling. ENVIRON International Corporation, Novato, CA. November. (http://www.ozoneaware.org/documents/DraftFinalProtocolDenver8-HourOzoneNov282007.pdf).

Morris R., E. Tai, L. Parker, J. Johnson, D. McNally and C. Loomis. 2008a. Initial Ozone Model Performance Evaluation of the June-July 2006 Denver Ozone Episode and Diagnostic Testing and Analysis. ENVIRON International Corporation, Novato, California. Prepared for Denver Regional Air Quality Council (RAQC), Denver, Colorado. May 13. (http://www.ozoneaware.org/documents/Prelim_Ozone_Eval_Denver_SIP_Feb27_2008.pdf)

Morris R., E. Tai, T. Sakulyanontvittaya, D. McNally and C. Loomis. 2008b. Model Performance Evaluation for the June-July 2006 Ozone Episode for the Denver 8-Hour Ozone State Implementation Plan. ENVIRON International Corporation, Novato, California. Prepared for Denver Regional Air Quality Council (RAQC), Denver, Colorado. August 29. (http://www.ozoneaware.org/documents/modeling/Denver_2006MPE_DraftFinal_Aug29_2008.pdf)

Morris R., T. Sakulyanontvittaya, E. Tai, D. McNally and C. Loomis. 2008c. 2010 Ozone Attainment Demonstration Modeling for the Denver 8-Hour Ozone State Implementation Plan Control Strategy. ENVIRON International Corporation, Novato, California. Prepared for Denver Regional Air Quality Council (RAQC), Denver, Colorado. September 22. (http://www.ozoneaware.org/documents/modeling/Denver_2010ControlStrat_Draft_Sep22_2008.pdf)

Morris R., T. Sakulyanontvittaya, E. Tai, D. McNally and C. Loomis. 2009a. Final 2010 Ozone Attainment Demonstration Modeling for the Denver 8-Hour Ozone State Implementation Plan Control Strategy. ENVIRON International Corporation, Novato, California. Prepared for Denver Regional Air Quality Council (RAQC), Denver, Colorado. January 12. (http://www.colorado.gov/airquality/documents/deno308/2010_Denver_Final_Control_Jan12_2009.pdf)

Morris R., T. Sakulyanontvittaya, E. Tai, D. McNally and C. Loomis. 2009b. 2015 and 2020 Ozone Projections for the Denver Area. ENVIRON International Corporation, Novato, California. Prepared for Denver Regional Air Quality Council (RAQC), Denver, Colorado. July 15. (http://www.ozoneaware.org/postfiles/documentsandpresentations/modeling/Denver_2015-2020_Ozone_Projections_Jul15_2009.pdf)

Morris R., E. Tai, B. Koo, D. McNally and C. Loomis. 2011. Sensitivity Modeling to Investigate Modeling Improvements for the June-July 2006 Denver Ozone Episode. Prepared for Denver Regional Air Quality Council (RAQC). Prepared by ENVIRON International Corporation, Novato, CA and Alpine Geophysics, LLC, Arvada, CO. June.

Morris R., E. Tai and T. Sturtz. 2011. Analysis of Predicted and Observed VOC Concentrations for the June-July 2006 Modeling Periods Used in the 2008 Denver Ozone SIP. ENVIRON International Corporation, Novato, CA. May.

Morris, R.E., E. Tai, D. McNally and C. Loomis. 2012a. Preliminary Ozone Model Performance Evaluation for the Denver 2008 Episode. ENVIRON International Corporation, Novato, California. June. (http://raqc.org/postfiles/ozone_modeling/modeling_forum/Denver_2008_Prelim_MPE_080912.pdf).

Morris, R., B. Koo, E. Tai, D. McNally and C. Loomis. 2012b. Revised Base Case Modeling and Model Performance Evaluation for the Denver 2008 Ozone Episode. ENVIRON International Corporation, Novato, CA. August.

Morris, R.E., T. Shah and C. Lindhjem. 2014. Procedures for Generating On-Road Mobile Source Emissions. ENVIRON International Corporation, Novato, CA. Prepared for Amanda Brimmer, Denver Regional Air Quality Council (RAQC). September 15.

Petron, G. et al. 2012. Hydrocarbon emissions characterization in the Colorado Front Range: a pilot study. *J. Geophy. Res.*, 117, D04304.

Pfister, G. and F. Flocke. 2017. Process-Based and Regional Source Impact Analysis for FRAPPÉ and DISCOVER-AQ 2014. Final Report. National Center for Atmospheric Research (NCAR), Atmospheric Chemistry Observations and Modeling Laboratory (ACOM), Boulder, Colorado. July 31. (https://www.colorado.gov/airquality/tech_doc_repository.aspx?action=open&file=FRAPPE-NCAR_Final_Report_July2017.pdf).

Ramboll. 2013. METSTAT Meteorological Model Statistical Evaluation Package. Ramboll, Novato, California. December 9. (http://www.camx.com/download/support-software.aspx).

Ramboll. 2018a. User’s Guide Comprehensive Air-quality Model with extensions Version 6.5. Ramboll, Novato, California. April. (http://www.camx.com/files/camxusersguide_v6-10.pdf).

Ramboll. 2018b. Denver Metro/North Front Range Base Year and Future Year Ozone SIP Modeling and Sensitivity Analysis. Response to Request for Proposal from Regional Air Quality Council. Ramboll, Novato, California. July.

Ramboll. 2018c. Relative Reduction Factors Using Anthropogenic Ozone Increments. Coordinating Research Council Report No. A-112. Ramboll US Corporation, Novato, CA. October. (https://crcao.org/reports/recentstudies2018/A-112/CRC_A-112_Executive%20Summary_22Oct18.pdf).

Ramboll and Alpine. 2015. Attainment Demonstration Modeling for the Denver Metro/North Front Range 2017 8-Hour Ozone State Implementation Plan – Modeling Protocol. Ramboll, Novato, California and Alpine Geophysics, Arvada, Colorado. August.

Ramboll and Alpine. 2015. Attainment Demonstration Modeling for the Denver Metro/North Front Range 2017 8-Hour Ozone State Implementation Plan -- Modeling Protocol. Ramboll, Novato, California and Alpine Geophysics, LLC, Arvada, Colorado. August.

Ramboll and Alpine. 2016a. Denver Metro/North Front Range 2017 8-Hour Ozone State Implementation Plan: 2017 Attainment Demonstration Modeling. Final Report. Ramboll, Novato, California and Alpine Geophysics, LLC, Arvada, Colorado. September. (https://raqc.egnyte.com/dl/GLuuTNMC8t/TSD_2017Modeling%26AttainmentDemonstration.pdf_).

Ramboll and Alpine. 2016b. Denver Metro/North Front Range 2017 8-Hour Ozone State Implementation Plan: Air Quality Technical Support Document (AQTSD). Final. Ramboll, Novato, California and Alpine Geophysics, LLC, Arvada, Colorado. October. (https://raqc.egnyte.com/dl/mm7FkWlbFy/TSD_AQTSD.pdf_).

Ramboll and Alpine. 2017a. Denver Metro/North Front Range 2017 8-Hour Ozone State Implementation Plan: 2011 Base Case Modeling and Model Performance Evaluation. Final Report. Ramboll, Novato, California and Alpine Geophysics, LLC, Arvada, Colorado. September. (https://raqc.egnyte.com/dl/pxHfZAhquy/TSD_2011_BaseCaseModeling%26MPE.pdf_).

RAQC and CDPHE. 2006. Early Action Compact -- Ozone Action Plan – Proposed Revision to the State Implementation Plan. Regional Air Quality Council and Colorado Department of Health and Environment, Denver, Colorado. Approved by Colorado Air Quality Control Commission December 17, 2006. (http://raqc.org/postfiles/sip/ozone_8hr/EAC_SIPRev121706.pdf).

RAQC and CDPHE. 2016. State Implementation Plan for the 2008 8-Hour Ozone National Ambient Air Quality Standard. Regional Air Quality Council and Colorado Department of Health and Environment, Air Pollution Control Division. Approved by the Colorado Air Quality Control Commission on November 17, 2018. (https://raqc.egnyte.com/dl/q5zyuX9QC1/FinalModerateOzoneSIP_2016-11-29.pdf_).

Reddy, P.J. and G.G. Pfister. 2016. Meteorological factors contributing to the interannual variability of midsummer surface ozone in Colorado, Utah, and other western U.S. states. *J. Geo. Res.:* Atmospheres (JGR).

10.1002/2015JD023840. March. (https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1002/2015JD023840).

Sakulyanontvittaya, T., G. Yarwood and A. Guenther. 2012. Improved Biogenic Emission Inventories across the West. ENVIRON International Corporation, Novato, CA. March 19. (http://www.wrapair2.org/pdf/WGA_BiogEmisInv_FinalReport_March20_2012.pdf).

Simon, H., K. Baker and S. Phillips. 2012. Compilations and Interpretation of Photochemical Model Performance Statistics Published between 2006 and 2012. *Atmos. Env.* 61 (2012) 124-139. December. (http://www.sciencedirect.com/science/article/pii/S135223101200684X).

Skamarock, W. C. 2004. Evaluating Mesoscale NWP Models Using Kinetic Energy Spectra. *Mon. Wea. Rev.*, Volume 132, pp. 3019-3032. December. (http://www.mmm.ucar.edu/individual/skamarock/spectra_mwr_2004.pdf).

Skamarock, W. C., J. B. Klemp, J. Dudhia, D. O. Gill, D. M. Barker, W. Wang and J. G. Powers. 2005. A Description of the Advanced Research WRF Version 2. National Center for Atmospheric Research (NCAR), Boulder, CO. June. (http://www.mmm.ucar.edu/wrf/users/docs/arw_v2.pdf)

Skamarock, W. C. 2006. Positive-Definite and Monotonic Limiters for Unrestricted-Time-Step Transport Schemes. *Mon. Wea. Rev.*, Volume 134, pp. 2241-2242. June. (http://www.mmm.ucar.edu/individual/skamarock/advect3d_mwr.pdf).

Stoeckenius, T.E., C.A. Emery, T.P. Shah, J.R. Johnson, L.K. Parker, A.K. Pollack. 2009. Air Quality Modeling Study for the Four Corners Region; Prepared by ENVIRON International Corporation, Novato, CA. Prepared for the New Mexico Environment Department, Air Quality Bureau, Santa Fe, NM.

Stoeckenius, T., T. Olevski and M. Zatko. 2018. Representativeness of Candidate Modeling Years for the Western U.S. Ramboll, Novato, California. July. (https://www.wrapair2.org/pdf/WESTAR_RTOWG_Representativeness_final.pdf)

Tesche, T.W., D.E. McNally, C. Loomis, R.W. Morris and G.E. Mansell. 2003. "Revised Ozone Modeling Protocol -- Air Quality Modeling Analysis for the Denver Early Action Ozone Compact: Modeling Protocol, Episode Selection, and Domain Definition". Alpine Geophysics, LLC, Ft. Wright, Kentucky and ENVIRON International Corporation, Novato, California. Prepared for Mr. Gerald Dilley, Denver Regional Air Quality Council. May.

UNC. 2008. Atmospheric Model Evaluation Tool (AMET) User's Guide. Institute for the Environment, University of North Carolina at Chapel Hill. May 30. (https://www.cmascenter.org/amet/documentation/1.1/AMET_Users_Guide_V1.1.pdf).

UNC and ENVIRON, 2014a. Three-State Air Quality Modeling Study (3SAQS) – Draft Modeling Protocol 2011 Emissions & Air Quality Modeling. University of North Carolina at Chapel Hill and ENVIRON International Corporation, Novato, CA. July. (http://vibe.cira.colostate.edu/wiki/Attachments/Modeling/3SAQS_2011_Modeling_Protocol_Finalv2.pdf).

UNC. 2015. SMOKE v3.6.5 User's Manual. University of North Carolina at Chapel Hill, Institute for the Environment. (https://www.cmascenter.org/smoke/documentation/3.6.5/html/).

UNC and ENVIRON, 2015a. Three-State Air Quality Modeling Study (3SAQS) – Weather Research Forecast 2011 Meteorological Model Application/Evaluation. University of North Carolina at Chapel Hill and ENVIRON International Corporation, Novato, CA. March 5. (http://vibe.cira.colostate.edu/wiki/Attachments/Modeling/3SAQS_2011_WRF_MPE_v05Mar2015.pdf).

UNC. 2018. SMOKE v4.6 User's Manuel. University of North Carolina at Chapel Hill, Institute for the Environment. Chapel Hill, North Carolina. September 24. (https://www.cmascenter.org/smoke/documentation/4.6/manual_smokev46.pdf).

Wesely, M.L. 1989. Parameterization of Surface Resistances to Gaseous Dry Deposition in Regional-Scale Numerical Models. *Atmos. Environ.*, 23, 1293-1304.

Wiedinmyer, C., T. Sakulyanontvittaya and A. Guenther. 2007. MEGAN FORTRAN code V2.04 User Guide. NCAR, Boulder, CO. October 29. (http://acd.ucar.edu/~guenther/MEGAN/MEGANguideFORTRAN204.pdf).

Yarwood, G., J. Jung, G. Z. Whitten, G. Heo, J. Mellberg and M. Estes. 2010. Updates to the Carbon Bond Mechanism for Version 6 (CB6). 2010 CMAS Conference, Chapel Hill, NC. October. (http://www.cmascenter.org/conference/2010/abstracts/emery_updates_carbon_2010.pdf)

Zhang, L., S. Gong, J. Padro, L. Barrie. 2001. A size-segregated particle dry deposition scheme for an atmospheric aerosol module. *Atmos. Environ.*, **35**, 549-560.

Zhang, L., J. R. Brook, and R. Vet. 2003. A revised parameterization for gaseous dry deposition in air-quality models. *Atmos. Chem. Phys*., **3**, 2067–2082.

# APPENDIX A

## Episode Selection for the DM/NFR 2020 and 2023 Ozone Attainment Demonstration Modeling

# Appendix A Episode Selection for the DM/NFR 2020 and 2023 Ozone Attainment Demonstration Modeling

## A.1 INTRODUCTION

EPA's current and past 8-hour ozone modeling guidance (EPA, 2007; 2014d; 2018d) contains recommended procedures for selecting modeling episodes for demonstrating attainment of the ozone NAAQS. The DM/NFR NAA 2020/2023 attainment demonstration modeling will use the summer of 2016 as the modeling period because it is representative of high ozone conditions for the region and of the candidate modeling periods satisfies the most criteria in EPA's episode selection discussion (EPA, 2018d). This Appendix provides details of the technical analysis used to justify the selection of the summer of 2016 modeling period presented in Chapter 3.

The summers of 2016 or 2017 were the two candidate modeling periods recommended by the RAQC, unless there is a reason to believe neither candidate year is appropriate. This Appendix contains analysis that supports the selection of the summer 2016 for the DM/NFR NAA 2020/2023 attainment demonstration modeling by conducting the following analysis:

- Extension of the WRAP Representative Year Analysis Study from 2014-2016 to 2014-2018 that takes a broad-brush review for identifying a representative year for ozone, $PM_{2.5}$ and Regional Haze modeling of the western U.S., including the DM/NFR NAA.

- Comparison of 2016 and 2017 ozone levels in the DM/NFR NAA with those for the most recent years (2011-2018).

- Extension of the analysis of ozone formation potential in the Colorado-Utah region by Pfister and Reddy (2016) for a longer period (1995-2018) including the 2016 and 2017 candidate modeling years. The Pfister and Reddy (2016) approach analyzes key summer average meteorological variables with ozone levels in the DM/NFR NAA and determines how representative the ozone formation potential of the candidate summers of 2016 and 2017 compares with a long period of record (> 20 years).

- Analyzing the relationship of key meteorological variables indicating ozone conducive formation conditions with DMA8 ozone concentrations in the DM/NFR NAA for the 20-highest observed MDA8 ozone days at key monitoring sites during 2016 and 2017 and compares them with a long-term (14-23 years depending on the monitoring site) period of record that spans through the b2018 most recent year.

- Analysis of Precipitation, Temperature, Drought and Fires that could influence ozone concentrations in the DM/NFR NAA in more recent years.

## A.2 RECENT WRAP REPRESENTATIVE YEAR ANALYSIS

The Regional Technical Operations Work Group (RTOWG) of the Western Regional Air Partnership (WRAP) evaluated the representativeness of three recent years (2014, 2015 and 2016) for their updated annual western regional photochemical modeling platform (Stoeckenius et al., 2018). The purpose of the WRAP RTOWG representative year study was to determine which of the 2014, 2015 and 2016 candidate modeling years was most representative of typical conditions for ozone, $PM_{2.5}$ and regional haze in the western U.S. and which year would be most appropriate base year for regional photochemical modeling. We extended the WRAP RTOWG representative year analysis to include 2017 so the analysis covered the 2014-2017 4-year period including the 2016 and 2017 candidate years for the DM/NFR NAA ozone SIP modeling.

The WRAP RTOWG representative year study noted that for regional air quality planning:

> "As significant resources are required to develop and exercise an annual air quality modeling platform for analysis of the issues of concern (primarily ground-level ozone, particulate matter, regional haze, and nitrogen deposition), it is important to establish the "degree of representativeness", or the degree of difference between calendar base year(s) selected for simulation and analysis. The objective of this study is to compare and contrast the key characteristics of each year analyzed both with respect to each other and with respect to long-term averages."

The key characteristics analyzed included: meteorology (e.g., 500 hPa heights, hydrology, surface temperatures); fires; emissions (EGUs and on-road); and air quality (visibility, nitrogen deposition, ozone and PM). The WRAP RTOWG study considered a large area of interest (i.e. entire western and central U.S. including the WRAP states and selected adjacent CenSARA states).

For some of the key characteristics analyzed, specific years were shown to exhibit particular characteristics. For example, 2015 exhibited severe drought conditions west of Rockies and significant fire activity in western Canada and northwestern U.S. that had important impacts on air quality in 2015. 2017 saw high wildfire impacts on air quality in the western U.S., that influenced ozone in the DM/NFR NAA. For many characteristics, however, seasonal variations and regional variations lead the authors to conclude that (Stoeckenius et al., 2018):

> "most if not every year exhibits significant deviations from long-term means somewhere within the full set of parameters, location, and seasons impacting the results of an annual photochemical simulation for ozone and PM. This points to the need to further develop modeling capabilities to enhance the feasibility of multi-year simulations. A minimum 3 to 5-year period is needed to provide robust results commensurate with averaging time specified in National Ambient Air Quality Standards which are intended to minimize the influence of year-to-year meteorological variability on the air quality metric used for the NAAQS."

Of the two candidate years for the DM/NFR NAA ozone SIP modeling, 2016 appeared to be more typical than 2017 that had higher wildfire impacts and lower ozone levels than recent years.

## A.3 COMPARISON OF OZONE LEVELS IN THE DM/NFR NAA OVER 2011-2018

One of the most important attributes of the DM/NFR NAA 2020/2023 ozone attainment demonstration modeling base year is to have ozone levels representative of high observed ozone concentrations that led to the DM/NFR NAA failure to attain the 2008 ozone NAAQS and being designated as nonattainment of the 2015 ozone NAAQS.

Figures A-1 through A-3 display the maximum (1st highest), the 4th highest and average of the 20 highest observed MDA8 ozone concentrations at monitoring sites in the DM/NFR NAA over the last 8-years (2011-2018), with the four key monitoring sites of RFNO, CHAT, NREL and FTCW highlighted by bold dotted lines. Although 2011 had the highest maximum MDA8 ozone concentrations at RFNO, CHAT and NREL during the 2011-2018 period, the maximum value may be only representative of one day during the ozone season so does not necessarily indicate a preferred modeling year. The summer of 2011 was the base year used in the 2016 Denver ozone SIP (RAQC and CDPHE, 2016) and is too old for current modeling needs.

