Final Report:
Representativeness Analysis of Candidate Modeling Years for the Western U.S.

Prepared for:
Tom Moore
Western States Air Resources Council /
Western Regional Air Partnership
Colorado State University
1375 Campus Delivery
Fort Collins, CO 80523-1375

Prepared by:
Till Stoeckenius, Tasko Olevski and Maria Zatko
Ramboll
773 San Marin Drive, Suite 2115
Novato, California, 94998
www.ramboll.com
P-415-899-0700
F-415-899-0707

July 2018

RAMBOLL

CONTENTS

TABLES

FIGURES

GLOSSARY

B20	best 20% days
Bext	light extinction coefficient
CAMD	Clean Air Markets Division (a division of the U.S. EPA)
CASTNET	Clean Air Status and Trends Network
CONUS	Contiguous United States (all states except AK and HI)
CENRAP	Central States Regional Air Planning Association
CY	Calendar year
EGU	Electric Generating Utility
EPA	(U.S.) Environmental Protection Agency
GIS	Geographic information system
ENSO	El Niño/Southern Oscillation
FINN	Fire Inventory from NCAR
NCAR	National Centers for Atmospheric Research
NCEI	National Centers for Environmental Information (NOAA)
NCEP	National Center for Environmental Prediction (NOAA)
NEI	National Emissions Inventory
NOAA	National Oceanic and Atmospheric Administration
NOx	Nitrogen oxides
O_3	Ozone
PM	Particulate matter
PM_{10}	Particulate matter with aerodynamic diameter less than 10 µm
$PM_{2.5}$	Particulate matter with aerodynamic diameter less than 2.5 µm
RTOWG	Regional Technical Operations Working Group
SST	Sea Surface Temperature
SW	southwest
W20	worst 20% days
WESTAR	Western States Air Resources Council

1.0 INTRODUCTION

The Regional Technical Operations Working Group (RTOWG) of the Western Regional Air Partnership (WRAP) is seeking to develop information to inform the application and uses of the results from a specific year (or years) for the updated annual western regional photochemical modeling platform, for regional air quality planning. Given computational resource constraints and the cost of model input data preparation, modeling will be based on a single calendar year (at least initially).

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. Within this context, “representativeness” can be taken to mean the degree to which simulations of the selected period using future emissions projections are likely to provide the most policy-relevant information and thus be most useful to decision makers for air quality planning purposes. In other words, the information developed in this analysis will allow air quality modelers and planners to understand “how representative” the selected modeling base year will be for projecting future conditions. Achieving this goal requires at a minimum that the base case simulation faithfully reproduces existing conditions and simulates the correct source-receptor relationships. Any unusual or difficult to simulate conditions in the selected base case year that might skew source-receptor relationships in an anomalous manner or lead to model performance issues would be detrimental to this goal. Thus, one aspect of “representativeness” might be the extent to which the selected period is least affected by any “unusual” or “atypical” conditions. On the other hand, simulations of more extreme conditions are also likely to hold some value for air quality managers who seek to better understand the influence of such conditions on future air quality. This is especially important as the return periods, intensities, and duration for some types of extreme events are expected to become shorter in the coming decades under the continued anthropogenic influence on climate.

It must be recognized that selection of a specific year for modeling involves considerations beyond questions about “representativeness”, foremost among which are availability of emissions and meteorological data, as well as observational data needed to evaluate model performance. However, this study is intended to focus on the representativeness of meteorological and air quality conditions during each candidate year. Thus, 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. More specifically, the objective of this study is not to recommend any specific year for modeling, but rather to point out the key features of each candidate year with respect to characteristic of interest to modelers and air quality planners.

A base case photochemical modeling simulation designed to provide policy-relevant information about current air quality conditions is best performed using data from a recent time period. For this reason, the RTOWG is focusing on selecting a modeling year within the 2014 – 2016 range. Given the goal of selecting a recent year for modeling and the availability of emissions data, the next annual western regional modeling platform to be employed for the contiguous US domain by the WRAP RTOWG will most likely be based on either CY2014 or CY2016[1] although it is still possible a different year may be selected, and a representative multi-year baseline period including these years may also be evaluated. To understand the "representativeness" of these candidate years, it will be necessary to compare them with each other and with other recent years. Thus, this analysis examines meteorological conditions, emissions, and air quality during 2014 through 2016 on an inter-annual basis and in relationship to long-term means and trends. Coincident with the objectives of the planned photochemical modeling study, this analysis focusses on the western and central U.S., including the WRAP states and selected adjacent CenSARA states within the contiguous U.S. using data on meteorology, emissions, and air quality. Available data from Alaska and Hawaii are also analyzed. While there are a vast amount of data and data analyses that could inform the representativeness analysis, we focus here on key features that are directly related to goal of selecting a year which will be most suitable for serving as the base case for useful predictions of future air quality under potential alternative future emissions scenarios

[1] CY denotes the calendar year: 1 January – 31 December.

