Regional Impacts of Oil and Gas Development on Ozone Formation in the Western United States

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ABSTRACT
The Intermountain West is currently experiencing increased growth in oil and gas production, which has the potential to affect the visibility and air quality of various Class I areas in the region. The following work presents an analysis of these impacts using the Comprehensive Air Quality Model with extensions (CAMx). CAMx is a state-of-the-science, “one-atmosphere” Eulerian photochemical dispersion model that has been widely used in the assessment of gaseous and particulate air pollution (ozone, fine [PM_{2.5}], and coarse [PM_{10}] particulate matter). Meteorology and emissions inventories developed by the Western Regional Air Partnership Regional Modeling Center for regional haze analysis and planning are used to establish an ozone baseline simulation for the year 2002. The predicted range of values for ozone in the national parks and other Class I areas in the western United States is then evaluated with available observations from the Clean Air Status and Trends Network (CASTNET). This evaluation demonstrates the model’s suitability for subsequent planning, sensitivity, and emissions control strategy modeling. Once the ozone baseline simulation has been established, an analysis of the model results is performed to investigate the regional impacts of oil and gas development on the ozone concentrations that affect the air quality of Class I areas. Results indicate that the maximum 8-hr ozone enhancement from oil and gas (9.6 parts per billion [ppb]) could affect southwestern Colorado and northwestern New Mexico. Class I areas in this region that are likely to be impacted by increased ozone include Mesa Verde National Park and Weminuche Wilderness Area in Colorado and San Pedro Parks Wilderness Area, Bandelier Wilderness Area, Pecos Wilderness Area, and Wheeler Peak Wilderness Area in New Mexico.

INTRODUCTION
High ozone (O_3) levels at the Earth’s surface, such as the photochemical smog that frequently envelopes Los Angeles in the summer, have typically been regarded as an urban air quality problem. However, a disturbing trend in recent years has been the rise of tropospheric O_3 in remote regions of the western United States, many of which are Class I areas (international parks, national wilderness areas that exceed 5000 acres in size, national memorial parks that exceed 5000 acres in size, and national parks that exceed 6000 acres in size) as designated by the Clean Air Act. Possible explanations for this trend include increasing background concentrations, largely due to emissions from Asia or changes in the magnitude or distribution of regional emissions.

O_3 is a strong oxidant that can reduce lung function and damage plant tissue at relatively low concentrations. In March 2008, the U.S. Environmental Protection Agency (EPA) tightened existing National Ambient Air Quality Standards (NAAQS) for O_3 to 75 parts per billion (ppb; assessed as the fourth highest monitored O_3 concentration value over a running average 8-hr period, averaged over 3 continuous years) from the previous 80 ppb, effectively reducing the compliance level of the O_3 NAAQS by 9 ppb. In April 2008, the EPA Clean Air Science Advisory Committee clarified earlier recommendations to the EPA administrator that a primary O_3 standard between 60 and 70 ppb is necessary to protect human health.

O_3 is formed through a complex series of chemical reactions involving nitrogen oxides (NO_x) and volatile organic compounds (VOCs) in the presence of sunlight. To combat rising O_3 levels, these precursors must be reduced. However, as oil and gas development in the western United States continues to accelerate, there is significant potential that emissions from these sources will
exacerbate the existing $O_3$ problem. Although emissions from oil and gas development may appear small as compared with other emission categories such as coal-fired power plants and automobiles, they typically occur in remote regions of the country, far removed from urban areas, and can have a disproportionate effect on the air quality of Class I areas. For example, $NO_x$ emissions from an internal combustion engine at a gas well may react with terpenes (a reactive VOC) emitted from pine forests and form $O_3$ in an area where the right mix of precursors was previously not available for this reaction to take place. This is especially worrisome because recent observations indicate that many remote wilderness areas and national parks, such as Mesa Verde National Park in southwestern Colorado, are confronted with $O_3$ concentrations that are trending toward the EPA’s acceptable limits. Very near Mesa Verde National Park are rapidly growing oil and gas extraction operations in northwestern New Mexico. As this type of development continues throughout the west, it is essential to understand its potential negative impact on air quality in some of our nation’s most cherished protected areas. It is important to notice that wintertime $O_3$ concentrations exceeding 140 ppb were recently observed near the Jonah-Pinedale Anticline natural gas field in Wyoming’s Upper Green River Basin.