When looking at the 4th highest and average of the 20 highest MDA8 ozone concentrations at the four key monitoring sites (Figures A-2 and A-3), 2011 – 2013 and 2018 generally have the highest MDA8 ozone concentrations, with 2014 and 2017 having lower ozone concentrations than typical and the 2015-2016 years having average to higher than typical ozone concentrations.

Thus, 2016 does not appear to have atypically high or low ozone concentrations although it is somewhat above average for recent years. 2017 also does not appear to have atypically higher or lower levels of ozone, although it has generally slightly lower than average year high ozone concentrations based on the maximum, 4th high and average of 20-highest observed MDA8 ozone concentration 2011-2018 trends analysis shown in Figure A-1 through Figure A-3.

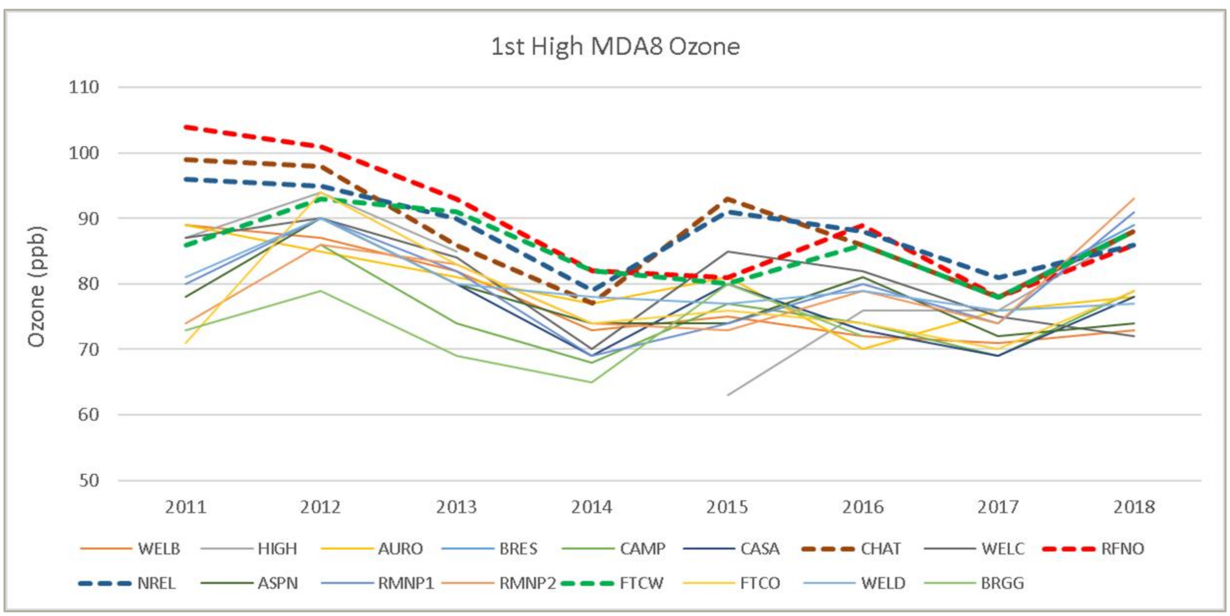



**Figure A-1. 2011-2018 maximum MDA8 ozone concentrations at each monitoring site in the DM/NFR.**

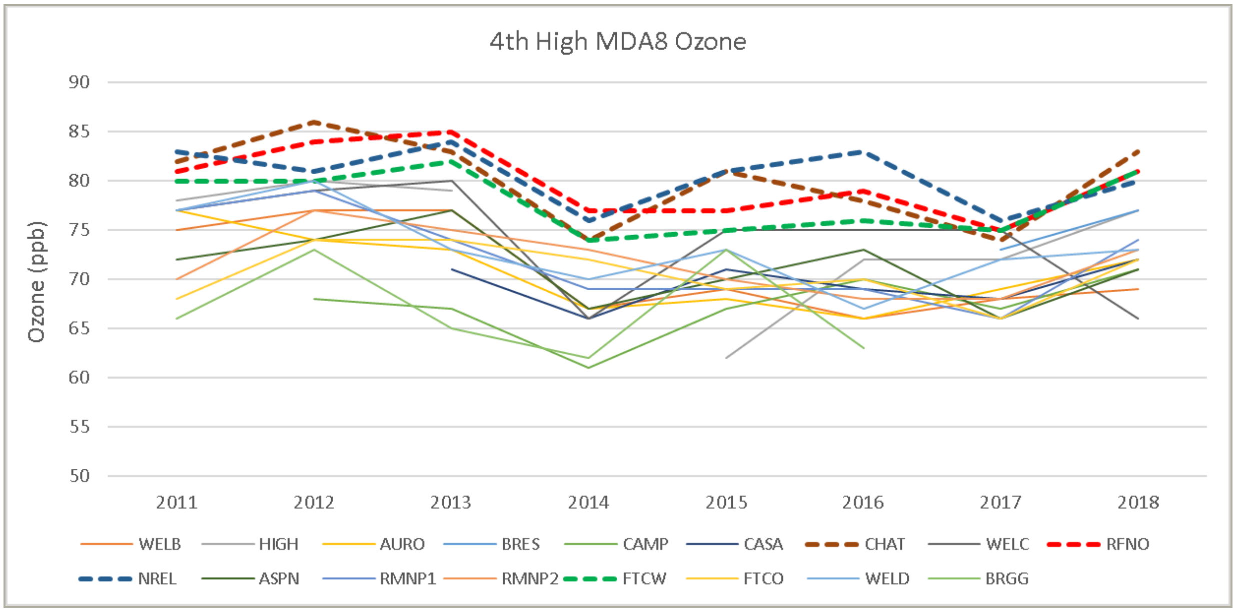



**Figure A-2. 2011-2018 4th highest MDA8 ozone concentrations at monitoring sites in the DM/NFR NAA.**

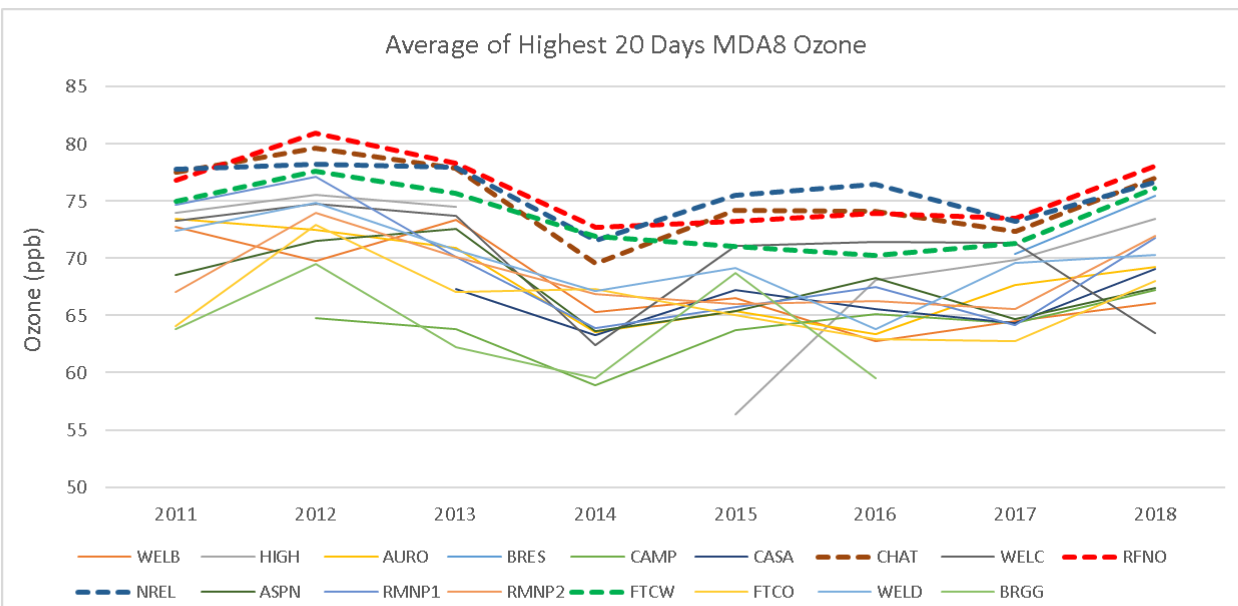



**Figure A-3. 2011-2018 average of the 20 highest MDA8 ozone concentrations at monitoring sites in the DM/NFR NAA.**

## A.4 TRENDS IN OZONE AND SUMMER AVERAGE METEOROLGICAL CONDITIONS CONDUCIVE TO HIGH OZONE CONCENTRATIONS IN THE DM/NFR NAA

Reddy and Pfister (2016) and CDPHE and RAQC (2016c) analyzed meteorological factors that contributed to the interannual variability in July average and midsummer average and 4$^{th}$ highest MDA8 ozone concentrations focusing mainly on Utah and Colorado. Reddy and Pfister (2016) analyzed monthly average ozone and meteorological conditions for July and the years 1995-2013 and found several meteorological variables that were able to explain the year-to-year variability in ozone formation conditions. The most powerful meteorological variable for describing high ozone formation potential conditions (i.e. ozone conducive conditions) was the height of the 500 hPa[68] or 500 mb pressure level. They explained that elevated 500 hPa heights were associated with a host of conditions conducive to high ozone, including light winds aloft, high temperatures in the mixed layer, limited mixing, well-developed mountain-plains circulations, and clear skies. In this sense, mean height can be considered an indicator for many other conditions that lead to high ozone as well as an indicator for the intensity of worst-case episodes throughout the summer. Figure A-4 reproduced from Reddy and Pfister (2016) displays a regression analysis for the years 1995-2013 of ozone against 500 hPa heights for two sites in the DM/NFR and shows that 2003 had the highest average July 500 hPa heights and the highest ozone, whereas the 1995 and 2004 years had the lowest July 500hPa heights and corresponding lowest ozone concentrations.

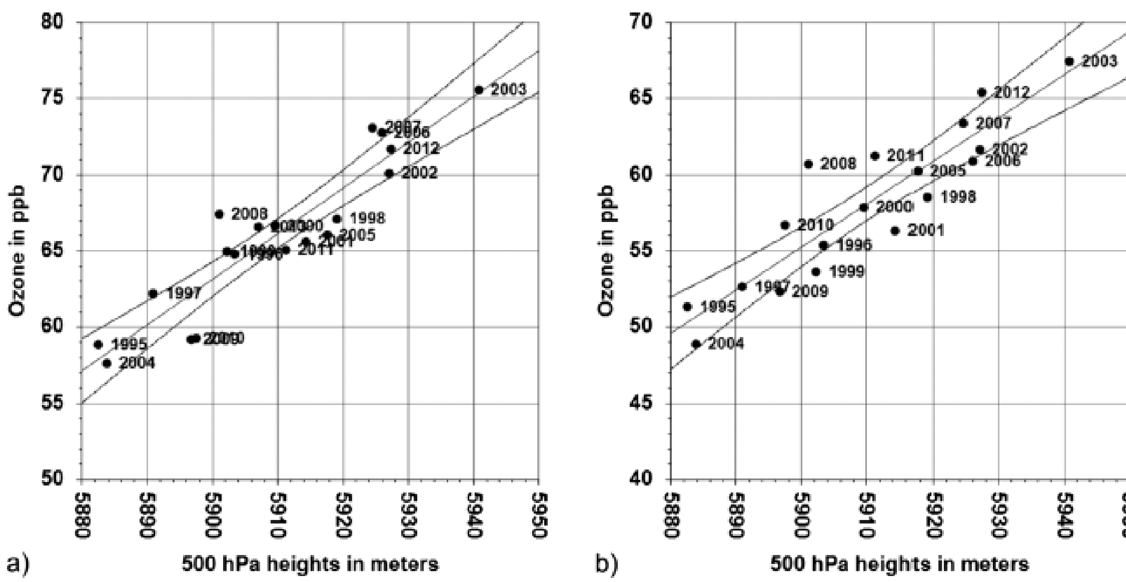



**Figure A-4. Linear regression with confidence limits between July mean MDA8 ozone and July mean 500 hPa heights for: (a) Rocky Flats North; and (b) Carriage monitoring sites (Source: Reddy and Pfister, 2016).**

[68] hPa is100 Pa where Pa is short for Pascal that is a unit of pressure where 500 hPa = 500 mb.

The CDPHE and RAQC (2016c) expanded the Reddy and Pfister (2016) July average ozone analysis for 1995-2013 to summer-average and 4$^{th}$ high MDA8 ozone conditions and demonstrated that the annual 4$^{th}$ high MDA8 ozone was strongly correlated with mean July through August 500 hPa heights. We have updated this analysis and extended it through the year 2018 so that it includes our two candidate summer base year modeling periods (2016 and 2017) as well as the most recent 2018 year that saw higher than expected observed ozone levels in the DM/NFR NAA. The height data were acquired from the NCEP/NCAR Reanalysis data set (Kalnay et al.,1996) provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their website[69]. Figures A-5 through A-9 show regressions of 4$^{th}$ highest MDA8 ozone against mean July through August 500 hPa heights for 1995 through 2018 and the RFNO, NREL, CHAT, and FTCW monitoring sites, respectively. R-squared values for these regressions were 0.32, 0.49, 0.51, and 0.39 for RFNO, NREL, CHAT, and FTCW, respectively. With correlation coefficients were 0.57, 0.70, 0.71, and 0.63 for the same sites. For each of these regressions, the null hypothesis is rejected (p = 0.05), and the slope is found to be nonzero.

2016 has higher summer-average 500 hPa heights than 2017 (Figures A-5 through A-9). 2016 also has substantially higher summer-average ozone than 2017 at RFNO, NREL and CHAT (Figures A-5 through A-8), and slightly higher summer-average ozone at FTCW (Figure A-9).

[69] https://www.esrl.noaa.gov/psd/

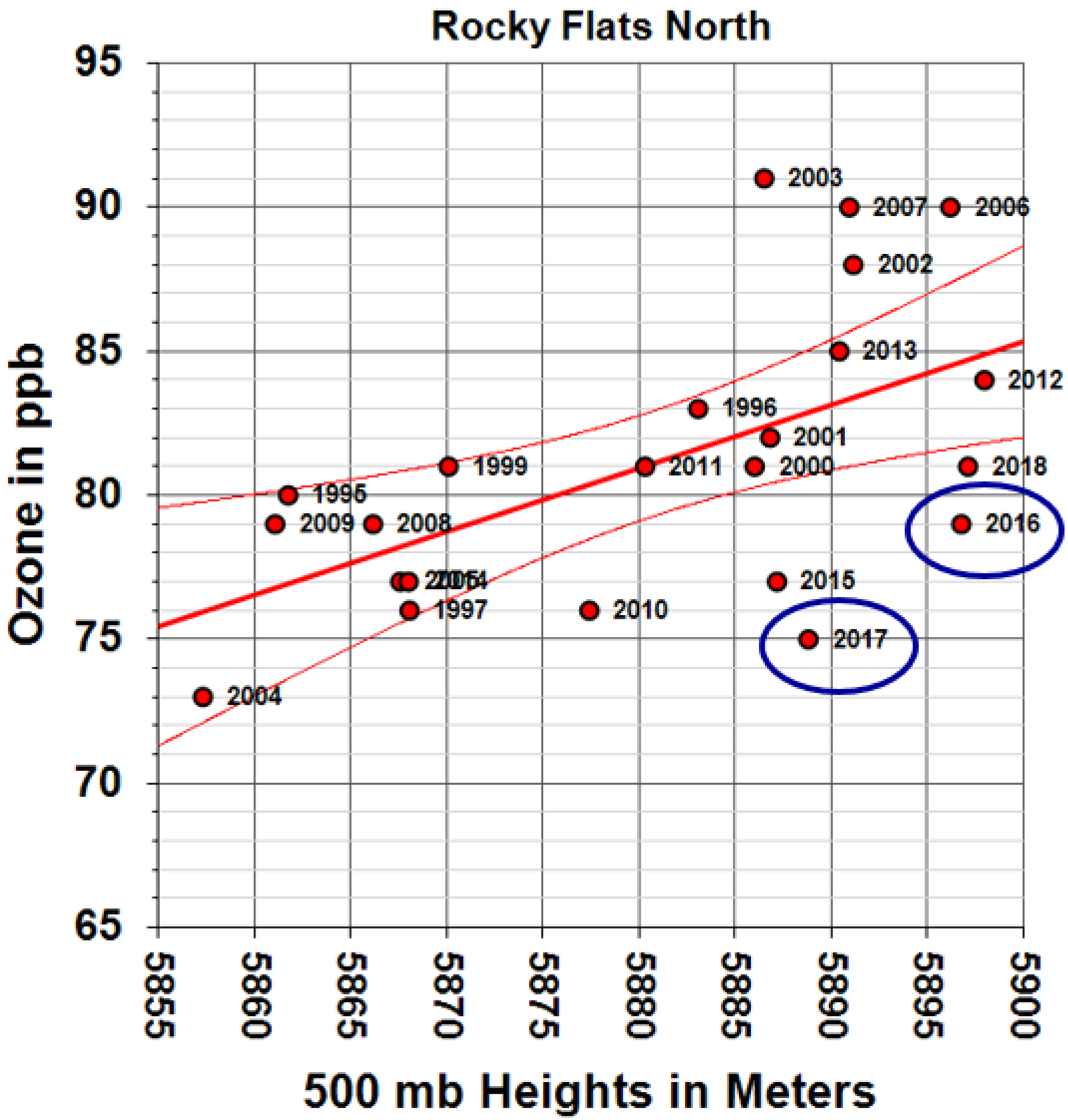



**Figure A-5. Linear regression of the annual 4th highest MDA8 ozone concentrations and mean July through August NCEP/NCAR Reanalysis 500 hPa (or 500 mb) heights for the DM/NFR region at the Rocky Flats North (RFNO) monitoring site for the years 1995 to 2018.**