2.0 DATA

Data for this analysis were obtained from a variety of sources as described in Section 3. To minimize the amount of custom data analysis that needed to be performed, an emphasis was placed on obtaining pre-analyzed data from online resources.

Given the large size of the area of interest to this study, separate regional summaries of key parameters were prepared where appropriate based on the NOAA Climate Regions as show on the map in Figure 1. These NOAA Climate Regions are more useful for this purpose than other possible geographic climate divisions such as NOAA's more finely detailed Climate Divisions, as it keeps the number of regions to be analyzed to a manageable level and conveniently uses state boundaries, thus eliminating the need for a GIS analysis. Data for Alaska and Hawaii were compiled separately where available.

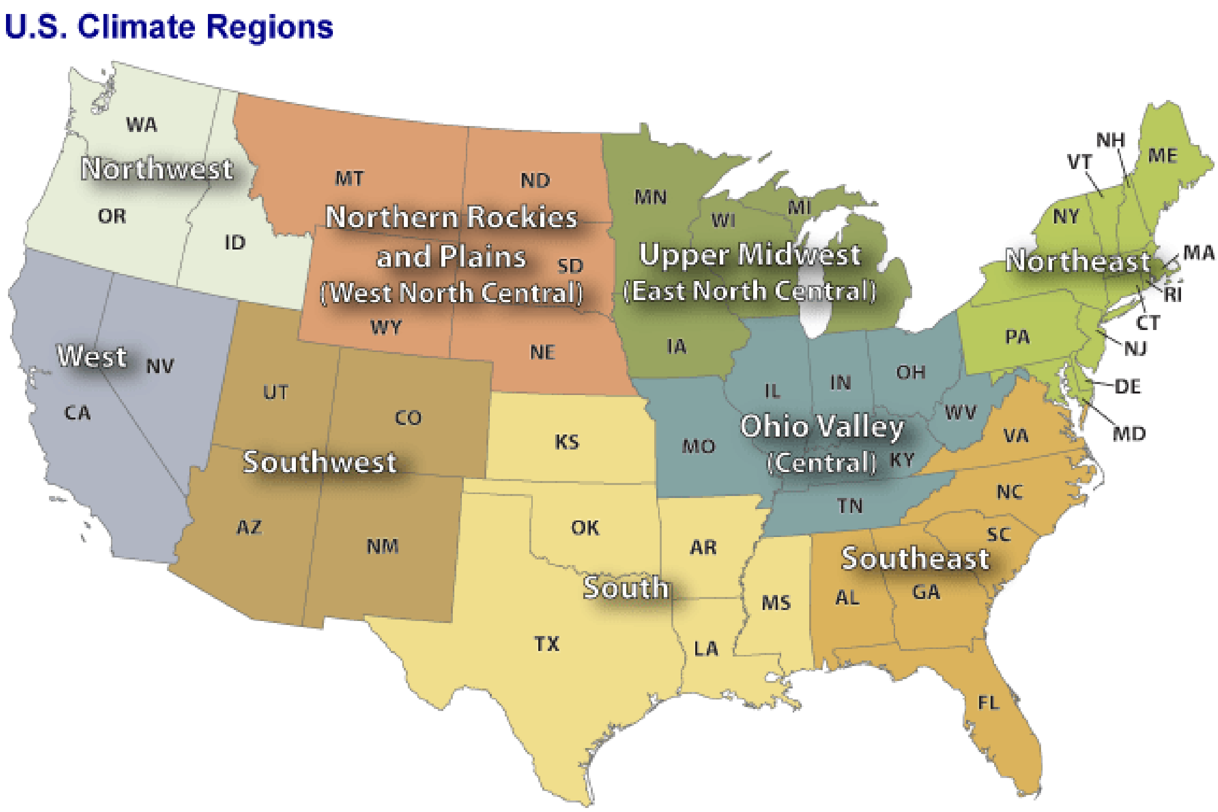

Figure 1. US Climate Regions (source: https://www.ncdc.noaa.gov/monitoring-references/maps/us-climate-regions.php).

