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Development of a statistical model to identify spatial and meteorological drivers of elevated O_3 in Nevada and its application to other rural mountainous regions

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HIGHLIGHTS

- Categorical trees are developed to identify factors contributing to elevated O_3.
- Factors associated with transport characterize periods with elevated O_3.
- Inclusion of ancillary pollutant data did not improve the predictive accuracy.

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ABSTRACT

Measurements of O_3 at relatively remote monitoring sites are useful for quantifying baseline O_3, and subsequently the magnitude of O_3 not controllable by local regulations. As the National Ambient Air Quality Standard (NAAQS) for O_3 becomes more stringent, there is an increased need to quantify baseline O_3 particularly in the Western US, where regional and global sources can significantly enhance O_3 measured at surface sites, yielding baseline mixing ratios approaching or exceeding the NAAQS threshold. Past work has indicated that meteorological conditions as well as site specific spatial characteristics (e.g. elevation, basin size, gradient) are significantly correlated with O_3 intercepted at rural monitoring sites. Here, we use 3 years of measurements from sites throughout rural Nevada to develop a categorical tree model to identify spatial and meteorological characteristics that are associated with elevated baseline O_3. Data from other sites in the Intermountain Western US are used to test the applicability of the model for sites throughout the region. Our analyses indicate that increased elevation and basin size were associated with increased frequency of elevated O_3. On a daily time scale, relative humidity had the strongest association with observed MDA8 O_3. Seventy-four percent of MDA8 O_3 observations > 60 ppbv occurred when daily minimum relative humidity was < 15%. Further, we found that including ancillary pollutant data did not improve the predictive accuracy for measurements > 60 ppbv whereas including upper air meteorological measurements improved the accuracy of predicting periods when O_3 was > 60 ppbv. These findings indicate that transport, rather than local production, influences O_3 measurements in Nevada, and that high elevation sites in rural Nevada, are representative of baseline conditions in the Intermountain Western US.

1. Introduction

The United States (US) Environmental Protection Agency (EPA) is expected to revise the current National Ambient Air Quality Standard (NAAQS) for ozone (O_3) to a more stringent threshold between 60 and 70 ppbv (US EPA, 2010). The Agency recently released a proposal to lower the NAAQS to between 65 and 70 ppbv; however, comments are also being accepted for a 60 ppbv standard (https://federalregister.gov/a/2014-28674). The metric used by the US EPA to determine compliance with the O_3 NAAQS is the maximum daily 8-h average (MDA8). An area is considered in compliance with the NAAQS if the design value, that is the 3-year average of the annual 4th highest MDA8, is at or below the NAAQS. Other work has indicated that measured MDA8 O_3 in rural areas of Nevada routinely exceeds 70 ppbv (Fine et al., 2015-in this issue). For example, Fine et al. (2015-in this issue) noted that, based on 20 years (1993 to 2013) of O_3 measurements at Great Basin National Park, NV, the design value was ≤70 ppbv on only 4 occasions. Given that Great Basin National Park is well-removed from any significant emissions sources (cf. emission inventories in Van Curen and Gustin, 2015-in this issue), designing compliance strategies for this area will be challenging. Other work has indicated that Great Basin National Park, and the state of Nevada in general, are well positioned to

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intercept O_3 and precursors from a variety of sources including Asian long-range transport (LRT) and stratospheric to troposphere transport (STT) (Fine et al., 2015-in this issue; Gustin et al., 2015-in this issue; Lin et al., 2012a, 2012b; Lefohn et al., 2012); which are sources that are not controllable by local or state regulations.

Baseline O_3 is the ambient concentration measured at sites removed from recent, local emissions (Dentener et al., 2011; McDonald-Buller et al., 2011). In the Intermountain Region of the Western US quantifying baseline O_3 is increasingly important as the O_3 NAAQS becomes more stringent, because this region is routinely impacted by sources of O_3 and precursors that are not controllable by local or state regulations (i.e. LRT, STT, wildfires). Modeling studies have indicated that in this region O_3 and precursors derived from non-regional sources contribute to ambient O_3 concentrations that approach and periodically exceed the proposed O_3 NAAQS threshold (Emery et al., 2012; Lin et al., 2012a, 2012b; Zhang et al., 2011). Further, several studies have pointed out that baseline O_3 in the Western US is increasing due to rapid industrialization and growth of urban centers in east Asia whereas emissions from urban areas of the Western US are decreasing (Reidmiller et al., 2009; Cooper et al., 2010, 2012). If this trend of increasing baseline and decreasing regional emissions continues, the efficacy of local regulations at controlling ambient O_3 in the Western US will be limited.

Baseline O_3 is generally measured at rural sites characterized as relatively remote monitoring sites or sentinel sites in the scientific and regulatory literature (cf. McDonald-Buller et al., 2011; NSTC, 2013). In 2011, prompted by concerns that compliance with a more stringent O_3 NAAQS at Great Basin National Park would be difficult, and the fact that ambient air monitoring was limited to the areas immediately in and around the metropolitan areas of Reno and Las Vegas, the Nevada Rural Ozone Initiative (NVROI) began. As part of the NVROI, 13 rural air quality monitoring sites were established across rural Nevada (see Gustin et al., 2015-in this issue for a detailed description of the NVROI monitoring sites).