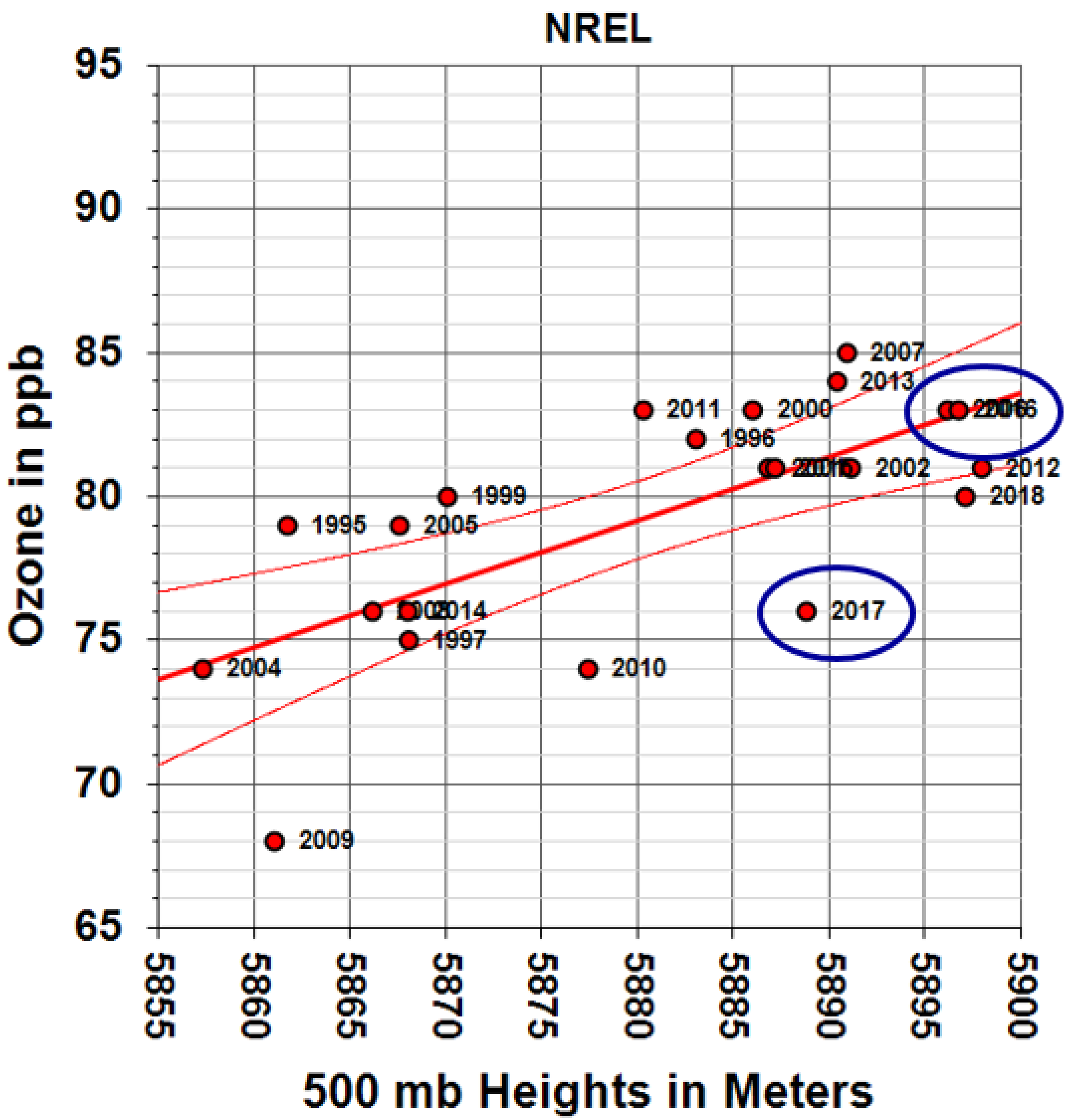



**Figure A-6. Linear regression of the annual 4th highest MDA8 ozone concentrations and mean July through August NCEP/NCAR Reanalysis 500 hPa (or 500 mb) heights for the DM/NFR region at the National Renewable Energy Laboratory (NREL) monitoring site for the years 1995 to 2018.**

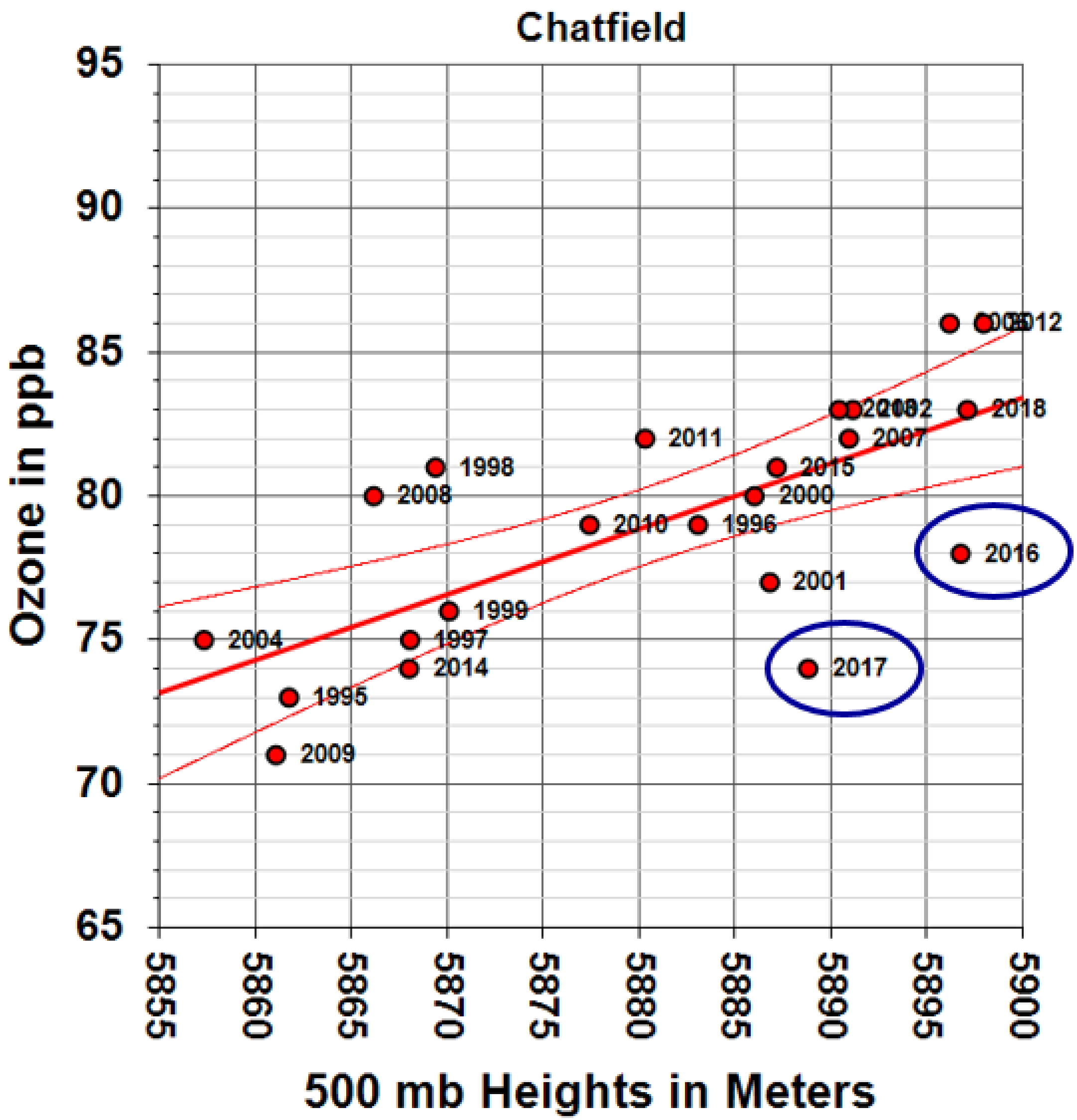



**Figure A-7. Linear regression of the annual 4th highest MDA8 ozone concentrations and mean July through August NCEP/NCAR Reanalysis 500 hPa (or 500 mb) heights for the DM/NFR region at the Chatfield Reservoir (CHAT) monitoring site for the years 1995 to 2018.**

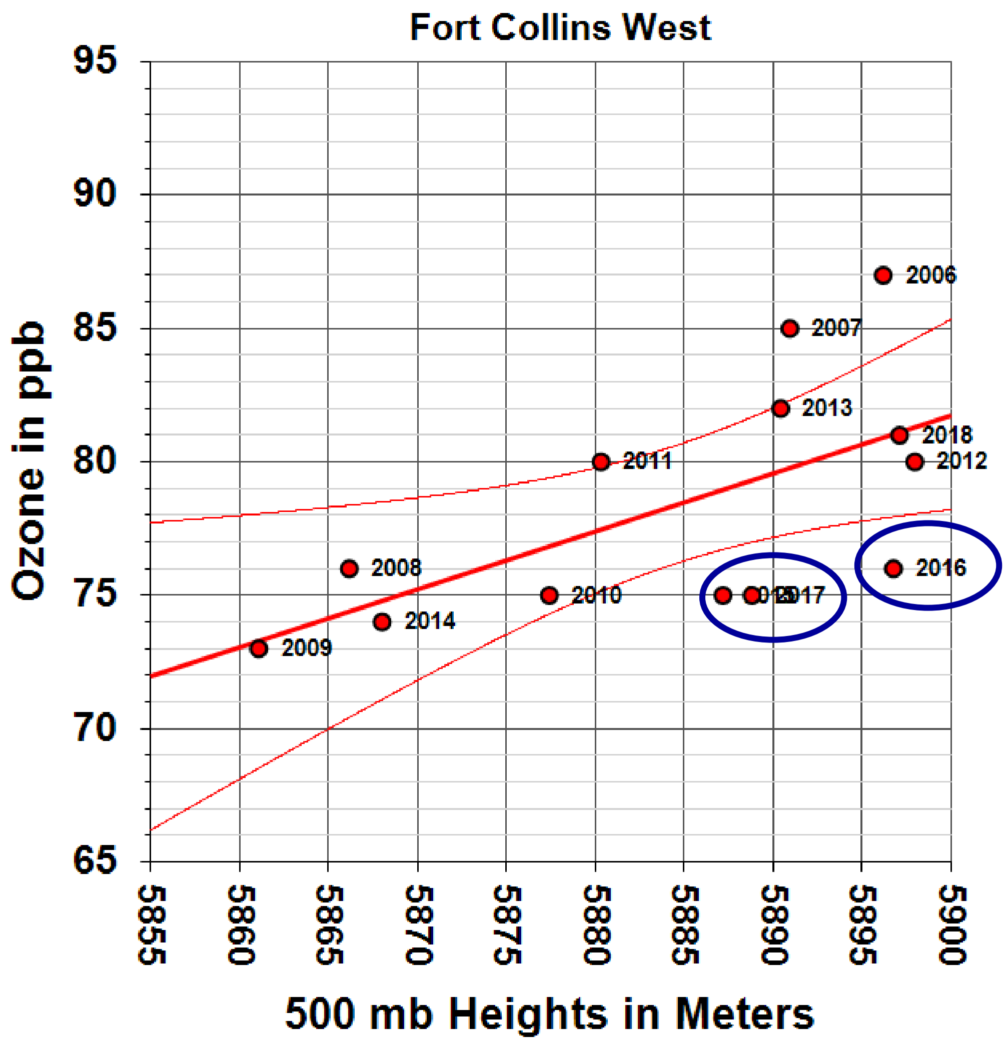



**Figure A-8. Linear regression of the annual 4th highest MDA8 ozone concentrations and mean July through August NCEP/NCAR Reanalysis 500 hPa (or 500 mb) heights for the DM/NFR region at the Fort Collins West (FTCW) monitoring site for the years 1995 to 2018.**

Figure A-9 presents the annual 4th high MDA8 ozone for these sites for 2006 through 2018. A linear regression with confidence limits and a LOESS smoothing curve (with a weighting factor of 0.30) have been fit to the data. Figure A-10 is the same but uses preliminary weather corrected 4th highest MDA8 ozone concentration based on the residuals in the four site-specific regressions in Figures A-5 through A-8 and the methods described by Reddy and Pfister (2016) and the CDPHE and RAQC (2016c). It is useful to consider these plots as well the site-specific regressions in Figures A-5 through A-8. Taken together, these provide information about the representativeness of 2016 and 2017, and why 2016 is the preferred model base year, and differences between recent years and the 2011 prior model base year used in the previous 2016 Denver ozone SIP.

Reddy and Pfister (2016) analyzed the years 1995-2013 and found that the Julys in 2002, 2003, 2006 and 2012 represents high periods of both MDA8 ozone and 500 hPa heights, while Julys of 1995, 1997, 2004 and 2009 represent years with lower values, especially in Colorado. This pattern of low and high years is also evident in Figure A-5 for RFNO, but the 4$^{th}$ high MDA8 values of 95 ppb at both NREL and CHAT in 2003 are not shown in Figures A-6 and A-7 since these values failed the studentized residual test for outliers described by Reddy and Pfister (2016). The updated regression and trend plot also show that 2014 is also a low year for ozone and heights. 2009 and 2010 are low in part because of the recession that resulted in lower emissions than would be expected. 2012 was a high fire year in the region. 2016 had the third highest July through August 500 hPa height with 5897 meters, indicating it was one of the summers with the highest potential for ozone production. The mean three-month summer heights for both 2016 and 2018 were at the 95$^{th}$ percentile level. Both 2015 and 2017 had heights fairly typical of the 2011 through 2018 period, a period with a generally warming climate. Except for 2014, the most recent years have had relatively high ozone formation potential as measured by the 500 hPa heights (Figure A-11).

The uncorrected 4$^{th}$ high MDA8 values in 2016 were neither unusually high nor unusually low compared with other values from 2012-2018 (Figure A-9). Weather-corrected ozone values show a steep decline from 2013 through 2017 (Figure A-10). NREL was an exception with corrected values hovering between 79 and 80 ppb in 2015 and 2016, and then falling dramatically in 2017. Using data from satellites and aircraft data from the FRAPPE and DISCOVER-AQ field campaigns, the RAQC and CDPHE made the hypothesis that NREL was responding more slowly to regional $NO_x$ reductions because it was frequently in the $NO_x$ plume from the Cherokee power plant on high ozone days. They also reasoned that the weather corrected 4$^{th}$ high MDA8 at NREL should decline significantly by 2017 due to anticipated reductions in Cherokee emissions, and the weather-corrected ozone data shows evidence that this happened. The trend in weather corrected ozone reverses in 2018. This might be due, in part, to wildfires in 2018. We will have a better idea about this in 2019 after CDPHE completes its analyses for flagging potential exceptional events that occurred in 2018.

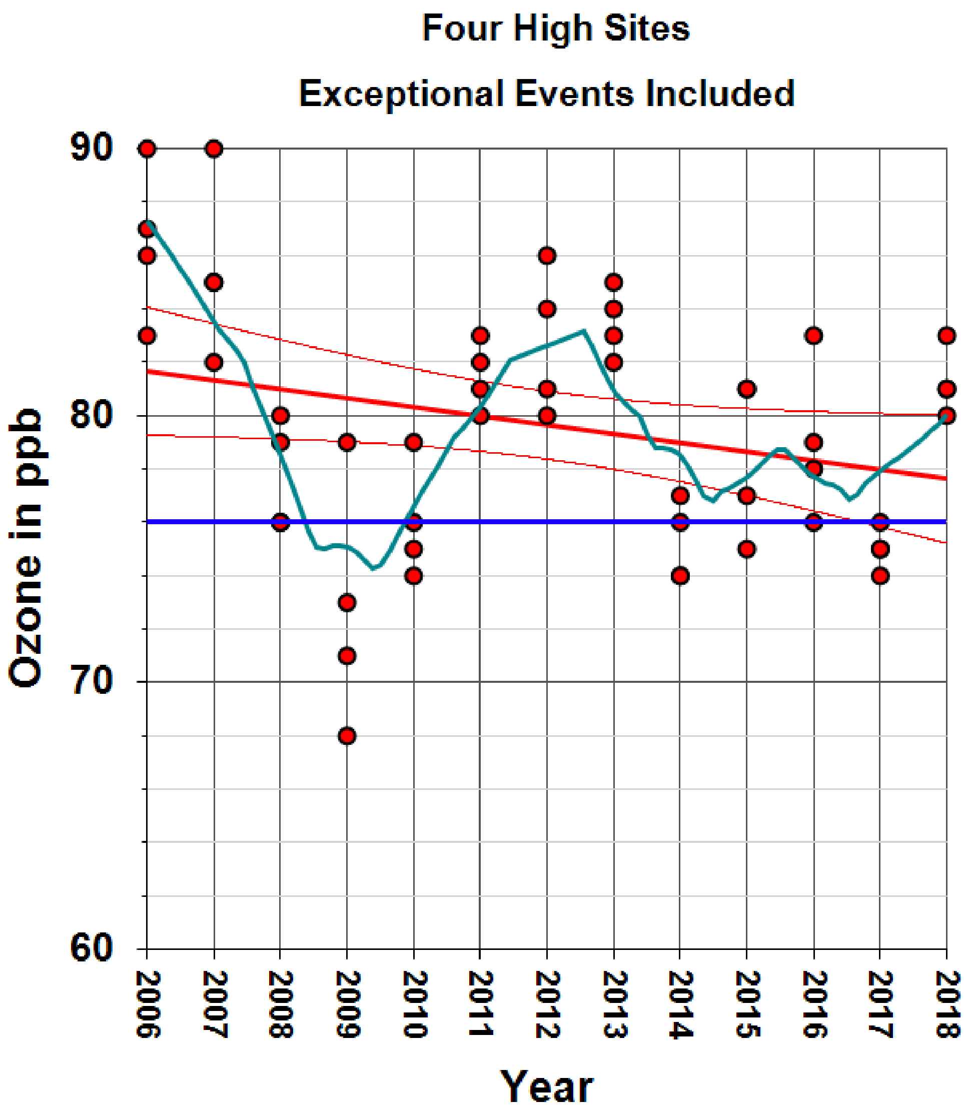



**Figure A-9. Trends in annual 4th high MDA8 ozone at RFLAT, NREL, CHAT, and FTCW for 2006 through 2018 with a linear regression with confidence limits and a LOESS smoothing curve. The blue line is the 76 ppb 8-hour standard.**

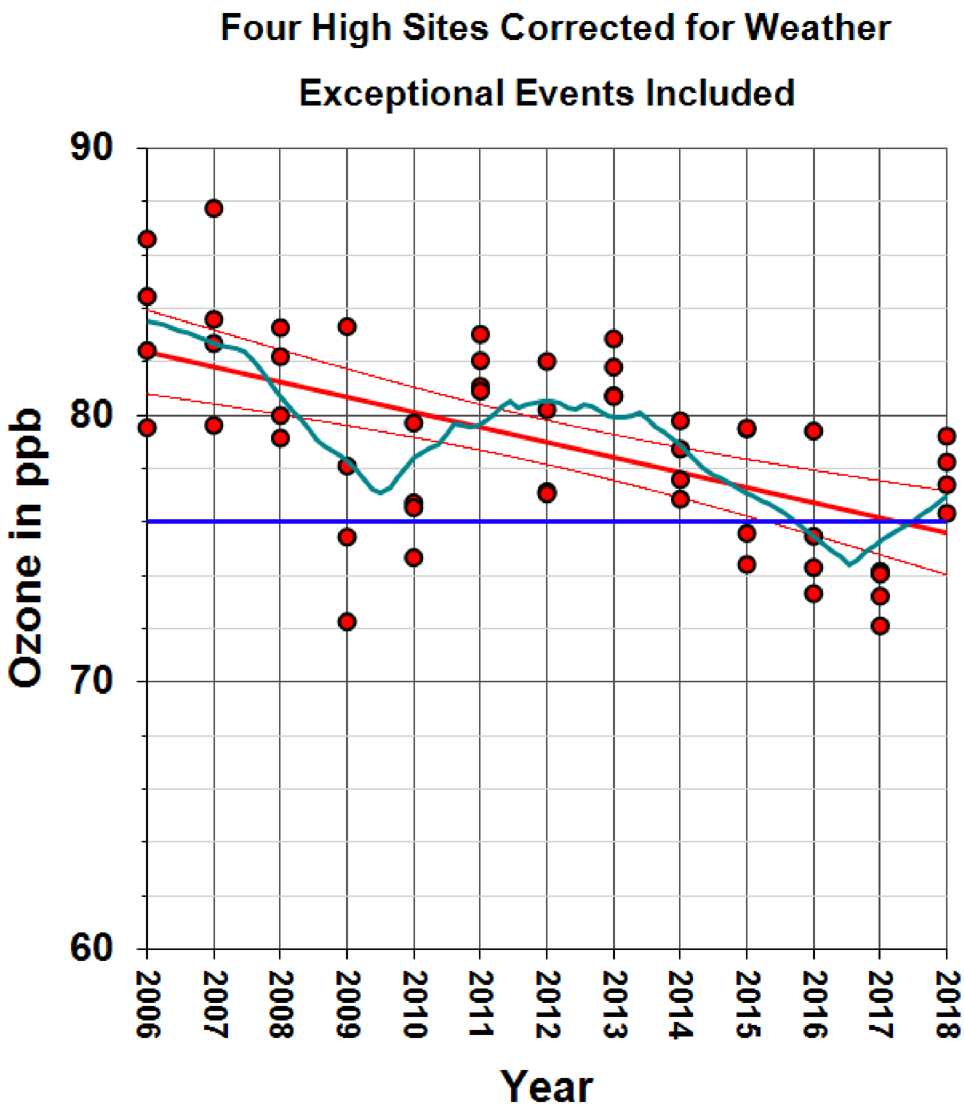



**Figure A-10. Trends in preliminary weather-corrected annual 4th high MDA8 ozone for 2006 through 2018 at RFLAT, NREL, CHAT, and FTCW with a linear regression with confidence limits and a LOESS smoothing curve. The blue line is the 76 ppb 8-hour standard.**