3.0 DATA GATHERING, ANALYSES AND DISPLAY

3.1 Meteorological Conditions

Analysis results for meteorological conditions are displayed in Section 2 of the data display appendix (see text box on this page). Data sources and analysis methods are described below.

> ***Online Appendix***
> *Data analysis results for this study are available in the online data display appendix in both Microsoft OneNote format and in Adobe Portable Document File (PDF) format, at:* http://www.wrapair2.org/RTOWG.aspx.

3.1.1 Temperature and Pressure

Maps of quarterly composite means and anomalies of 500 hPa geopotential heights, sea level pressure, and 1000 hPa temperatures for North America and the eastern Pacific including Hawaii based on NCEP/NCAR reanalysis fields (Kalnay, et al., 1996) were prepared using the NOAA/ESRL Physical Sciences Division's online mapping tool (http://www.esrl.noaa.gov/psd/). Anomalies are defined as departures from the 30-year (1991 through 2010) composite means.

3.1.2 Precipitation and Drought

Annual total precipitation maps for the CONUS were obtained from the PRISM Climate Group (http://prism.oregonstate.edu/recent/). Maps of quarterly precipitation departures from 20th Century average values for the CONUS based on the 5 km gridded observations (nClimGrid) dataset were obtained from NOAA/NCEI (https://www.ncdc.noaa.gov/temp-and-precip/us-maps/1/201805?products[]=prcp-diff#us-maps-select).

Charts for the CONUS, Alaska and Hawaii displaying U.S. Drought Monitor results at the beginning and end of each year (2014 through 2016) were obtained from NOAA/NCEI (https://www.ncdc.noaa.gov/sotc/drought/201413). The Drought Monitor methodology is based on a combination of drought indices and local observations with expert review and represents an overview of drought severity and length throughout the U.S.

3.1.3 Other Meteorological Parameters

3.1.3.1 Ozone Conducive Conditions

Day-to-day variations in ozone are largely driven by local meteorological conditions and the frequency of conditions conducive to ozone formation can vary significantly from year to year. Camalier et al. (2007) developed a statistical method to quantify the expected contribution of meteorological conditions to seasonal ozone concentrations in major urban areas in terms of seasonal ozone adjustment factors. Maps of ozone adjustment factors for major U.S. metropolitan areas based on summer season weather conditions are routinely calculated by EPA (https://www.epa.gov/air-trends/trends-ozone-adjusted-weather-conditions). In these maps, positive values indicate more favorable than average conditions for ozone formation while negative values indicate less favorable conditions. Experience indicates that the Camalier et al. ozone adjustment factors are generally better able to explain interannual ozone variations in the central and eastern U.S. where surface temperature and humidity are leading explanatory variables. Meteorological parameters influencing ozone levels in western U.S. cities, however, tend to vary more from location to location due to topographic effects and more widely varying climates.

3.1.3.2 El Niño – Southern Oscillation

Interannual variations in sea surface temperature (SST) patterns in the tropical Pacific have a well-documented impact on weather over North America. A key mode of such variability is the El Niño – Southern Oscillation (ENSO) phenomenon. The positive phase of the ENSO (known as El Niño) is associated with a reduction in the strength of the trade winds which leads to suppression of upwelling and above average SSTs off the northwest coast of South America. El Niño events have been associated with warmer and wetter than average conditions in the southwestern U.S. and warmer than average winters in southern Alaska, western Canada, and the northwestern U.S. (https://www.pmel.noaa.gov/elnino/impacts-of-el-nino). In contrast, these northern areas tend to be cooler and wetter than average during the negative phase of the ENSO (known as La Niña). We obtained a 2007 through 2017 time series of the Niño 3.4 SST anomaly from NOAA/NCEI (https://www.ncdc.noaa.gov/teleconnections/enso/indicators/sst.php). The Niño 3.4 SST anomaly is a common ENSO index which takes on positive values during El Niño events and negative values during La Niña events.