The landscape of Nevada is characterized by basin and range topography with hundreds of mountain ranges, primarily running north–south, crossing the state. Elevation ranges from 147 m in the Colorado River Basin to 4007 m in the White Mountains. Nevada is considered the most mountainous state in the continental US, based on the number (172 in NV) of mountain prominences >2000 m. The widespread presence of complex terrain promotes interception of air aloft and subsequent entrainment of O_3 and precursors derived from non-local sources into the surface boundary layer. Past studies have noted a positive correlation between O_3 and elevation in mountainous terrain (cf. Brodin et al., 2010; Jaffe, 2011; Burley and Bytnerowicz, 2011; Gustin et al., 2015-in this issue). Only a handful of studies have investigated the influence of terrain features other than site elevation (Klingberg et al., 2012; Gustin et al., 2015-in this issue); however, studies of urban street canyons have noted that urban canyon geometry influences the concentration of measured pollutants (cf. Price et al., 2014; Scaperdas and Colvile, 1999). Analyses of data measured at NVROI sites in rural Nevada and associated site terrain, indicated that in addition to site elevation, the slope of adjacent terrain, area of the associated basin(s), and the distance to the nearest high point were associated with variations in measured O_3 concentrations (Gustin et al., 2015-in this issue). The relationships between O_3 and other air pollutants (NO, NOx, CO, SO_2, PM) were variable and episodic supporting the theory that transport plays a more significant role in influencing ambient O_3 concentrations than any local emission sources (Miller et al., 2015–in this issue).

The goals for this particular set of analyses were to (1) develop a statistical model that would be useful for a wide-range of stakeholders that would contribute to our understanding of factors associated with elevated baseline O_3 as measured in rural Nevada, and (2) test the model's applicability to other rural sites in the Western US. Given our past work, we hypothesized that upper air transport and site terrain would be the most important factors impacting O_3 concentrations.

2. Methods

2.1. Data considered

In our analyses, we considered ambient surface O_3 and meteorological measurements (wind speed, wind direction, sigma theta of wind direction, relative humidity, temperature, and barometric pressure) collected between July 2011 and June 2014 at NVROI sites throughout rural Nevada (Fig. 1; Table 1). Detailed site descriptions and discussion of data quality and assurance protocols are discussed in Gustin et al. (2015-in this issue). At Great Basin National Park (GBNP), measurements of ancillary parameters including CO, NO, NOx, SO_2, and PM2.5 were also considered. A detailed description of the instruments and quality assurance protocols for these ancillary parameters are given in Gustin et al. (2015-in this issue) and Miller et al. (2015–this issue).

Terrain characteristics including site elevation, basin area, the distance to the nearest high point, and the maximum topographic gradient to the site were also considered (Table 1). These measurements were calculated using digital elevation models in ArcGIS (ESRI, Redlands, CA). A detailed description of the methodologies used in the calculations can be found in Gustin et al. (2015-in this issue).

In addition, we considered ambient temperature, wind direction, wind speed, water mixing ratios, and geopotential heights measured at 700 hPa and 500 hPa by twice daily sonde flights from 3 locations in Nevada: Reno, Elko, and Las Vegas (Table SI 1). Sonde flights were initiated at 00 UTC (1600 LST) and 12 UTC (0400 LST). We considered upper air data collected between July 2011 and June 2014. Upper air data were downloaded from the database maintained by the University of Wyoming (http://weather.uwyo.edu/upperair/sounding.html). As our analyses progressed and the utility of upper air measurements emerged, we also incorporated spatially averaged measurements of geopotential height, zonal wind speed, specific humidity, and temperature at the 500 hPa level from the NCEP Reanalysis data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at http://www.esrl.noaa.gov/psd/.

2.2. Analyses

Other work indicated that both discrete and continuous variables influenced observed O_3 in rural Nevada (cf. Fine et al., 2015-in this issue; Gustin et al., 2015-in this issue). As such, we chose to construct categorical tree models, because it was possible to include predictor variables that were nominal, ordinal, and continuous. Categorical tree models also have the advantage of being readily interpretable relative to other multivariate tools such as neural networks, which have more of a black box computational environment (cf. Choi et al., 2013; Dye et al., 2003; National Research Council, 1991; Horie, 1988). To grow our trees, we used chi-squared automatic interaction detection (CHAID), which is a chi-squared-based test that identifies independent variables that have the strongest interactions with a dependent variable (i.e. O_3 for the analyses presented here). In our analyses, we allowed predictor variables that were not significantly different in their interactions with O_3, to be merged.

To build our tree models, we considered hourly and daily time-resolution data measured at NVROI sites for the period ranging from July 2011 to June 2014. Initially, data from 10 rural Nevada sites were considered; however, as the analyses progressed we chose to focus on data collected at the six sites located at ≥1728 m elevation (Fig. 1) during the months of May to July because the frequency of elevated O_3 was highest during this time at those locations relative to the other NVROI sites. Human health and ecosystem effects occur under conditions of elevated O_3 and thus sites with more frequent elevated O_3 are of greatest regulatory significance. The EPA has recently proposed to revise the NAAQS for O_3 to a range between 65 and 70 ppbv and is also accepting comments on a 60 ppbv standard (https://federalregister.gov/a/2014-28674). Thus, we chose to use 65 ppbv as the target variable for the first iteration in our analyses, because it represented the midpoint of