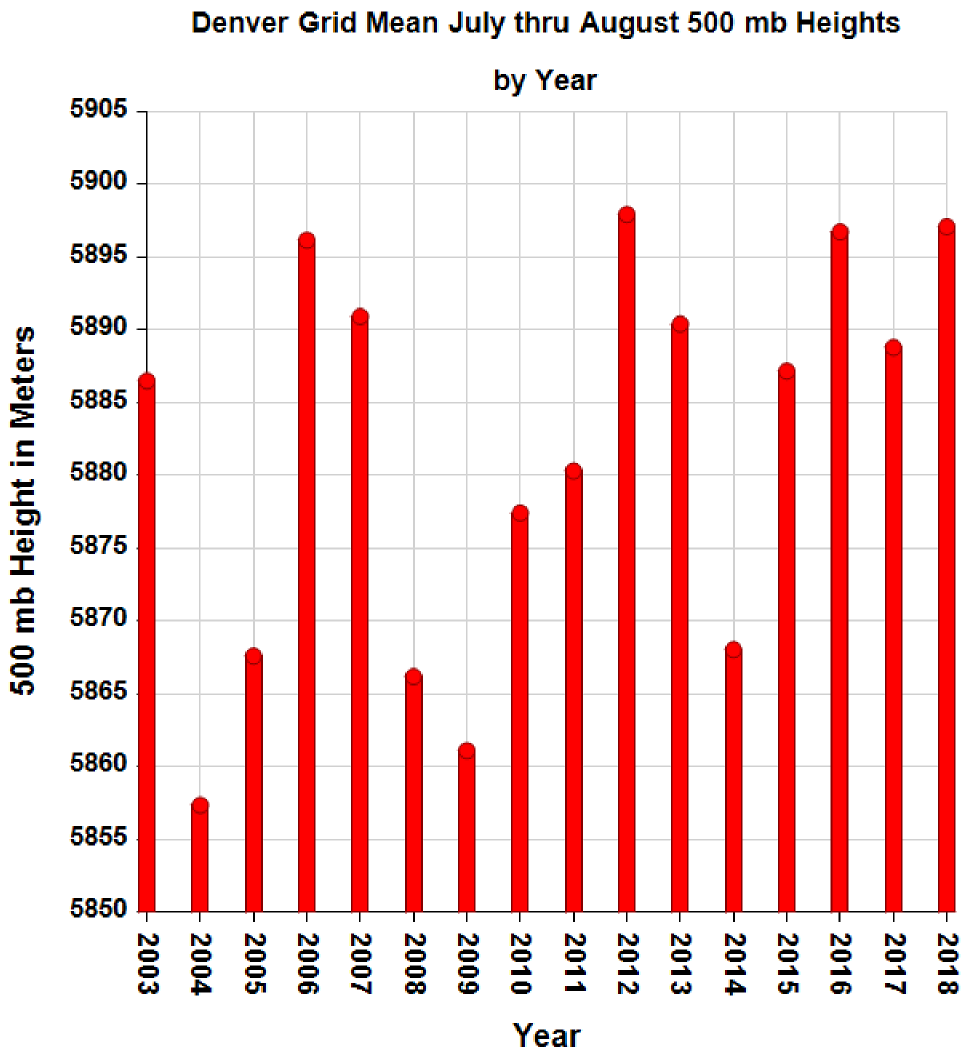



**Figure A-11. Mean July through August 500 hPa (500 mb) heights in meters from the NCEP/NCAR reanalysis data set for a grid cell encompassing much of the DM/NFR region.**

Reddy and Pfister (2016) demonstrated that ozone is high in the DM/NFR NAA when deep thermally-driven upslope and mountain-plains circulations are present. They showed that the 700 hPa (700 mb) vector winds and the departure of these winds from normal can be a useful indicator for conditions favorable for high ozone production. Decreased westerlies or increased easterlies aloft are conducive to ozone formation. We acquired maps of the anomaly in 700 hPa vector winds from the NCEP North American Regional Reanalysis data set (from the web site at https://www.esrl.noaa.gov/psd/ ). These maps are presented in Figures A-12 through A-15 for the June through July periods of 2011, 2016, 2017, and 2018, respectively. These plots represent the vector difference between 1981-2010 climatology and the year of interest. In Figure A-12 the map for 2011 (the model baseline year in the previous SIP) is difficult to interpret, but it suggests a reduction in northerly flow and/or an increase in southerly flow. In Figure A-13, there is evidence for either a reduction of westerlies and/or an increase in upslope easterlies during 2016, a pattern conducive to thermally-driven upslope. The patterns for 2016 and 2018 in Figures A-13 and A-15 are very similar, while 2017 in Figure A-14 shows an increase in northeasterly flow and/or a reduction in southwesterly flow. Both 2016 and 2018 clearly show the pattern for high ozone potential under regimes favorable for thermally-driven upslope and mountain-plains circulations. These conditions and high 500 hPa heights are also consistent with the conceptual model for high ozone episodes in the DM/NFR region (CDPHE and RAQC, 2016a) and indicate that 2016 would be a better base modeling year ozone SIP modeling than 2017.

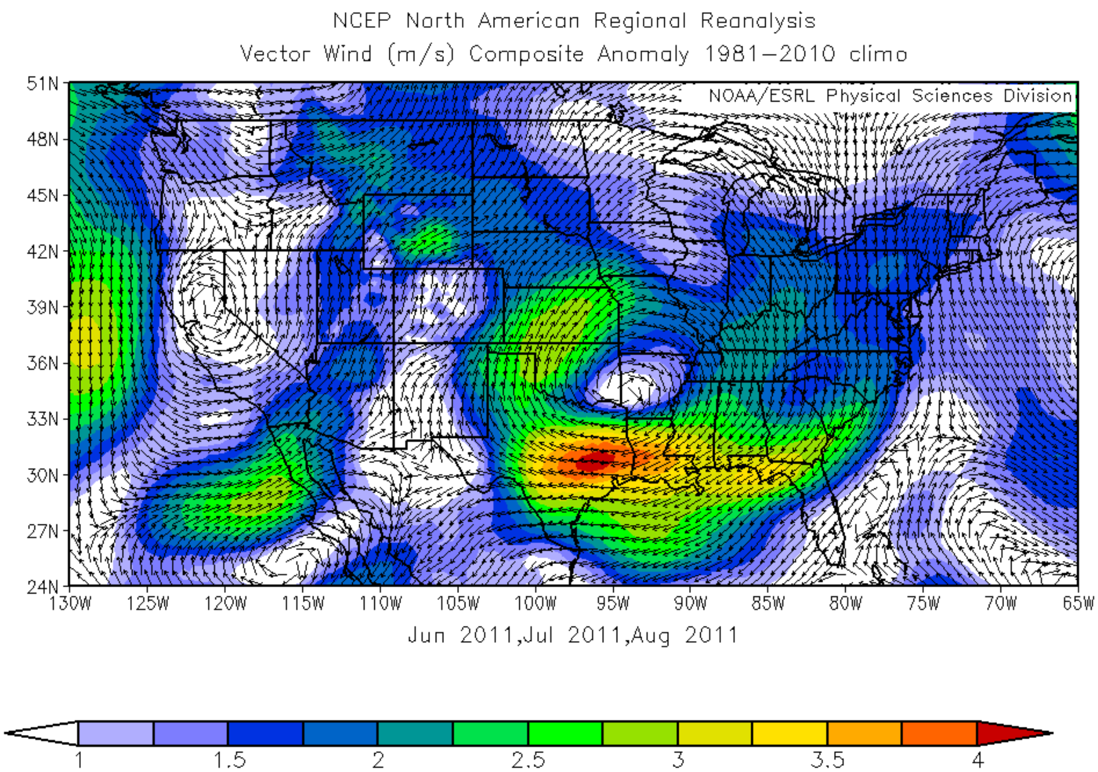



**Figure A-12. Vector differences between the mean July through August 700 hPa (700 mb) vector winds in 2011 and 1981-2010 climatology in meters per second from the NCEP North American Regional Reanalysis.**

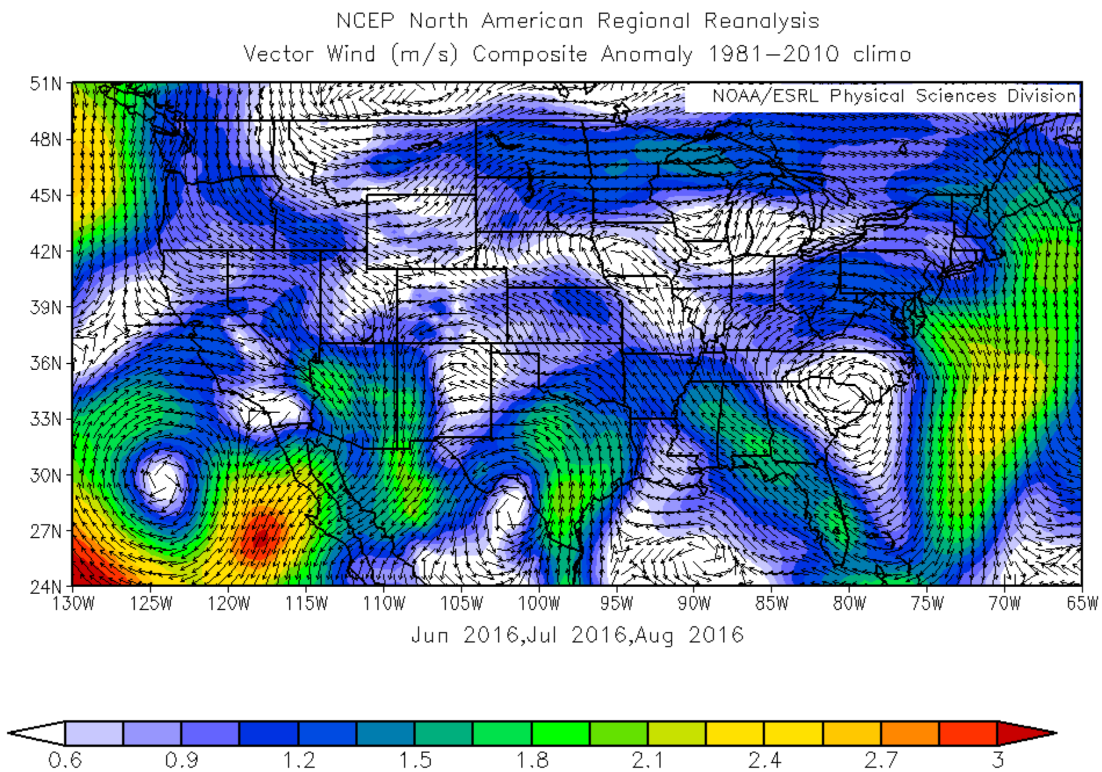



**Figure A-13. Vector differences between the mean July through August 700 hPa (700 mb) vector winds in 2016 and 1981-2010 climatology in meters per second from the NCEP North American Regional Reanalysis.**

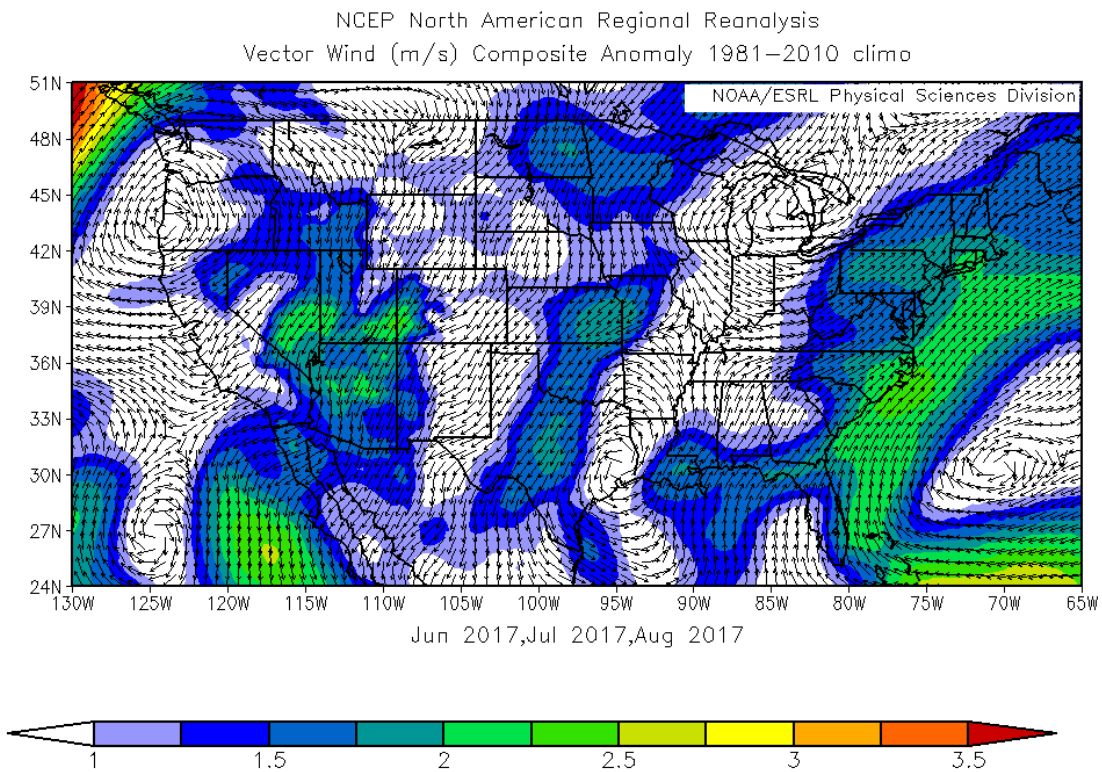



**Figure A-14. Vector differences between the mean July through August 700 hPa (700 mb) vector winds in 2017 and 1981-2010 climatology in meters per second from the NCEP North American Regional Reanalysis.**

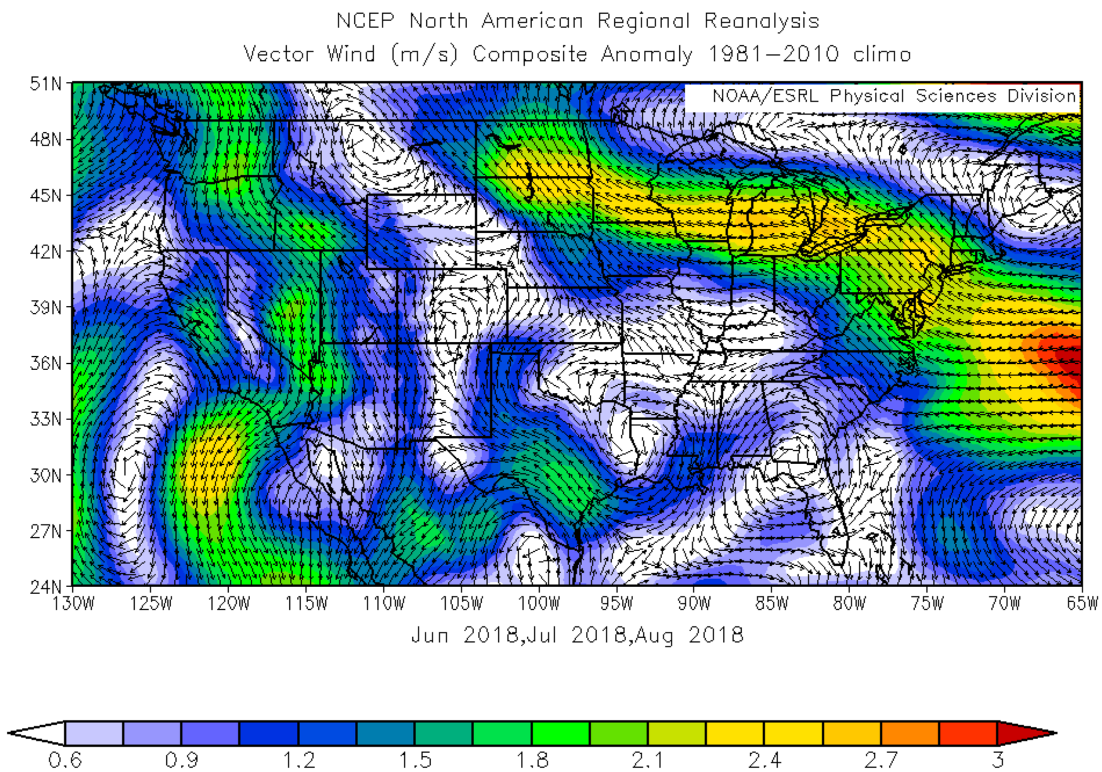



**Figure A-15. Vector differences between the mean July through August 700 hPa (700 mb) vector winds in 2018 and 1981-2010 climatology in meters per second from the NCEP North American Regional Reanalysis.**

## A.5 TRENDS IN HIGH OZONE AND METEOROLOGICAL CONDITIONS ON HIGH OZONE DAYS

EPA's ozone SIP modeling guidance (EPA, 2007; 2014d; 2018d) recommends making future year ozone projections using modeling results for the 10-highest modeled base year MDA8 ozone days. Thus, the representativeness of these 10-highest modeled base year MDA8 ozone days is an important parameter to examine in the episode selection analysis. In the 2016 Denver ozone SIP (RAQC and CDPHE, 2016), we found that most of the 10-highest modeled base year MDA8 ozone days overlapped with 20-highest observed MDA8 ozone days in the base year, so we are using the 20-highest observed MDA8 ozone days as a surrogate to determine the representativeness of the most important modeling days that will be used in making the future year ozone projections. We used a similar analysis of the relationship between ozone and 500 hPa heights in the DM/NFR NAA as discussed above, only we analyzed it using daily MDA8 ozone and 500 hPa height data (instead of monthly or summer average) and used the 500 hPa height observations from the Denver upper-air sounding instead of the re-analysis fields. Note that for July-average MDA8 ozone vs. 500 hPa height comparisons we found essentially the same relationship using the Denver upper-air sounding as Reddy and Pfister (2016), CDPHE and RAQC (2016c) and our analysis given above using the re-analysis fields.

Figure A-16 compares the relationship between ozone and 500 hPa heights for the 20 highest observed MDA8 ozone days at the RFNO monitor during 1995-2018. The ozone-500 hPa relationship for the 20 highest observed MDA8 ozone day metric is similar to the July-average analysis presented by Reddy and Pfister (2016) for 1995-2013 presented in Figure A-4 and for summer-average ozone for the years 1995-2018 presented in Figure A-5. The years of 2003 (high) and 2004 (low) are at opposite extremes of ozone formation meteorological conditions in all of the analysis at RFNO. There is increased scatter of the plots using 20-highest MDA8 days compared to the July or summer averages, but qualitatively we see similar relationships and trends. The more recent years of 2015-2018 show that 2015-2017 have similar slightly above average 500 hPa heights on the 20 highest MDA8 ozone days and similar ozone levels. 2018 has unusually high 500 hPa heights for the 20-highest days that are very similar to the 2003 heights. 2003 and 2018 have the highest 500 hPa heights and ozone formation potential at RFNO for 20-highest ozone days for the 23-year period analyzed. However, even if the ozone formation potential conditions in the DMA/NFR NAA were identical in 2003 and 2018, 2018 would produce lower ozone since the emissions are lower, as shown in Figure A-16. The results in Figure A-16 suggest that for RFNO, the 2016 and 2017 candidate modeling years have similar ozone formation potential conditions and ozone levels for the 20 highest observed MDA8 ozone days.