3.1.3.3 Significant Climate Anomalies

Annual “storyboard” summaries of significant climate anomalies compiled by NOAA/NCEI (https://www.ncdc.noaa.gov/sotc/) were downloaded and reviewed for 2014 through 2017. These summaries provide a useful summary of key climate events in each year in the CONUS, Alaska and Hawaii.

3.2 Emissions

Summaries of fire emissions described below are displayed in Section 3 of the online data display appendix (see text box, p. 4). Summaries of anthropogenic emissions are displayed in Section 4 of the online appendix.

3.2.1 Fire Emissions

Gridded quarterly fire emissions over the CONUS derived from satellite observations were compiled from the National Center for Atmospheric Research’s (NCAR’s) FINN (Fire Inventory from NCAR) inventory for 2014 through 2016 (https://www2.acom.ucar.edu/modeling/finn-fire-inventory-ncar). FINN PM2.5 emissions were used as a surrogate for represent fire emissions. Readers should note that, while these maps show the magnitudes and locations of fire emissions, they do not indicate which areas were impacted by smoke. In addition, fire summary statistics (annual number of fires and total acres burned by state) were obtained from the National Interagency Fire Center (NIFC; https://www.nifc.gov/fireInfo/fireInfo_statistics.html).

3.2.2 Anthropogenic Emissions

State-level summaries of anthropogenic emissions for major (Tier 1) source categories for 2010 through 2016 were obtained from EPA's Emissions Trends webpage (https://www.epa.gov/air-emissions-inventories/air-pollutant-emissions-trends-data). Year-specific emissions for EGUs from EPA's Clean Air Markets Division (CAMD system https://www.epa.gov/airmarkets) and on-road vehicles were plotted for analysis. Most other source categories lack year-specific estimates and are either interpolated between NEI years or assumed to remain constant. Recent NEI years are 2008, 2011, and 2014; the 2017 NEI is currently under development.

3.3 Air Quality Conditions

A variety of air quality summaries are displayed in Section 5 of the online data display appendix (see text box, p. 4).

3.3.1 Rural Air Quality (IMPROVE and CASTNET)

Data from the IMPROVE monitoring network for 2000 through 2016 (the IMPROVE Aerosol "RHR III" dataset) were downloaded from the Federal Land Manager Environmental Database website (http://views.cira.colostate.edu/fed/DataWizard/Default.aspx). An interactive graphing tool based on open source software was developed to assist in developing visual summaries (bar charts, line charts, and thematic maps) of these data focused on daily species-specific light extinction (Bext) values with quarterly and annual averaging and sub-setting for days with best and worst 20% total Bext (B20 and W20, respectively) and 20% "most impaired" days based on EPA's anthropogenic visibility impairment metric (EPA, 2016) that is focused on excluding days with significant impacts from fires and other "natural" sources.

Summaries of nitrogen and sulfur deposition data from CASTNET/NTN network sites for 2014 through 2016 were downloaded from EPA's website (https://java.epa.gov/castnet/clearsession.do). CONUS maps of annual nitrate and ammonium ion wet deposition based on spatial interpolation of NTN precipitation chemistry measurements and PRISM gridded precipitation data were obtained from the National Acid Deposition Program website (http://nadp.slh.wisc.edu/ntn/annualmapsByYear.aspx#2016).

Summaries of daily maximum 8-hour average ozone concentrations at rural sites were obtained from the CASTNET data archive (https://www.epa.gov/castnet). Maps were generated showing annual maximum and 90th percentile values at each monitoring site for 2014 through 2017.

Given the particular importance of rural ozone levels in spring when many sites experience their annual maximum values due to enhanced intercontinental transport and increased frequency of stratospheric ozone intrusions, boxplots were generated for this study showing the annual distributions of standardized anomalies of daily maximum 8-hour average concentrations in Q2 for each of the climate regions shown in Figure 1 for 2014 through 2017. Similar boxplots were developed for Q3 to evaluate interannual variations in summer season ozone distributions. Standardized anomalies were computed by calendar quarter for each site based on site quarterly means and standard deviations derived from the 2000 through 2017 data record.

3.3.2 Urban Air Quality (AQS Data)

Annual summary statistics for O_3 (annual 4th highest daily maximum 8-hour average), PM_{10} (2nd highest daily average), and $PM_{2.5}$ (98th percentile daily average) in urban areas contained in EPA's AQS database were obtained from the AirData Air Quality Statistics Report (https://www.epa.gov/outdoor-air-quality-data/air-quality-statistics-report) for 2014 through 2016 and displayed on maps showing the corresponding values in each urban area.

In addition, composite mean daily-maximum 8-hour average ozone and composite annual mean $PM_{2.5}$ concentrations for 2000 through 2016 for each climate region depicted in Figure 1 were obtained from EPA's Air Quality Trends website (https://www.epa.gov/air-trends).

4.0 SUMMARY AND CONCLUSIONS

A wide variety of meteorological, emissions, and air quality conditions were observed during the 2014 through 2016 focus period as summarized in Table 1. Results are summarized here with an emphasis on the western CONUS study region which is roughly defined as the area west of a north-south line running approximately from Minneapolis to Houston. Results for Alaska and Hawaii are also included where available.

4.1 Meteorological Conditions

Meteorological conditions during 2014 through 2016 were characterized by an anomalous upper-level (500 hPa) high pressure ridge centered over the CONUS west coast during winter and spring of 2014 and 2015. The amplitude of the ridge decreased and the ridge axis shifted eastward by Q4 of 2015.[2] Coincident with this pattern change, a strong low anomaly established itself over the eastern North Pacific by Q1 of 2016 which helped bring the return of more normal levels of winter rain and snow to the West. Another major meteorological feature of this period was the emergence of a strong El Niño – Southern Oscillation (ENSO) event starting in late 2015 and extending into 2016. While the ENSO phenomenon is statistically correlated with weather patterns in North America, there are significant variations in the details of individual El Niño events as well as the superposition of El Niño with other inter-seasonal and interannual climate oscillations (Madden-Julian Oscillation, Pacific-N. American Oscillation, etc.) which can impact these relationships (Barnston and Livezey, 1987). In particular, the strong 2015 through 2016 El Niño did not produce the string of vigorous, wet winter storms in California and elsewhere in the West that has been associated with previous El Niño events, although above average precipitation was observed in parts of Washington and northwestern California in Q1 of 2016.

4.1.1 Hydrological Conditions

The 2014 through 2017 period was characterized by dry conditions throughout most of the country west of the Mississippi at the start of 2014 which increased in severity during the year from the High Plains westward. During 2015, the drought eased in most areas east of the Rockies but further increased in severity west of the Continental Divide, becoming especially severe in California, Oregon, and western Nevada. Rains returned to the Northwest and Northern California during the 2015-16 winter season but drought persisted in southwestern California. Another notable feature was the wetter than average southwest monsoon in the Intermountain West during the 2014 season.

4.1.2 Temperatures

Relative to 2016, Q1 near-surface (1,000 hPa) temperatures in 2014 and especially 2015 were well above average in the western North America, consistent with increased subsidence and reduced influence of cooler northerly air masses during the drought. However, 2016 was anomalously warm in Alaska and western Canada. Near-surface temperature anomalies were less apparent during other times of the year although somewhat above average temperatures

[2] Q1 = January – March, Q2 = April – June, Q3 = July – September, Q4 = October – December.

were observed in 2014 during Q3 in the Northwest and during Q4 throughout the West. Of these three years, temperatures were closest to normal throughout all quarters in 2016.

4.2 Emissions

4.2.1 Fires

Satellite-derived fire emission emissions (FINN Fire) showed significant fire activity in western Canada and the northwestern U.S. during 2015 which likely impacted air quality in many locations. The high fire activity in 2015 is also reflected in the number of wildland fires and number of acres burned statistics compiled by the National Interagency Fire Center (https://www.nifc.gov/fireInfo/fireInfo_statistics.html). In contrast, the total acres burned by wildland fires was well below average in the CONUS during 2014 and slightly below average in 2016 as noted in NOAA's State of the Climate report (https://www.ncdc.noaa.gov/sotc/fire/201713). However, in the 16 western and plains states comprising the West, Northwest, Southwest, and Northern Rockies climate regions plus Texas, Oklahoma and Kansas, the total acres burned by wildland fires in 2016 was just 6% less than in 2015. Overall fire activity in 2014 was the lowest activity of the 3 years in the both in the 16 western states and the conus and was the third lowest since 2000 (within 5% of the 2010 record low) in the CONUS. Nevertheless, the FINN fire data for Q3 show more acres burned in the northwestern US and western Canada in 2014 as compared to 2016. So, although 2014 fire activity was lower overall for the year, there was more fire activity during the 2014 dry season in the northwest than was the case in 2016.