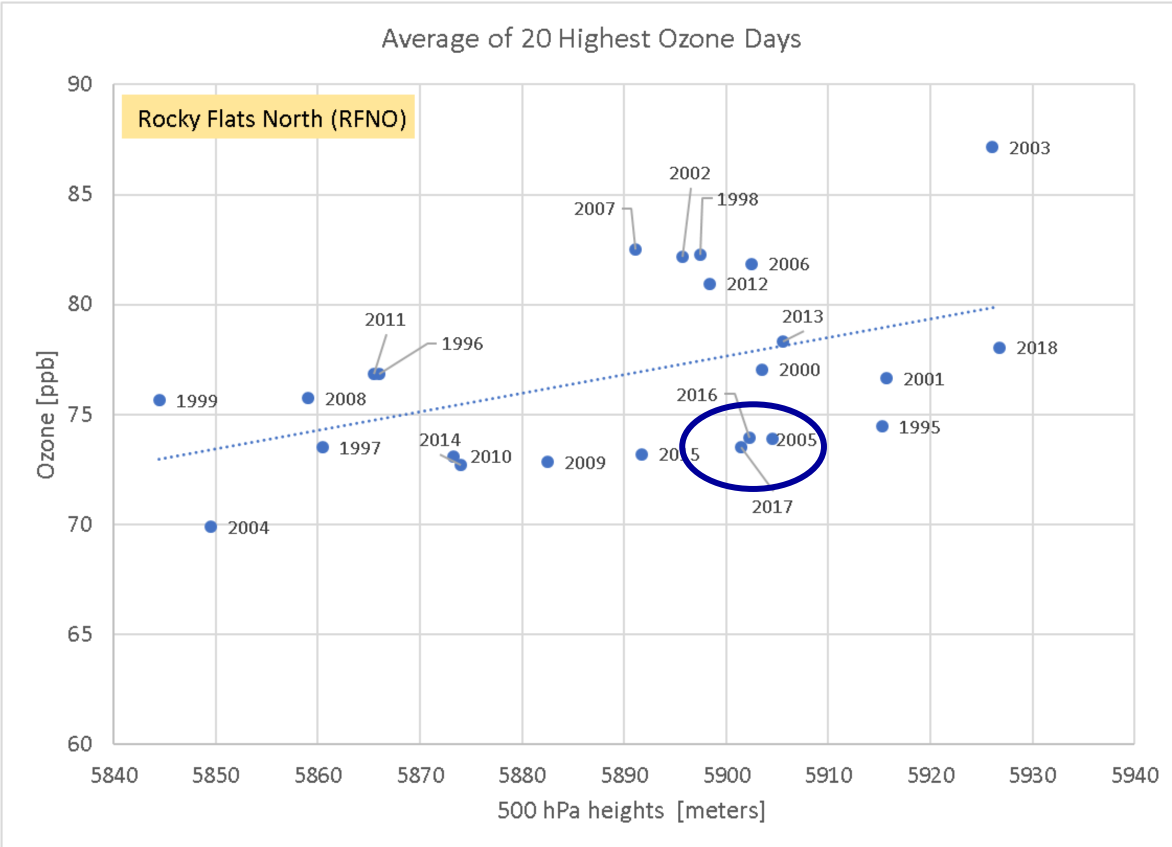



**Figure A-16. Linear regression of the mean MDA8 ozone concentrations and Denver sounding 500 hPa heights for the 20 highest MDA8 ozone concentrations days at Rocky Flats North (RFNO) monitoring site for the years 1995 to 2018.**

Results for the 20 highest MDA8 ozone days at NREL (Figure A-17) are similar to those for RFNO and the July-average results from Reddy and Pfister (2016) and summer-average results given in Figure A-6. Of the recent years, 2018 has the highest ozone formation potential and 2016 and 2017 having above average and similar ozone formation potential conditions using the 20 highest MDA8 ozone days. Using the observed 20 highest MDA8 ozone days, 2016 has slightly higher ozone formation potential conditions (Figure A-17), while using summer average data, the separation between 2017 and 2016 is greater (Figure A-6).

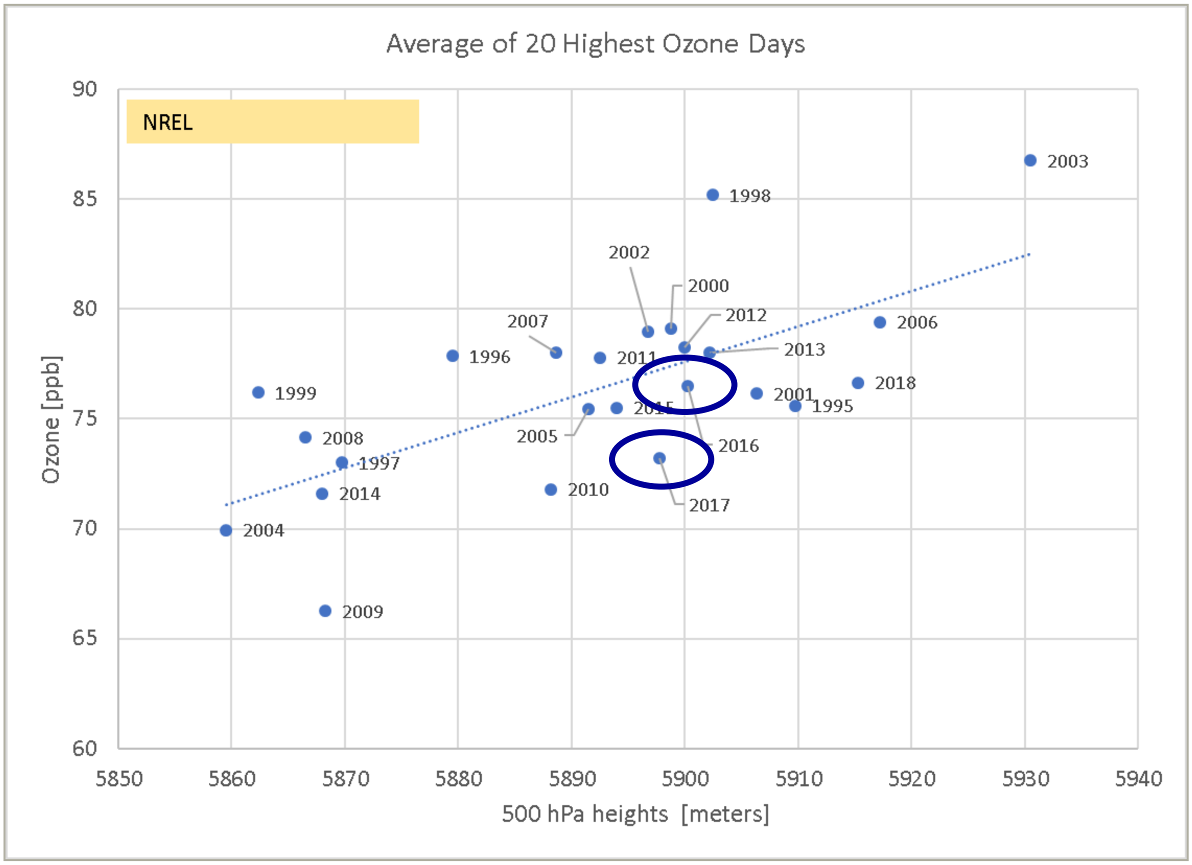



**Figure A-17. Linear regression of the mean MDA8 ozone concentrations and Denver sounding 500 hPa heights for the 20 highest MDA8 ozone concentrations days at National Renewable Energy Laboratory (NREL) monitoring site for the years 1995 to 2018.**

The CHAT and FTCW do not have as long a period of record as RFNO and NREL, but their results for the average MDA8 ozone and 500 hPa heights for the 20 highest observed ozone days (Figures A-18 and A-19) are similar to RFNO and NREL and the results reported by Reddy and Pfister (2016) and using summer average conditions (Figures A-7 and A-8). Of the most recent years, 2018 clearly has the highest ozone formation potential conditions with 2016 and 2017 having above average and similar ozone formation potential conditions at CHAT. 2016 is slightly more conducive to ozone formation than 2017 at FTCW but has comparable ozone levels (Figure A-19).

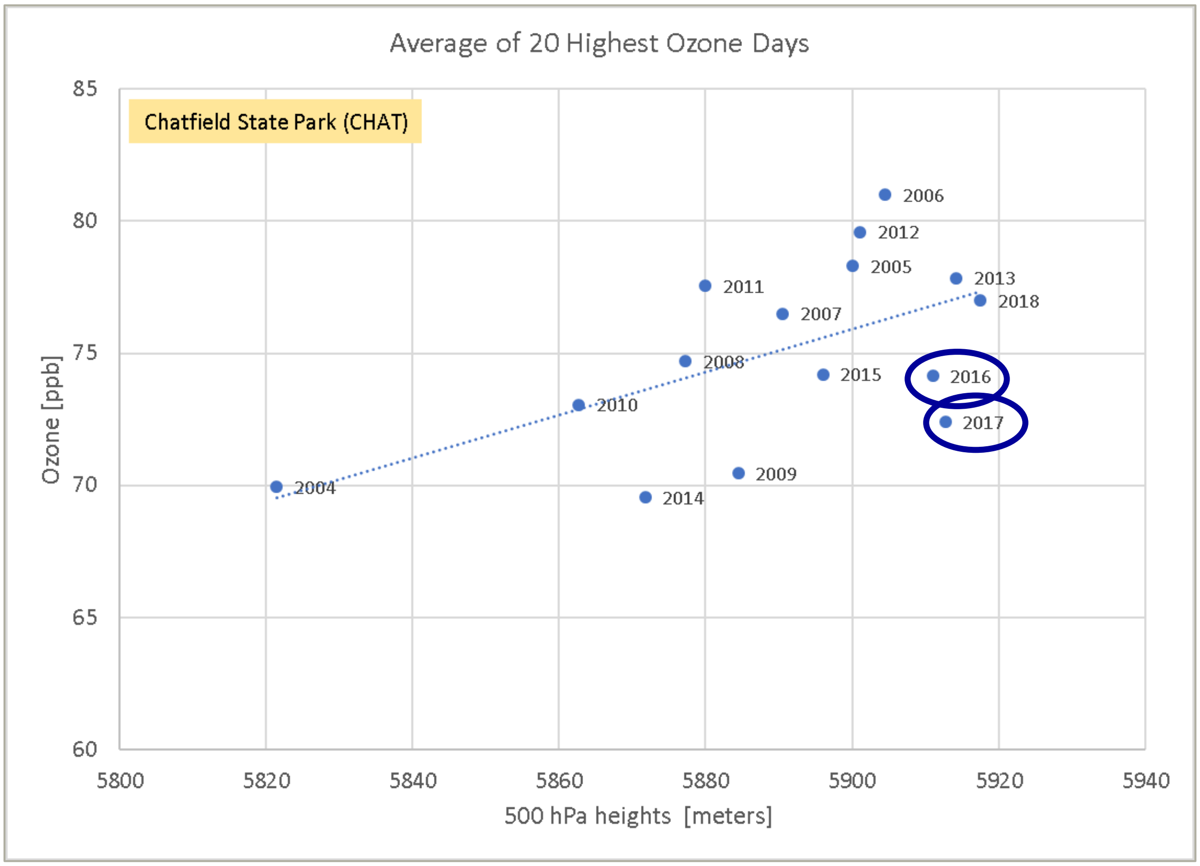



**Figure A-18. Linear regression of the mean MDA8 ozone concentrations and Denver sounding 500 hPa heights for the 20 highest MDA8 ozone concentrations days at Chatfield Reservoir (CHAT) monitoring site for the years 2004 to 2018.**

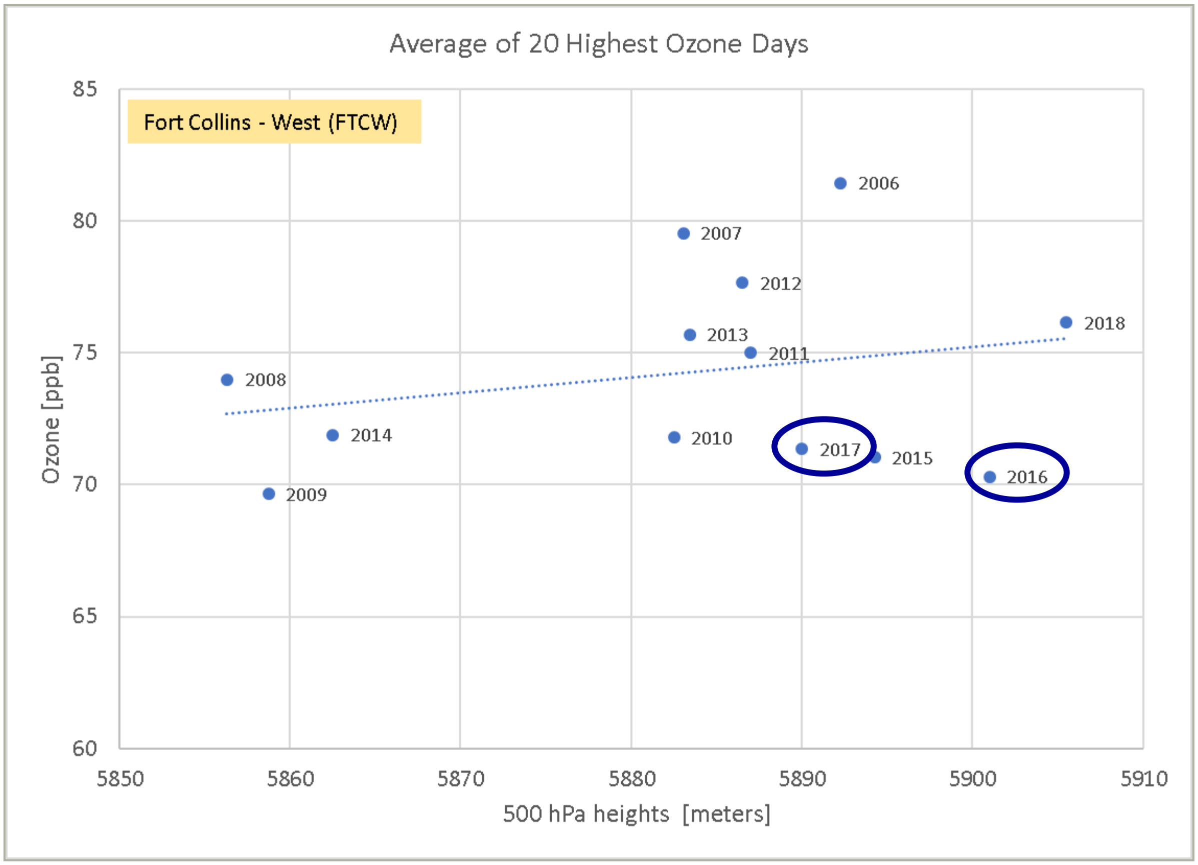



**Figure A-19. Linear regression of the mean MDA8 ozone concentrations and Denver sounding 500 hPa heights for the 20 highest MDA8 ozone concentrations days at Fort Collins West (FTCW) monitoring site for the years 2006 to 2018.**

Figure A-20 displays the distribution of daily 500 hPa heights from the Denver sounding for the ozone seasons during 2011-2018 using box-and-whisker plots. These box-and-whisker plots displays the distribution of daily 500 hPa heights where the box represents values in the 25 to 75 percentiles and is called the interquartile range (IQR), the mean and medium are represented by the line and X in the box. The whiskers above and below the box, represent the daily 500 hPa heights maximum and minimum values, respectively, provided the values do not extend more than 1.5 times the IQR from the edge of the box in either direction, in which case the point is considered an outlier and presented as a dot outside the range of the whiskers.

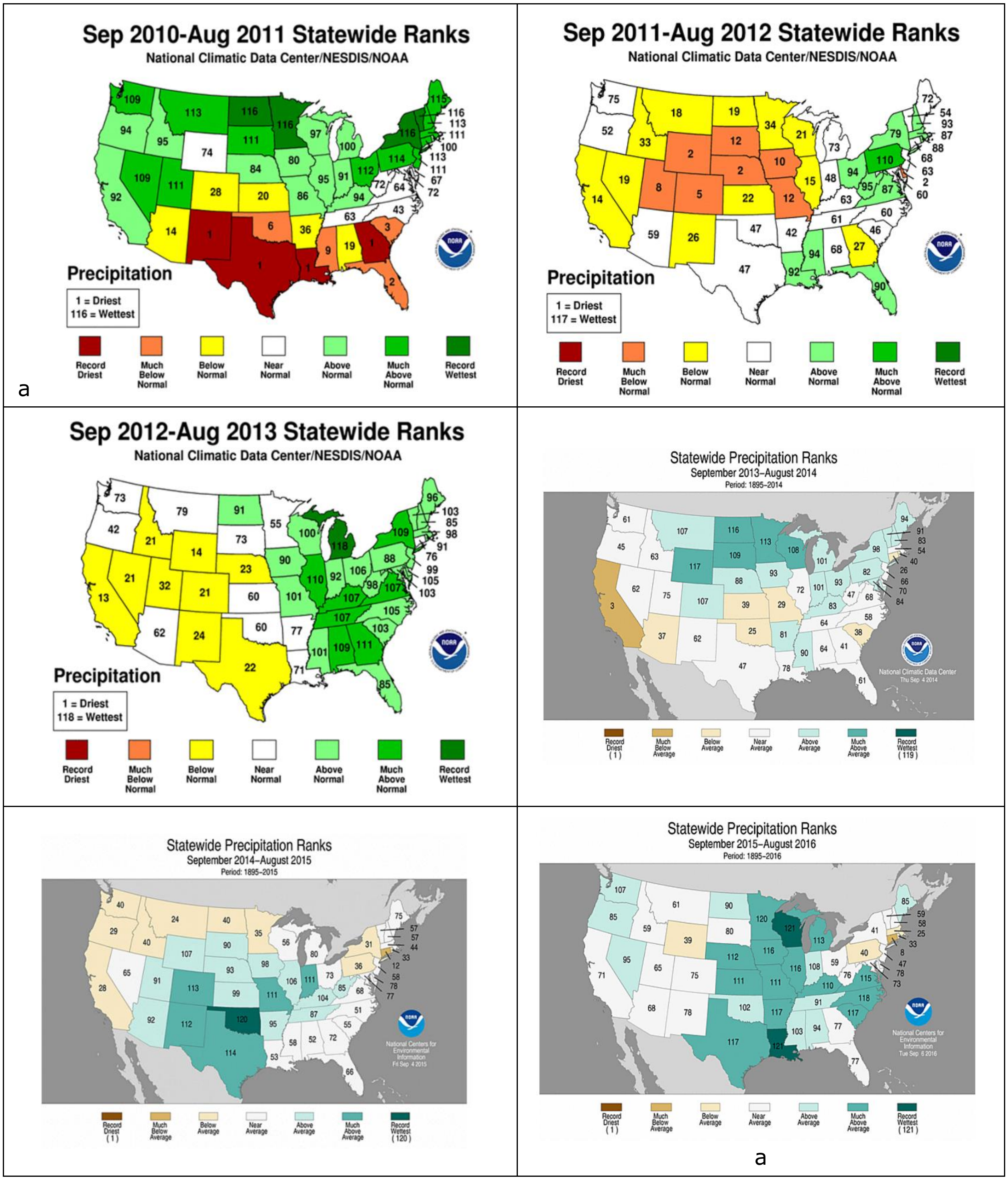
## A.6 Precipitation, Surface Temperatures, Drought, Fires and Synoptic Conditions

Below we present: (1) maps of ranked precipitation; (2) maps of ranked summer temperatures for 2011 to 2018; (3) monthly maps of drought index for April – September 2015 – 2017; and (4) summary of fire statistics (# acres burned for western U.S. for 2014 – 2017). In addition, monthly synoptic conditions summary for June, July, August 2016 and 2017 are presented. 2016 was not found to be anomalous compared to other recent years regarding those parameters. The most notable 2016 meteorological phenomenon was that in August 2016*:" Troughs in the jet stream flow funnelled cold fronts into the western and central U.S., giving the Rockies to Great Plains region a colder-than-normal month".* This explains the reason for few high ozone days in the DM/NFR NAA in August 2016 compare to Augusts in other years.

### A.6.1 Precipitation

For the 12 months prior to and including the August of each year we identify years with precipitation "much above", "much below", or near normal records for Colorado in Figure A-20. 2016 does not have atypically high or low precipitation leading up to the summer ozone season. Years with higher or lower precipitation ahead of the ozone season include:

- 12 months up to August 2012 had much below precipitation.
- 12 months up to August 2015 had much above precipitation.
- 12 months up to August 2018 had much below precipitation.


Sep 2010-Aug 2011 Statewide Ranks
National Climatic Data Center/NESDIS/NOAA
Precipitation
1 = Driest
116 = Wettest
Record Driest
Much Below Normal
Below Normal
Near Normal
Above Normal
Much Above Normal
Record Wettest
a
Sep 2011-Aug 2012 Statewide Ranks
National Climatic Data Center/NESDIS/NOAA
Precipitation
1 = Driest
117 = Wettest
Record Driest
Much Below Normal
Below Normal
Near Normal
Above Normal
Much Above Normal
Record Wettest
Sep 2012-Aug 2013 Statewide Ranks
National Climatic Data Center/NESDIS/NOAA
Precipitation
1 = Driest
118 = Wettest
Record Driest
Much Below Normal
Below Normal
Near Normal
Above Normal
Much Above Normal
Record Wettest
Statewide Precipitation Ranks
September 2013–August 2014
Period: 1895–2014
National Climatic Data Center
Thu Sep 4 2014
Record Driest (1)
Much Below Average
Below Average
Near Average
Above Average
Much Above Average
Record Wettest (119)
Statewide Precipitation Ranks
September 2014–August 2015
Period: 1895–2015
National Centers for Environmental Information
Fri Sep 4 2015
Record Driest (1)
Much Below Average
Below Average
Near Average
Above Average
Much Above Average
Record Wettest (120)
Statewide Precipitation Ranks
September 2015–August 2016
Period: 1895–2016
National Centers for Environmental Information
Tue Sep 6 2016
Record Driest (1)
Much Below Average
Below Average
Near Average
Above Average
Much Above Average
Record Wettest (121)
a

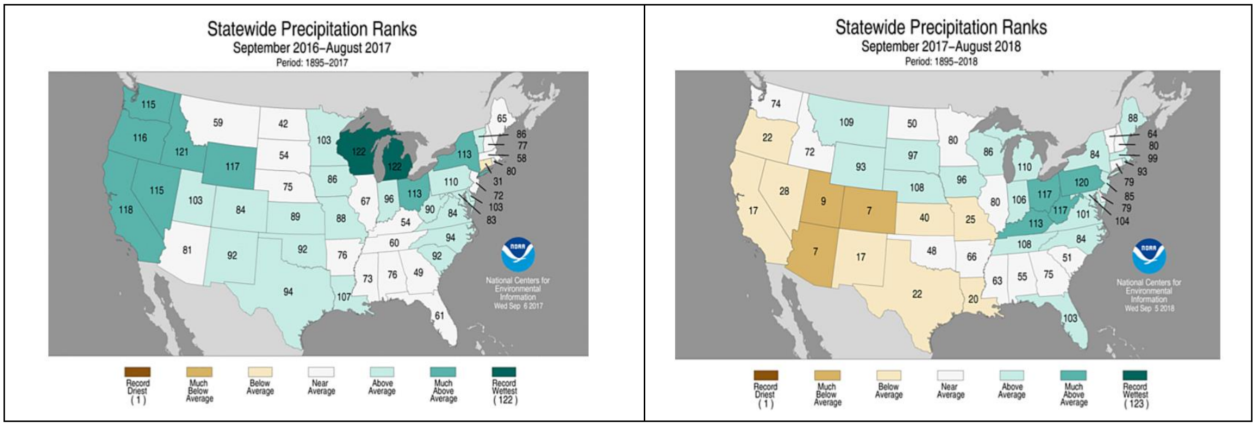


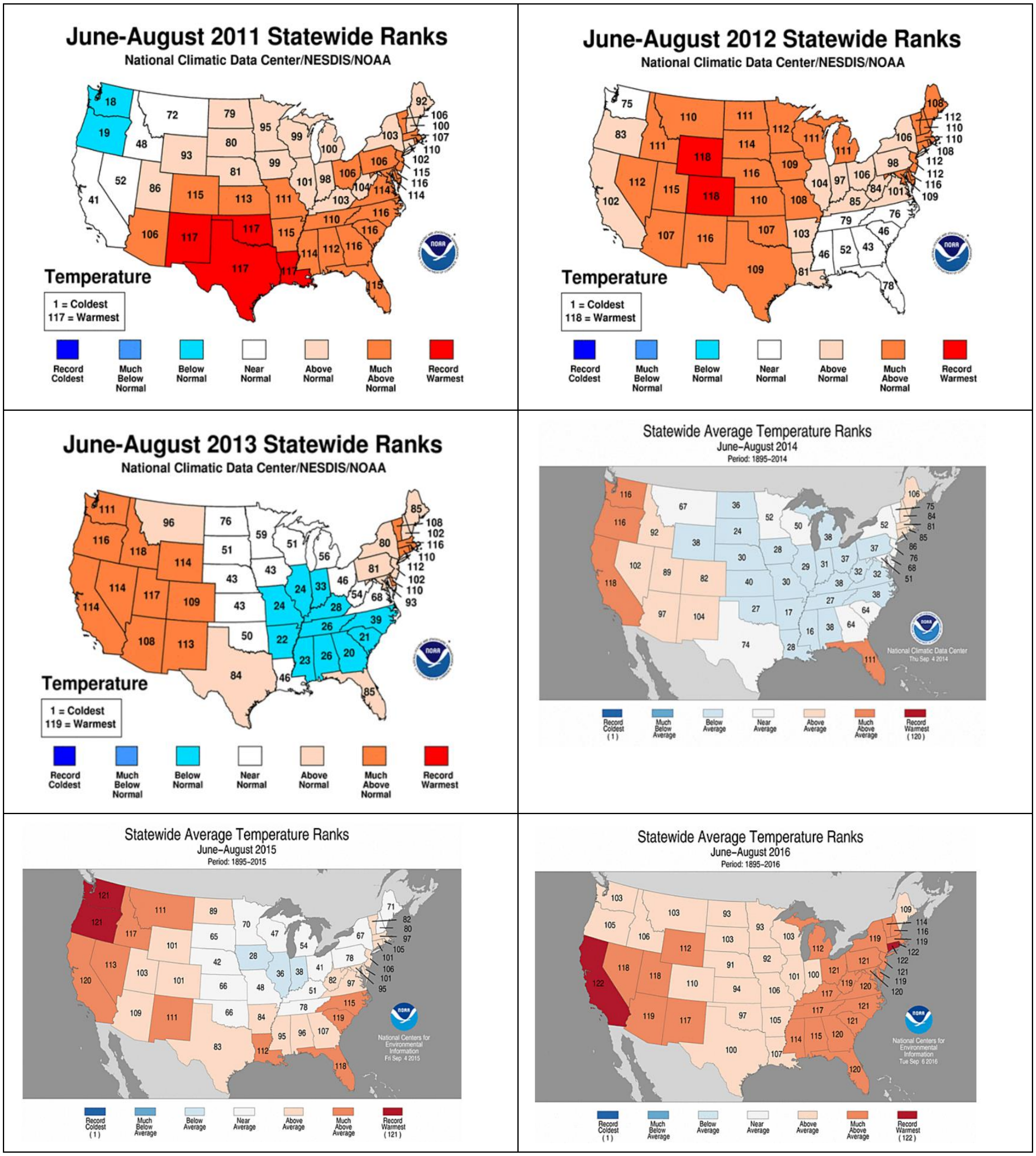

**Figure A-20. Ranked annual precipitation maps before summers of 2011-2018.**

### A.6.2 Summer Temperature

For June – August period we report temperature ranking for Colorado from Figure A-21.

- 2011 = 3$^{rd}$ hottest; 98$^{th}$ percentile; 115 (of 117)
- 2012 = 1$^{st}$ hottest; 100$^{th}$ percentile; 118 (record)
- 2013 = 11$^{th}$ hottest; 92$^{nd}$ percentile; 109 (of 119)
- 2014 = 39$^{th}$ hottest; 68$^{th}$ percentile; 82 (of 120)
- 2015 = 21$^{st}$ hottest; 83$^{rd}$ percentile; 101 (of 121)
- 2016 = 13$^{th}$ hottest; 90$^{th}$ percentile; 110 (of 122)
- 2017 = 20$^{th}$ hottest; 85$^{th}$ percentile; 104 (of 123)
- 2018 = 3$^{rd}$ hottest; 98$^{th}$ percentile; 122 (of 124)

2016 summer temperatures (90$^{th}$ percentile) are hotter compared to the ~120 year historical record but are not atypically hot compared to more recent years. Over the last 8 years there are about equal number of hotter and colder summers in Colorado than 2016.


June-August 2011 Statewide Ranks
National Climatic Data Center/NESDIS/NOAA
Temperature
1 = Coldest
117 = Warmest
Record Coldest
Much Below Normal
Below Normal
Near Normal
Above Normal
Much Above Normal
Record Warmest
June-August 2012 Statewide Ranks
National Climatic Data Center/NESDIS/NOAA
Temperature
1 = Coldest
118 = Warmest
Record Coldest
Much Below Normal
Below Normal
Near Normal
Above Normal
Much Above Normal
Record Warmest
June-August 2013 Statewide Ranks
National Climatic Data Center/NESDIS/NOAA
Temperature
1 = Coldest
119 = Warmest
Record Coldest
Much Below Normal
Below Normal
Near Normal
Above Normal
Much Above Normal
Record Warmest
Statewide Average Temperature Ranks
June–August 2014
Period: 1895–2014
National Climatic Data Center
Record Coldest (1)
Much Below Average
Below Average
Near Average
Above Average
Much Above Average
Record Warmest (120)
Statewide Average Temperature Ranks
June–August 2015
Period: 1895–2015
National Centers for Environmental Information
Record Coldest (1)
Much Below Average
Below Average
Near Average
Above Average
Much Above Average
Record Warmest (121)
Statewide Average Temperature Ranks
June–August 2016
Period: 1895–2016
National Centers for Environmental Information
Record Coldest (1)
Much Below Average
Below Average
Near Average
Above Average
Much Above Average
Record Warmest (122)

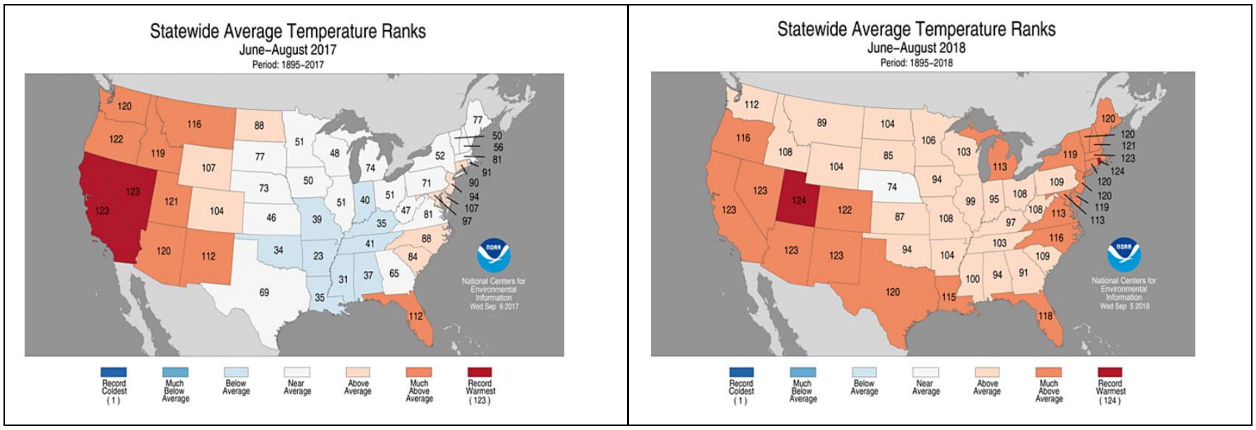



**Figure A-21. Ranked summer temperature maps 2011-2018.**

Focusing on 2016, Figure A-22 shows the temperature ranking of each summer month separately. June – July 2016 were relatively hotter than normal with August relatively much cooler.

- Jun - Aug = 13$^{th}$ hottest; 90$^{th}$ percentile; 110 (of 122)
- Jun = 3$^{rd}$ hottest; 98$^{th}$ percentile; 120 (of 122)
- July = 18$^{th}$ hottest; 86$^{th}$ percentile; 105 (of 122)
- Aug = 37$^{th}$ coldest; 30$^{th}$ percentile; 37 (of 122)

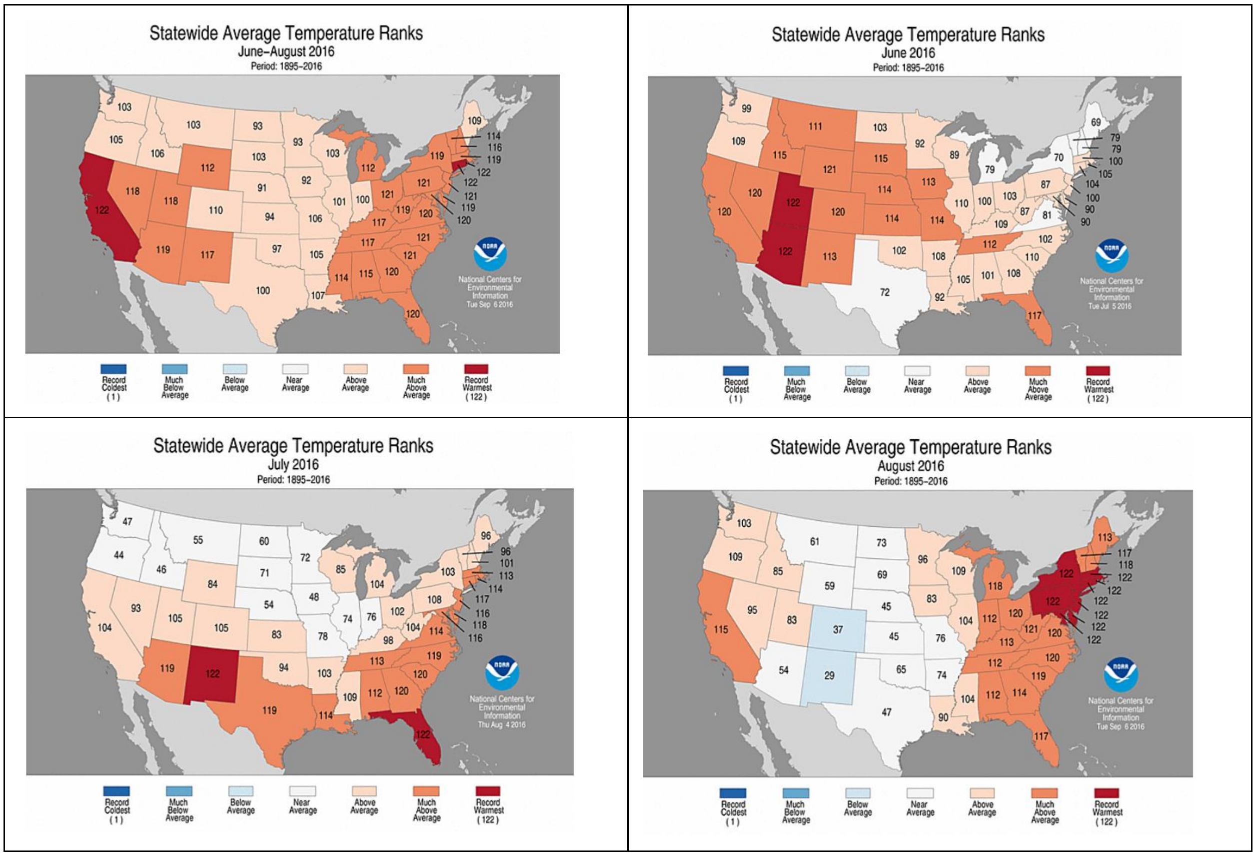
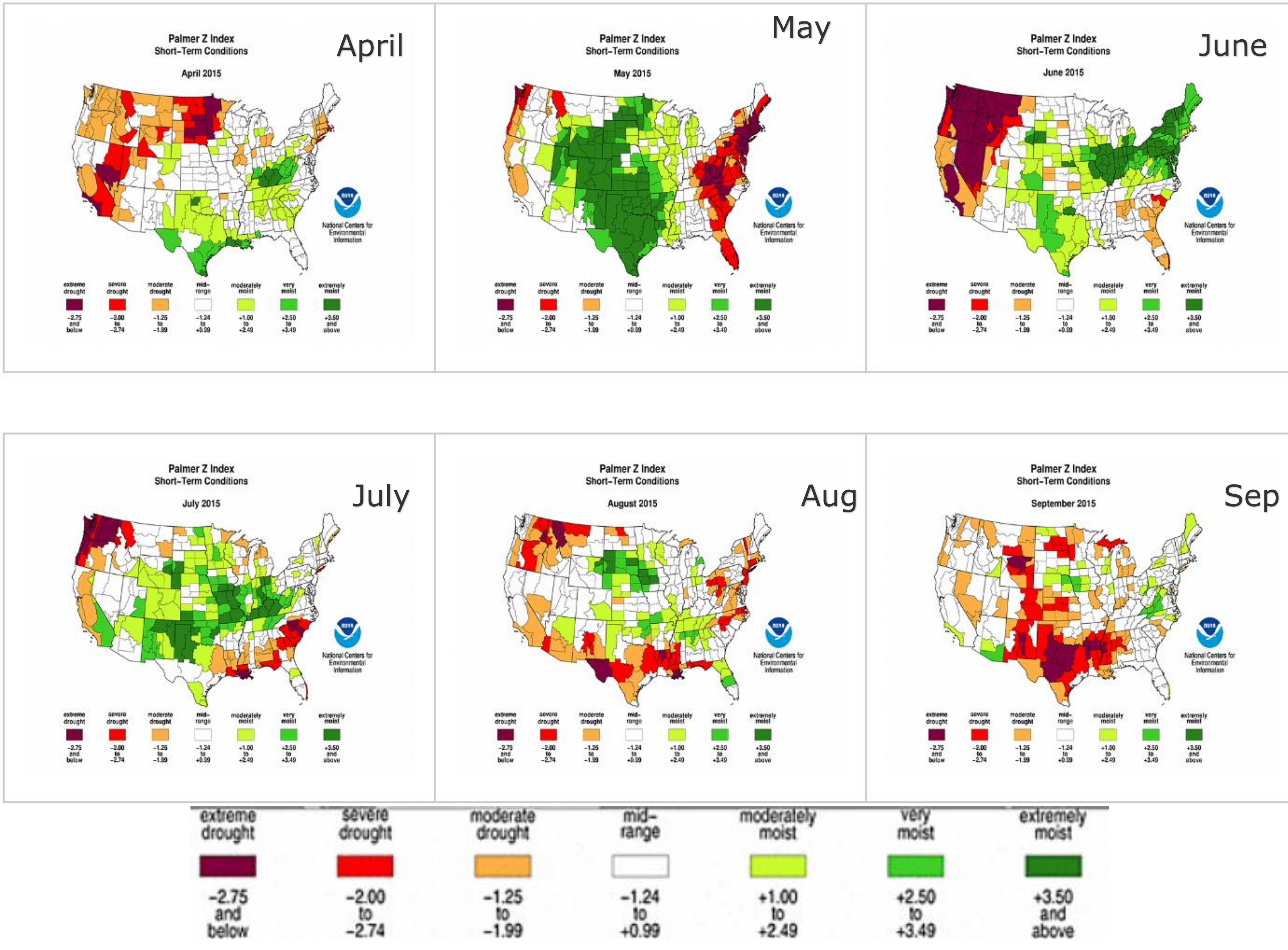