4.2.2 Anthropogenic Sources

Year-specific estimates of emissions from on-road vehicles and electric generating utility (EGU) power plants for the period 2010 through 2016 show EGU NOx and SO_2 emissions were much lower in 2016 in all regions as compared to prior years. Note that year-specific estimates of EGU PM_{10} emissions are not available for 2015 or 2016. On-road emission trends showed some regional variations, especially in PM_{10}: during 2014 through 2016, PM_{10} emissions declined by 19% in the Northern Rockies and Plains and 15% in the South but remained essentially unchanged in the West, Southwest, and Northwest; NOx emissions declined ~26% in the Northern Rockies and Plains and the Northwest with 16% - 21% reductions in the other regions. Aside from fire emissions described above, reliable year-specific emissions for 2014 through 2016 are not readily available for other major source sector sectors.

4.3 Air Quality

4.3.1 Light Extinction

Year-to-year variations in annual average total light extinction (Bext) and average Bext on the worst 20% (W20) days are largely driven by variations in organic matter (OM) concentrations associated with fire events. For 2014 through 2016, OM was highest during 2015 in all regions, especially in the Northern Rockies and Plains. In contrast, 2016 exhibited the lowest total Bext (best visual air quality as measured by IMPROVE) since 2000 in all regions due primarily to record low nitrate, sulfate, and elemental carbon combined with very low OM. Bext on the 20% most impaired days as defined by EPA (2016) declined monotonically between 2014 and

2016 with total Bext in 2016 being the lowest observed since 2000 in all regions except the Northwest where Bext was slightly lower in 2012 due to a very low contribution from NO_3. These observations are consistent with NOx and SO_2 emission reductions in all regions and the near record low fire activity described above.

Notable variations in the quarterly average Bext summaries include:

- Q1 of 2014 had the highest NO_3 extinction since 2007 in the West. The underlying causes of this are not immediately apparent and will require a more detailed analysis to identify.
- High dust light extinction occurred during Q2 of 2014 in the Southwest but similar dust levels are not uncommon during Q2 in the longer-term record. Although not confirmed here, it seems reasonable to assume that this is due to the occurrence of one or more high wind events following a drier than usual Q1 as shown by the quarterly precipitation maps.

4.3.2 Nitrogen Deposition

No obvious large-scale trends were observed in nitrogen deposition measurements over the 2014 through 2016 period. The only significant feature identified during this period was an increase in nitrogen deposition in eastern Colorado, the Texas panhandle, and southeastern Texas in 2015 relative to 2014. Deposition in some of these areas appears to have decreased again in 2016 but the comparisons are complicated by year-to-year changes in the arrangement of operating sites. Local nitrogen wet deposition trends are impacted by changes in emissions of NOx, precipitation, and a host of factors controlling NO_3 formation and gas – particle partioning, making it difficult to relate observed changes to specific causative factors.

4.3.3 Ozone

Data from the CASTNET network provide an overview of rural surface ozone concentration variations during 2014 through 2017. Maps showing the average of the top 10% of daily maximum 8-hour average (DMAX8) ozone in each year lack any obvious interannual variations. However, some interannual variations are seen in the overall distribution of DMAX8 ozone concentrations during the spring (Q2) when rural ozone in the western U.S. is typically at a maximum due to enhanced intercontinental transport and a higher frequency of stratospheric intrusion events. Boxplots are provided in Section 5 of the online data display appendix (see text box, p. 4) depicting the distribution of standardized anomalies of DMAX8 ozone concentrations during Q2 by year. Similar boxplots are provided for summer (Q3). Note that insufficient data were available from the CASTNET network to plot ozone distributions in the Northwest region.