**Figure A-22. Ranked temperature maps for June-August 2016.**

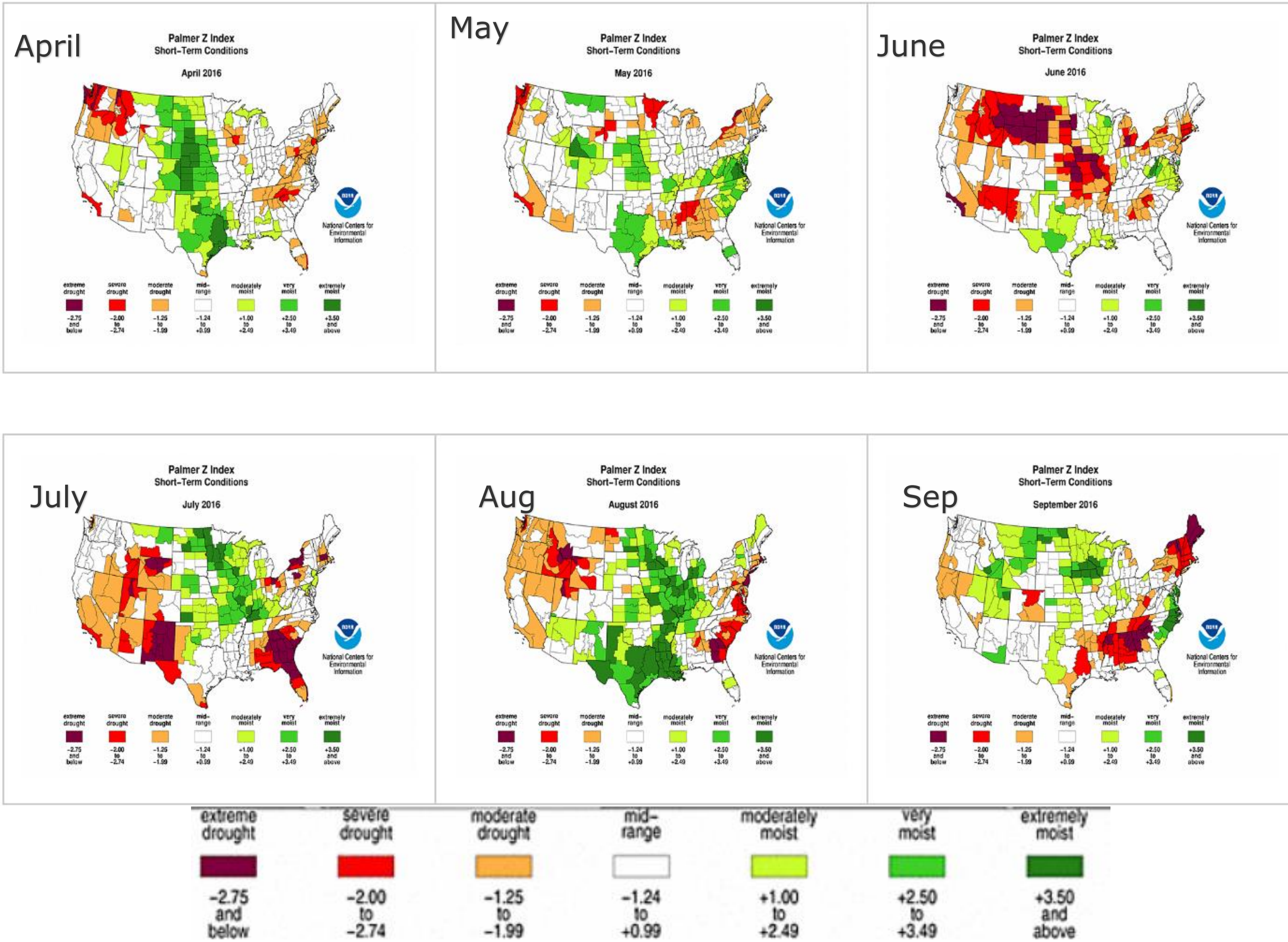
### A.6.3 Drought

The Palmer Z Index incorporates moisture supply (precipitation) and moisture demand (evapotranspiration) to depict the total moisture status each month. Figure A-23 shows 2015 – 2017 drought index form April – September. There is considerable month to month variability and spatial variability. 2016 is not atypical high or low drought year in Colorado.

# 2015


April
Palmer Z Index
Short-Term Conditions
April 2015
May
Palmer Z Index
Short-Term Conditions
May 2015
June
Palmer Z Index
Short-Term Conditions
June 2015
July
Palmer Z Index
Short-Term Conditions
July 2015
Aug
Palmer Z Index
Short-Term Conditions
August 2015
Sep
Palmer Z Index
Short-Term Conditions
September 2015
National Centers for Environmental Information
extreme drought
-2.75 and below
severe drought
-2.00 to -2.74
moderate drought
-1.25 to -1.99
mid-range
-1.24 to +0.99
moderately moist
+1.00 to +2.49
very moist
+2.50 to +3.49
extremely moist
+3.50 and above

# 2016


April
Palmer Z Index
Short-Term Conditions
April 2016
May
Palmer Z Index
Short-Term Conditions
May 2016
June
Palmer Z Index
Short-Term Conditions
June 2016
July
Palmer Z Index
Short-Term Conditions
July 2016
Aug
Palmer Z Index
Short-Term Conditions
August 2016
Sep
Palmer Z Index
Short-Term Conditions
September 2016
National Centers for Environmental Information
extreme drought
severe drought
moderate drought
mid-range
moderately moist
very moist
extremely moist
-2.75 and below
-2.00 to -2.74
-1.25 to -1.99
-1.24 to +0.99
+1.00 to +2.49
+2.50 to +3.49
+3.50 and above

# 2017

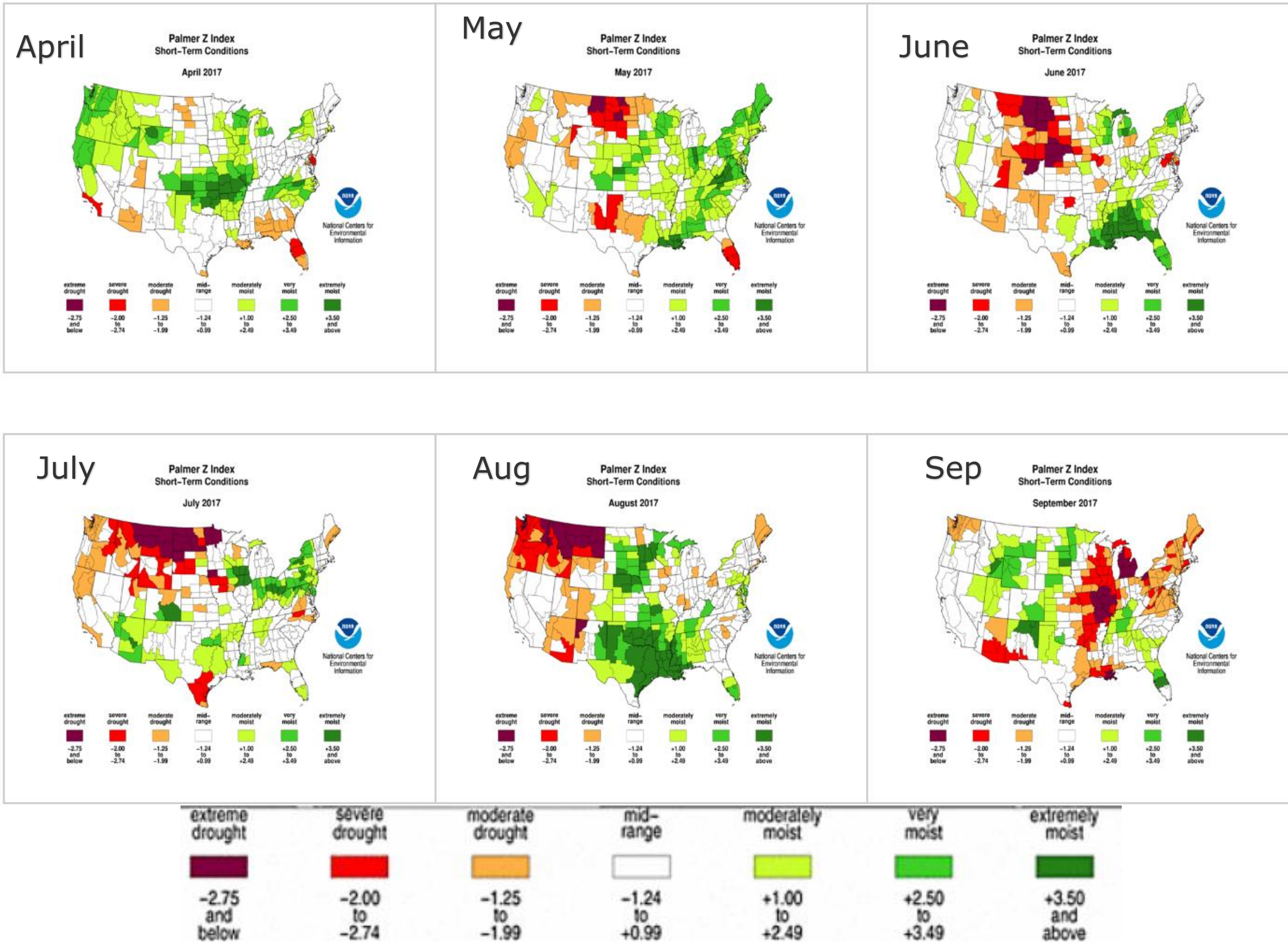



**Figure A-23. Palmer Z drought index for summer months 2015 – 2017.**

### A.6.4 Fires

Figure A-24 show number of acres burned by wildfires and prescribed burns 2014 – 2017, for 16 western states (AZ, CA, CO, ID, KS, MT, ND, NM, NV, OK, OR, SD, TX, UT, WA and WY) according to historical year-end fire statistics by state (source NICC; https://www.nifc.gov/fireInfo/fireInfo_statistics.html). 2017 has most acres burned and also had many high ozone days in the DM/NFR NAA flagged as possible Exceptional Event days due to fires. The CDPHE prepared an Exceptional Event package (CDPHE, 2018) for two days from 2017 (September 2 and 4) that was accepted by EPA as wildfire Exceptional Event days. Wildfires in 2016 do not appear to be atypical, whereas 2017 is a high wildfire year in the western states.

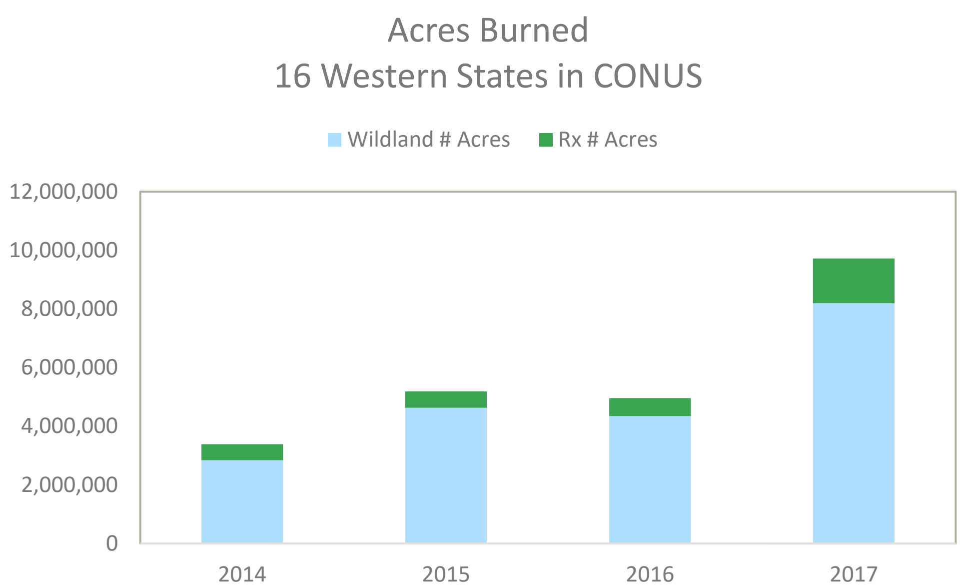



**Figure A-24. Number acres burned in western states 2014-2017.**

### A.6.5 Synoptic Conditions in Summer 2016 and 2017

Monthly synoptic conditions for the months of June, July, and August for 2016 and 2017 are excerpted in this section from:
https://www.ncdc.noaa.gov/sotc/synoptic/201706.
The only noted synoptic feature for 2016 that may be relevant to DM/NFR NAA ozone SIP modeling is highlighted in yellow for August 2016 and explains the conditions that led to August 2016 being colder than normal resulting in less high ozone levels during that month. An important component of the synoptic weather conditions in the western U.S. is the El Nino Southern Oscillation (ENSO[70]).

[70] https://www.cpc.ncep.noaa.gov/products/precip/CWlink/MJO/enso.shtml

### A.6.6 2016

June

"*The atmosphere was in an ENSO-neutral state during June 2016 — coming out of an El Niño but before entering an expected La Niña. Subtropical high pressure dominated the weather over the contiguous United States (CONUS), deflecting the jet stream and storm track to the Canadian border and blanketing much of the CONUS with unusually warm and dry weather. The high pressure ridge inhibited the development of severe weather, deflected tropical systems mostly away from the CONUS, aided the development of large wildfires in the Southwest, and contributed to the expansion or development of drought in many areas. The upper-level circulation, temperature, and precipitation anomaly patterns reflected the chaotic nature of an atmospheric-oceanic system in transition.* "

July

"*The atmosphere was in an ENSO-neutral state during July 2016. Subtropical high pressure dominated the weather over the contiguous United States (CONUS), deflecting the jet stream and storm track to the Canadian border and blanketing much of the CONUS with unusually warm and dry weather. Heavier rains fell along stalled fronts from the Central and Northern Plains to Ohio Valley. The high pressure ridge inhibited the development of severe weather over the southern CONUS, aided the development of large wildfires in the West, and contributed to the expansion or development of drought in many areas. The upper-level circulation, temperature, and precipitation anomaly patterns reflected the chaotic nature of an atmospheric-oceanic system in transition, but also suggested the atmospheric drivers originating in the North Atlantic had the greatest influence on the month's weather*. "

August

"*The atmosphere was in an ENSO-neutral state during August 2016. The weather over the contiguous United States (CONUS) this month was dominated by a complex interplay between subtropical high pressure systems, jet stream weather systems, and tropical cyclone rainfall. Troughs in the jet stream flow funneled cold fronts into the western and central U.S., giving the Rockies to Great Plains region a colder-than-normal month, while the Bermuda High and North Pacific High kept the West Coast and the U.S. east of the Mississippi warmer than normal. Much of the West was drier than normal due to the North Pacific High and a northwesterly jet stream flow, with the dry weather being a factor in the development of numerous large wildfires across the West. The Bermuda High kept the Southeast to Mid-Atlantic Coast drier than normal, but rain from slow-moving cold fronts and tropical systems made for a wetter-than-normal month from the Southern Plains to Great Lakes. The fronts and upper-level troughs provided the dynamics that triggered severe weather, resulting in an above-average number of tornadoes for the month. Drought expanded in some areas and contracted in others, with the overall national drought footprint shrinking to about 19.5 percent of the CONUS. The upper-level circulation and temperature anomaly patterns suggested the atmospheric drivers originating in the North Atlantic and North Pacific had the greatest influence on the month's weather.* "

### *A.6.7 2017*

June

*"The Earth's ocean-atmosphere system was technically in an ENSO-neutral state during June 2017. An upper-level ridge dominated the western half of the contiguous United States (CONUS) with attendant warmer- and drier-than-normal weather, which set the stage for an active wildfire season. An upper-level trough set up over the eastern CONUS and its associated short-wave troughs, fronts and low pressure systems brought cooler- and wetter-than-normal weather. Rain in the South and Southeast contracted drought and abnormal dryness, but persistent dry conditions in the West and, especially, northern Plains expanded and intensified drought. The fronts and lows generated rounds of severe weather, but fewer than the average number of tornadoes occurred. Without ENSO-related inhibitors shearing tropical systems, the Atlantic and East Pacific basins saw slightly more active tropical cyclone activity than average. The upper-level circulation, temperature, and precipitation anomaly patterns suggested that the atmospheric drivers originating in the North Pacific may have had an influence on the month's weather, but none of the drivers could be identified as strongly influential."*

July

"*The Earth's ocean-atmosphere system was technically in an ENSO-neutral state during July 2017. Like last month, an upper-level ridge dominated the western half of the contiguous United States (CONUS) with attendant warmer- and drier-than-normal weather, which set the stage for an active wildfire season. An upper-level trough set up over the eastern CONUS and its associated short-wave troughs, fronts and low pressure systems brought cooler- and wetter-than-normal weather. Monsoon rain in the Southwest contracted drought and abnormal dryness, but persistent dry conditions in the Far West, northern Rockies, and, especially, northern Plains expanded and intensified drought. Without ENSO-related inhibitors shearing tropical systems, the Atlantic and East Pacific basins saw slightly more active tropical cyclone activity than average. The upper-level circulation, temperature, and precipitation anomaly patterns suggested that the atmospheric drivers originating in the Arctic and North Atlantic had the greatest influence on the month's weather."*

August

"*The Earth's ocean-atmosphere system was technically in an ENSO-neutral state during August 2017. An upper-level ridge dominated the western half of the contiguous United States (CONUS) with attendant warmer- and drier-than-normal weather, which continued conditions for an active wildfire season. An upper-level trough set up over the eastern CONUS and its associated short-wave troughs, fronts and low pressure systems brought cooler-than-normal weather. Parts of the Plains, South, and Mid-Atlantic regions had wetter-than-normal weather due to rain associated with the fronts and troughs, and Hurricane Harvey inundated eastern Texas and the Lower Mississippi Valley at the end of the month. Drought and abnormal dryness expanded and intensified in the Pacific Northwest and High Plains of Montana under the relentless heat and dryness, but storms in the Plains contracted drought areas, especially in the hard-hit Dakotas. The fronts and lows, and especially Hurricane Harvey, generated rounds of severe weather, with more than the average number of tornadoes occurring. Without ENSO-related inhibitors shearing tropical systems, the Atlantic and East Pacific basins* *saw more active tropical cyclone activity than average. The upper-level circulation, temperature, and precipitation anomaly patterns suggested that the atmospheric drivers originating in the subtropical North Pacific may have had an influence on the month's weather. "*

# APPENDIX B

# Estimation of Contributions of International Emissions to Ozone Levels in the DM/NFR NAA

# Appendix B. Estimation of Contributions of International Emissions to Ozone Levels in the DM/NFR NAA

## B.1 Introduction

This Appendix describes how global and regional photochemical modeling will be conducted to estimate the contributions of international emissions to ozone concentrations in the Denver Metropolitan and North Front Range (DM/NFR) ozone nonattainment area (NAA). The GEOS-Chem global and CAMx regional photochemical grid models will be used to model two emissions scenarios, a 2016 base case and a 2016 no international emissions case. In the 2016 no international emissions case, anthropogenic emissions from sources outside of the United States are eliminated (this scenario is also called Zero Out the Rest of the World, or ZROW). The differences in ozone contributions from the two simulations are the 2016 contributions of international emissions to ozone concentrations in the DM/NFR NAA. At this time EPA has not issued any formal guidance on how to conduct an international emissions contribution to ozone analysis.