Spring rural ozone was dramatically lower during 2016 than in other years in the West and somewhat lower in the Southwest but the West experienced much higher ozone during the summer of 2016 than in 2014 or 2015. Means and 75th percentiles were higher in spring and summer of 2015 in the Northern Rockies and during summer in the South but the Southwest experienced lower ozone during the summer of 2015 compared to other summers. High summer ozone in the Northern Rockies in 2015 may be associated with fire impacts. High 2016 and 2017 summer ozone in the West may be due to local fire impacts or transport from urban areas (especially in 2017 when Southern California experienced an increase in peak ozone concentrations). Comparisons of key meteorological parameters during Q2 for 2014 through 2016 do not provide any obvious reasons for the low ozone in the West and Southwest in 2016; the major distinguishing feature of Q2 is a somewhat larger positive 500 hPa height anomaly over western Canada. It is possible that this is associated with a flow pattern less favorable for intercontinental transport in 2016 but additional analysis would be needed to evaluate this.

While emission reductions in 2016 could also have contributed to the lower Q2 ozone concentrations, the annual AQS ozone trends – which are largely reflective of urban sites – show relatively little change for 2014 through 2016 in the West and Southwest while median and 90th percentile concentrations were the lowest since 2000 in the Northwest, Northern Rockies, and Southwest. Also in these three regions, 2015 median and 90th percentiles were higher than in 2014 or 2016, especially in the Northwest where they were the highest observed since 2006. The AQS trends in these three regions are consistent with strong fire impacts in 2015 and reduced fire and anthropogenic emissions in 2016 but the large urban areas which dominate the AQS network trends in in the West and Southwest did not experience similar reductions.

4.3.4 PM

Annual mean $PM_{2.5}$ concentrations at the mostly urban AQS network sites were at record low values in the South, Northern Rockies, and Northwest in 2016 (based on 2000 through 2016 trends). The reduction from 2014 and 2015 levels was especially sharp in the Northwest. Low fire impacts in 2016 as well as reductions in emissions from EGUs and on-road vehicles likely contributed to these reductions. Concentrations in 2015 exceeded those in 2014 and 2016 in the Northern Rockies and Northwest, consistent with elevated fire impacts in 2015. Negative $PM_{2.5}$ trends were observed for 2000 through 2016 in the West and Southwest but there was relatively little change in these areas over the 2014 through 2016 period.

4.4 Conclusions

A review of the key features of 2014, 2015, and 2016 as described above indicates that conditions during 2015 were dominated by culmination of the western U.S. drought which was already present to some extent in 2014 and resulted in high fire activity which impacted air quality in many locations. In many respects, this made 2015 the “odd year out” of the three years. Conditions were generally closer to normal in 2014 except for an anomalously wet southwest monsoon season and near record low annual fire activity. The defining features of 2016 were reduced emissions from at least two major source categories (EGUs and on-road vehicles) which are not expected to increase in the future and a return to more normal levels of precipitation and other meteorological parameters. Total acres burned by wildfires in 2016 in the western US were nearly as high as in 2015.

Results from this analysis provide support for the idea that most if not every year exhibits significant deviations from long-term means somewhere within the full set of parameters, locations, 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 times specified in National Ambient Air Quality Standards which are intended to minimize the influence of short-term meteorological fluctuations on long-term planning.

Table 1. Summary of meteorological, emissions, and air quality conditions within the CONUS during 2014 – 2016.[a]

	2014	2015	2016	Notes
Meteorology: 500 hPa heights	Positive height anomalies over much of the western U.S. throughout the year with the most widespread anomalies in Q4	Strong anomalous ridging over the entire western US in Q1 with positive anomalies lingering into Q2 over the Northwest. This is replaced with a negative anomaly by Q4.	Lower put still positive anomalies over the west in Q1 as ridge weakens and shifts slightly east and anomalously strong trough develops offshore south of the Aleutians. The offshore trough is replaced by a slight positive height anomaly in Q3 and then splits into a dipole in Q4 with positive anomalies to the southwest and a strong negative anomaly centered over the Pacific northwest coast.	Anomalous ridging over the western US resulted in worsening drought conditions in 2014 which turned severe in 2015. A pattern shift starting late in 2015 leads to closer to normal precipitation patterns
Meteorology: hydrology	Increasing drought in west Abundant SW monsoon rains	Severe drought conditions west of Rockies, drought eases east of Rockies	Drought eases or eliminated in most of the west, drier conditions develop in plains states	2016 closest to normal; 2015 and to some extent 2014 unusually dry
Meteorology: temperature	Q1 pattern like 2015 but less extreme	Q1 especially warm in the west; cool in the Great Lakes and Northeast	Relatively cool Q3	2015 most extreme
Meteorology: other	Relatively low O_3 formation potential in Texas and surrounding region	Developing phase of a strong El Niño	Strong El Niño from late 2015 declines rapidly with the Niño 3.4 index going negative by mid-summer No strong met. influence on ozone west of the Mississippi	El Niño impacts perhaps most unusual feature of early 2016

	2014	2015	2016	Notes
Fires	Overall fire activity low although Q3 northwest fires covered more acres than in 2016. Total CONUS acres burned third lowest since 2000 (within 5% of the 2010 record low).	Significant fire activity in western Canada and Northwestern US	Total acres burned in western and plains states almost as high as in 2015; costly Ft. McMurray, Alberta fire in May	Overall high fire activity in 2015; unusually low fire activity in 2014 except in Northwest where 2016 was lower
Emissions: EGUs and On-road		EGU NOx in Southwest highest of all three years	Lowest EGU and on-road NOx emissions in all regions since at least 2010; large %EGU reduction in West from 2014; large %EGU reduction in Southwest from 2015	Lowest NOx emissions from on-road vehicles and EGUs in the western half of the country. On-road vehicle PM_{10} declined year-over-year in N. Rockies and South with flat trend elsewhere.
Air Quality: Bext (annual avg)			Lowest EC in all four western regions	
Air Quality: W20 Bext		High Bext from OM in Q3	Lowest Q1, Q2 Bext; lowest Q3 except in West region; Q4 lowest except in West and Southwest regions	Largest interannual variations in W20 Bext driven by fires
Air Quality: Bext (quarterly avg)	Q2 high dust in Southwest region and low OM in N. Rockies; Q1 highest NO_3 since 2007 in the West region	High OM all regions, especially Northern Rockies and Plains	Q1 lowest period of record total Bext in all regions; Q2 period of record low total Bext in West and Southwest (low OM plus low NO_3 in west, low SO4 and EC in Northwest and Southwest);	
Air Quality: Nitrogen Deposition		Higher deposition in eastern CO, TX Panhandle, and SE Texas compared to 2014, 2016		

	2014	2015	2016	Notes
Air Quality: CASTNET O3	Standardized anomalies do not appear unusual relative to other years (including 2017)	Some higher extreme values during Q3 in N. Rockies and South regions; Q3 ozone low in SW; Q2 ozone low in South	Low Q2 ozone in West and SW	Q3 elevated in 2016-2017 relative to 2014-2015 in West
Air Quality: O3 in Urban areas		Higher median than 2014 or 2016 in all areas except West; highest median since 2006 in NW and since 2007 in N. Rockies	Lowest median and 90th percentile since at least 2002 in all areas outside of the West and NW (except 90th percentile in NW)	Relatively flat trends 2014-2016 in West and SW compared to sharper downtrends in other regions; high 2015 values in NW and N. Rockies might be fire impacts
Air Quality: PM in urban areas		Evidence of high PM events at AQS sites in Northwest region consistent with fires; lowest $PM_{2.5}$ since at least 2000 in SW	Lowest median $PM_{2.5}$ since at least 2000 in all regions except SW	2014 – 2016 trends relatively flat in West and Southwest regions

[a]See Glossary for abbreviations used.

5.0 REFERENCES

Barnston, A. G., and R. E. Livezey, 1987. Classification, seasonality and persistence of low-frequency atmospheric circulation patterns. Mon. Wea. Rev., 115, 1083-1126.

Camalier, L., W. Cox and P. Dolwick, 2007. The effects of meteorology on ozone in urban areas and their use in assessing ozone trends. Atmospheric Environment 41, 7127-7137.

EPA, 2016. Draft Guidance on Progress Tracking Metrics, Long-term Strategies, Reasonable Progress Goals and Other Requirements for Regional Haze State Implementation Plans for the Second Implementation Period. EPA-457/P-16-001, U.S. Environmental Protection Agency, July.

Kalnay, E. and Coauthors, 1996. The NCEP/NCAR Reanalysis 40-year Project. Bull. Amer. Meteor. Soc., 77, 437-471.

Louise Camalier, William Cox, and Pat Dolwick, 2007. The Effects of Meteorology on Ozone in Urban Areas and their use in Assessing Ozone Trends. Atmospheric Environment, Volume 41, Issue 33, October 2007, pages 7127-7137.