### B.1.1 Background Ozone Concentrations

The subject of ozone background[71] has been an important topic as part of EPA's efforts to define a new ozone National Ambient Air Quality Standard (NAAQS). A recent report on the "Scientific Assessment of Background Ozone over the U.S.: Implications for Air Quality Management" (Jaff et al., 2018[72]) considered more than 100 published studies and concluded that seasonal spring and summer mean background ozone was highest at high elevation locations, such as Denver. They found monthly mean Maximum Daily Average 8-hour (MDA8) U.S. Background Ozone (USBO), or ozone formed from natural sources (within and outside of the U.S.) and anthropogenic emissions from outside of the U.S., approaching 50 ppb at high elevation sites with 4$^{th}$ highest annual MDA8 ozone exceeding 60 ppb at some sites. The DM/NFR NAA Chatfield (CHAT) monitoring site was analyzed in the Jaff et al., (2018) report and USBO found to contribute 30-50 ppb to the highest 10 modeled MDA8 ozone concentrations.

### B.1.2 International Contributions using the 2016 Denver Ozone SIP 2011 Modeling Platform

After the preparation of the 2016 Denver ozone SIP (RAQC and CDPHE, 2016), the GEOS-Chem global and CAMx 36/12/4-km regional 2011 photochemical modeling platform was applied with and without international anthropogenic emissions to determine their influence on ozone Design Values (DVs) in the DM/NFR NAA. Results were presented at a November 2, 2017 Modeling Forum in Denver.[73] The contributions of international emissions to ozone DVs in the DM/NFR NAA was obtained by conducting two 2011 simulations of the GEOS-Chem global and CAMx 36/12-km regional models: (1) a base case with all emissions; and (2) a no international emissions case where non-U.S. anthropogenic emissions were eliminated from the 2011 base case (Morris and McNally, 2017[74]). The results were processed using EPA's ozone DV projection procedures (EPA, 2014d) to determine the contributions of international emissions to ozone DVs in the DM/NFR NAA. For the four key

[71] https://www.epa.gov/ground-level-ozone-pollution/background-ozone-workshop-and-information

[72] https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6198683/

[73] https://raqc.org/inventory/2017-ozone-modeling-forum/

[74] https://raqc.egnyte.com/dl/1bxdDBEdXP/II.b_2017_Denver_Mod-Forum_International_2017-11-02v2.pdf_

DM/NFR NAA monitoring sites (RFNO, NREL, CHAT and FTCW), the elimination of international anthropogenic emissions reduced 2011 ozone DVs by 6.2 to 6.6 ppb. All of the 2011 ozone DVs in the DM/NFR NAA were below the 75 ppb 2008 ozone NAAQS when international anthropogenic emissions were eliminated.

## B.2 APPROACH FOR ESTIMATING CONTRIBUTIONS OF INTERNATIONAL EMISSIONS

The GEOS-Chem global and CAMx 36/12/4-km regional photochemical modeling platforms for the summer of 2016 will be used to estimate the contributions of international anthropogenic emissions to ozone DVs in the DM/NFR NAA. The procedures will be similar to those used to estimate the international contributions to 2011 ozone DVs discussed in Section A.1.2 above, only updated to current models. The 2016 no international emissions ozone modeling will leverage the set-up of a 2016 GEOS-Chem platform for an EPRI study whose ultimate objective is to estimate the contributions of international emission to 2028 regional haze, and the 2016 modeling platform developed as part of the 2020 and 2023 DM/NFR NAA ozone attainment demonstration work effort described in this Modeling Protocol.

### B.2.1 Justification for Using the 2016 Modeling Year for Estimating International Contributions

The 2016 year is appropriate for estimating the contributions of international anthropogenic emissions to ozone DVs in the DM/NFR NAA as it is relevant for both the 2008 and 2015 ozone NAAQSs. The DM/NFR NAA is currently a Moderate NAA under the 2008 ozone NAAQS that was supposed to attain by 2017. The 2016 year is part of the three-year period (2015-2017) used in the 2017 ozone DV that determined the DM/NFR NAA failed to attain. Since all the 2017 4$^{th}$ high MDA8 ozone concentrations in the DM/NFR NAA were below 75 ppb, the DM/NFR NAA was granted a 1-year extension to attain by 2018. But the 2018 ozone DVs were also above the 2008 ozone NAAQS so the DM/NFR NAA again failed to attain and the 2018 4$^{th}$ highest MDA8 ozone were too high to grant the area another 1-year extension to attain. 2016 was also part of the 2016-2018 ozone DVs that the DM/NFR Moderate NAA failed to attain the 2008 ozone NAAQS.

The DM/NFR NAA was designated a Marginal NAA under the 2015 ozone NAAQS based on the 2014-2016 ozone DVs. Thus, the 2016 year is also included in the ozone DVs used to designate the DM/NFR NAA under the 2015 ozone NAAQS.

Thus, the 2016 year is related to both the continued nonattainment and the designation of nonattainment of the DM/NFR NAA for the 2008 and 2015 ozone NAAQS, respectively.

### B.2.2 GEOS-Chem Version and Setup

GEOS-Chem version 11-02rc will be used for the two model runs described above. This 'release candidate' version was made available a month before the public release of GEOS-Chem version 12 (August 10, 2018). GEOS-Chem version 11-02rc includes some key updates, such as improvements to the complex treatment scheme for secondary organic aerosol (SOA)[75] and implementation of lightning counts and methane concentrations specific

[75] http://wiki.seas.harvard.edu/geos-chem/index.php/Secondary_organic_aerosols#SOA_schemes_in_v11-02_and_later

to 2016. Additional emission inventories not available in previous model versions are also included, which is described in more detail below.

GEOS-Chem will be run using its standard chemical mechanism configuration, which includes detailed tropospheric and stratospheric chemistry (UCX mechanism) along with complex SOA chemistry[76]. For all model runs, GEOS-FP ('forward processing') reanalysis meteorology, a horizontal grid resolution of 2°x2.5° (approximately 220 km), and 72 hybrid sigma-pressure vertical layers will be used. Table B-1 presents the GEOS-Chem model configuration to be used in this study.

**Table B-1. GEOS-Chem Model Configurations**

| Science Options | GEOS-Chem |
|---|---|
| Version | Version 11-02r |
| Vertical Grid Mesh | 72 Layers |
| Chemistry mechanism | GEOS-Chem standard chemistry with complex SOA option |
| Horizontal Grids | 2x2.5 degree (Nx, Ny = 144, 91) |
| Initial Conditions | 6-month spin-up; starting from provided initial conditions for standard chemistry |
| Meteorology | 2016 GEOS-FP meteorology |
| Photolysis mechanism | Default (FAST-J) |
| Advection Scheme | Default (TPCORE) |
| Cloud convection scheme | On / Relaxed Arakawa-Schubert |
| Planetary Boundary Layer (PBL) mixing | On / non-local scheme implemented by Lin and McElroy |
| Dry deposition scheme | Default (Wesely) |
| Chemistry Solver | Default (FLEXCHEM) |
| Parallelization | Open Multi-Processing (OMP) |

### B.2.3 GEOS-Chem Emission Inventories

GEOS-Chem contains multiple global and regional emission inventories that vary by resolution, pollutant, source category, regional coverage, and time period. A complete listing of available inventories is provided on the GEOS-Chem wiki page[77]. In the default approach, if the user-defined model year (e.g., 2016) falls outside of the periods available in the emissions database (i.e., pre-1980 or post-2014), GEOS-Chem automatically uses emissions from the closest available year. However, in this study we will override this default and use the most recent global and regional emission inventories and project them as needed to the 2016 modeling year.

Table B-2 describes the global and regional emissions inventories used in GEOS-Chem. Regional anthropogenic inventories are used in the US (NEI2011), Canada (APEI), and China (MEIC). The 2011 National Emission Inventory (NEI) emission inventory[78] is used

[76] Semivolatile primary organic aerosol (POA) chemistry was not included and the source code was modified to turn off isoprene SOA reactions via the volatility-based scheme (VBS) described in Pye et al. (2010). Isoprene SOA reactions via VBS are turned off to avoid the risk of double-counting in the complex SOA chemistry scheme. For more information, see http://maraisresearchgroup.co.uk/Publications/GC-v11-02-SOA-options.pdf
[77] http://wiki.seas.harvard.edu/geos-chem/index.php/HEMCO_data_directories
[78] https://www.epa.gov/sites/production/files/2015-10/documents/nei2011v2_tsd_14aug2015.pdf

across the continental US (CONUS). The Environment and Climate Change Canada (ECCC) compiled the Air Pollutant Emission Inventory (APEI) which is a comprehensive Canada emission inventory[79]. We will use the Multi-resolution Emission Inventory for China (MEIC) to represent anthropogenic emissions in 2016 (Zheng et al., 2018). The Community Emission Data System (CEDS; Hoesly et al., 2018) inventory is a default global anthropogenic inventory in GEOS-Chem and will be used in the rest of the world in our study. GEOS-Chem uses CEDS to fill gaps in the regional inventories. For example, the Canada's APEI does not include VOC so CEDS VOC emissions are used in Canada. Regional shipping emissions are used along the coasts of the continental US (NEI) and Europe (EMEP). In the rest of the world, shipping emissions from the Hemispheric Transport of Air Pollution (HTAP) version 2 inventory will be used. Meteorology-driven natural emissions (i.e., volcanic $SO_2$, biogenic VOCs, soil NOx, sea-salt, lightning NOx, mineral dust) are calculated within GEOS-Chem as a function of local values of meteorological variables (temperature, insolation, soil moisture, precipitation, wind speed, convective cloud tops).

All anthropogenic and natural emission inventories listed in Table B-2 are used in the 2016 baseline. In the 2016 no international emissions ZROW scenario, all anthropogenic emission inventories are turned off except for NEI (including shipping) and CEDS. The CEDS inventory is turned on only in Alaska and Hawaii.

[79] https://www.canada.ca/en/environment-climate-change/services/pollutants/air-emissions-inventory-overview.html

### Table B-2. Emission Inventories Used in GEOS-Chem*

| Region/Emission Type | Inventory | Base Year |
|---|---|---|
| United States | NEI hourly[1,2] | 2011 |
| Canada | APEI[3] | 2014 |
| Mexico | CEDS[4] | 2014 |
| China | MEIC[5] | 2016 |
| Rest of World | CEDS | 2014 |
| Shipping | U.S. Coast - NEI hourly | 2011 |
| | Europe Coast – EMEP[6] | 2012 |
| | Rest of World – HTAP[7] | 2010 |
| Aircraft | AEIC[8] | 2005 |
| Biomass Burning | QFED[9] | 2016 |
| $C_2H_6$ from oil, gas, and biofuel | Tzompa-Sosa et al., 2017[10] | 2010 |
| Volcanic Degassing $SO_2$ | AEROCOM[11,12] | 2009 |
| Lightning | NASA LIS/OTD High Resolution Monthly Climatology[13] | 2016 |
| Natural $NH_3$ | GEIA[14] | 1990 |
| Bromocarbon and Iodocarbon | Ling et al., 2010, Ordonez et al., 2012[15] | 2000 |
| Methane Concentrations | CMDL flask observations[16] | 2016 |
| Meteorology-Driven Natural Emissions | In-line Calculations | 2016 |

[1]http://wiki.seas.harvard.edu/geos-chem/index.php/EPA/NEI11_North_American_emissions.
[2]The CEDS emission inventory is used in Alaska and Hawaii.
[3]http://ftp.as.harvard.edu/gcgrid/data/ExtData/HEMCO/APEI/v2016-11/README
[4]http://wiki.seas.harvard.edu/geos-chem/index.php/CEDS_anthropogenic_emissions
[5]MEIC emissions described in Zheng et al. (2018). Not yet available in public version of GEOS-Chem.
[6]http://wiki.seas.harvard.edu/geos-chem/index.php/EMEP_European_anthropogenic_emissions
[7]http://edgar.jrc.ec.europa.eu/htap_v2/index.php?SECURE=123
[8]http://ftp.as.harvard.edu/gcgrid/data/ExtData/HEMCO/AEIC/v2015-01/README
[9]http://ftp.as.harvard.edu/gcgrid/data/ExtData/HEMCO/QFED/v2018-07/README
[10]http://ftp.as.harvard.edu/gcgrid/data/ExtData/HEMCO/C2H6_2010/v2017-05/README
[11]http://wiki.seas.harvard.edu/geos-chem/index.php/Volcanic_SO2_emissions_from_Aerocom.
[12]Note only volcanic degassing is included in GEOS-Chem simulations.
[13]http://ftp.as.harvard.edu/gcgrid/data/ExtData/HEMCO/LIGHTNOX/v2017-09/README
[14]http://ftp.as.harvard.edu/gcgrid/data/ExtData/HEMCO/NH3/v2014-07/README
[15]http://ftp.as.harvard.edu/gcgrid/data/ExtData/HEMCO/BROMINE/v2015-02/README
[16] http://wiki.seas.harvard.edu/geos-chem/index.php/GEOS-Chem_v11-02#Update_CH4_latitude_bands_for_2014-2016
*Last access to the weblinks above was on December 20, 2018

### B.2.4 GEOS-Chem Emission Projections to 2016

With one exception, separate scaling factors are applied to each emissions inventory type in Table B-2 to project the emissions from the Base Year to 2016. Country-specific scaling factors are compiled for the U.S., Canada, and China. The exception was for emissions with the 2014 Base Year that were used as is for the 2016 modeling as the uncertainties in the global emissions were greater than the scaling factors between 2014 and 2016.

Continental United States: The 2016 CONUS emissions are calculated by applying scaling factors to the 2011 NEI hourly emission inventory included in GEOS-Chem. EPA developed multiple future year emission inventories (i.e., 2017, 2023, 2025, 2028) based on the 2011 NEI inventory and used them for regulatory applications. Based on EPA's 2017 and 2028 projections, we derived the CONUS-wide scale factors for 2016.

Alaska and Hawaii: Global CEDS emissions are used in Alaska and Hawaii because NEI emissions in GEOS-Chem do not cover these states. The CEDS 2014 emissions are used to represent 2016 emissions in Alaska and Hawaii.

Canada: The APEI inventory in GEOS-Chem is available through 2014 which we assume representative of the year 2016. The 2028 scale factors are based on ECCC's emission projections of year 2025 from 2013, as available in the projected NEI 2028 modeling platform[80].

### B.2.5 CAMx 2016 Modeling

The CAMx 2016 36/12/4-km modeling platform developed for the DM/NFR NAA 2020 and 2023 ozone attainment demonstration modeling and described in the body of this Modeling Protocol will be used in the international emissions contribution analysis. CAMx will be run for two2016 36/12/4-km emission scenarios: (1) a 2016 base case of all emissions using boundary conditions (BCs) from the GEOS-Chem 2016 base case; and (2) a 2016 no international emissions case where anthropogenic emissions from Mexico and Canada are eliminated and BCs based on the GEOS-Chem no international emissions simulation.

### B.2.5 Post-Processing of 2016 Modeling Results

Spatial maps of ozone concentrations in the 2016 base and no international emissions cases and their differences across the U.S. will be generated. For example, Figure B-1 displays the maximum MDA8 ozone in July from the 2011 no international emissions analysis (Morris and McNally, 2017) presented at the November 2, 2017 Modeling Forum. Note that the CAMx ozone results have much (~15x) finer resolution (12-km) than GEOS-Chem (~200-km) and that CAMx has approximately twice the ozone contribution due to international sources than GEOS-Chem. One change in this study using the 2016 platform over the previous one using the 2011 platform is that we will use a 4-km Colorado domain so the CAMx results will be even more refined (~50x) than those provided by GEOS-Chem.

The latest EPA (2018d) ozone DV projection approach will be used to estimate the contributions of international emissions to 2016 ozone DVs. The EPA ozone DV projection procedures are designed to project base year ozone DVs to the future year using base and future year PGM modeling results as described in Chapter 9. The same approach will be used here, only the CAMx 2016 4-km no international emissions modeling results will be used as the future year. The 2016 ozone DVs will be tabulated with and without the contributions of international emissions.

[80] https://www.epa.gov/sites/production/files/2017-11/documents/2011v6.3_2023en_update_emismod_tsd_oct2017.pdf

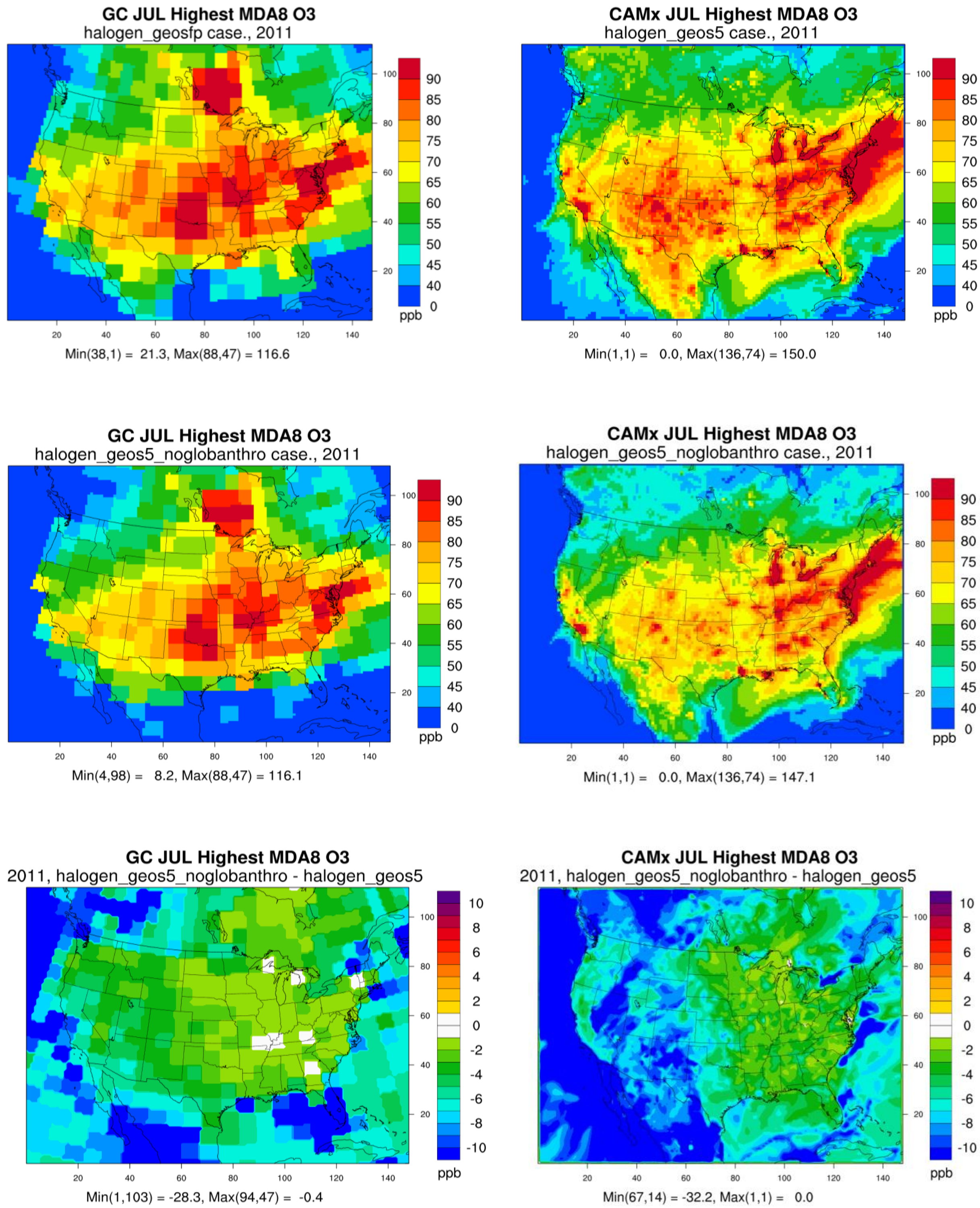



**Figure B-1. Example 2011 GEOS-Chem (left) and CAMx (right) base case (top) and no international emissions case (middle) and their differences (bottom) using the 2016 Denver ozone SIP 2011 modeling platform.**