This study uses sophisticated meteorological and air pollution models to simulate air quality in the western United States, with a particular focus on $O_3$ concentrations in our national parks and wilderness areas. The Western Regional Air Partnership (WRAP) provided the necessary inputs to the model for meteorology, emissions, and boundary concentrations, originally developed for regional haze analysis and planning. The modeling system used in this work is similar to other systems used in demonstrating compliance with current NAAQS.7,8

Understanding the impacts of emissions from particular source categories such as oil and gas development is crucial to develop effective strategies that help reduce regional air pollution. Although this article focuses on the impact of $O_3$ pollution, the concept of “one-atmosphere” computer modeling is identified in the WRAP 2008-12 Strategic Plan for future regional air quality analyses.9 This approach is used to investigate several issues related to regional formation and transport of air pollutants such as the primary and secondary NAAQS for $O_3$ and particulate matter, visibility protection, and mitigating health and ecosystem effects due to excessive nitrogen deposition and toxic air pollutants such as mercury.

**APPRAOH**

The modeling system comprises three major components: the Penn State University/National Center for Atmospheric Research Mesoscale Model (known as MM510), a regional weather model; CAMx (Comprehensive Air Quality Model with Extensions11), a chemistry transport model; and SMOKE (Sparse Matrix Operator Kernel Emissions12), an emissions processing system that chemically, spatially, and temporally allocates the raw emissions data. CAMx simulates the emissions, dispersion, chemical reactions, and removal of pollutants in the troposphere by solving the pollutant continuity equation for each chemical species on a three-dimensional grid. Although computationally expensive, this type of simulation accounts for the complex physical and chemical processes that govern the fate of pollutants. The 36-km coarse-grid horizontal domain used for the air quality modeling consists of the contiguous 48 U.S. states, contiguous lands and waters of southern Canada and northern Mexico, portions of the Pacific and Atlantic oceans, most of the Gulf of Mexico, all of the Gulf of California, and the southern Hudson Bay region. The CAMx 36-km grid includes 148 cells in the east-west dimension and 112 cells in the north-south dimension. The vertical grid used in the MM5 modeling defines the CAMx vertical structure. The MM5 simulations used a terrain-following coordinate system defined by pressure using 34 layers that extend from the surface to the model top at 100 mbar. To reduce computational costs, a layer-averaging scheme was adopted, reducing the original 34 layers to 19 vertical layers. Figure 1 presents a map of the computational modeling domain; it also shows the states that form the western region of the United States, the area of interest for this analysis. MM5 provides the wind fields that CAMx needs to determine the transport of chemical species, as well as other meteorological variables such as temperature and pressure. A detailed emission inventory specifies the hourly flux of emissions from numerous area and point pollutant sources. The emission inventory focuses on pollutants that are important for regional haze and visibility in the selected model domain, which includes the contiguous United States, southern Canada, and northern Mexico. The inventory consists of 22 emission categories (e.g., automobiles, power plants, forest fires, and oil and gas development) and was originally developed in support of WRAP’s regional haze simulations.13 Figure 2 shows the annual $NO_x$ emissions associated with oil and gas development in the western United States. Note that significant emissions occur throughout the Intermountain West, particularly in the Four Corners region of northwestern New Mexico.

The oil and gas emission inventory used here was initially compiled for WRAP’s regional modeling, with a focus on $NO_x$ and oxidized sulfur ($SO_x$) emissions, which are precursors to fine particulate nitrate and sulfate, respectively. However, subsequent versions of this inventory have been developed and improved, and emissions of some species, such as VOCs, have been substantially revised. Although this study uses an earlier version of the WRAP oil and gas emission inventory, it is anticipated that the general trends presented provide a gross indication of the impact of this source category on regional $O_3$ formation.

In this study, a simulation for the year 2002 is performed with CAMx and corresponds to the “base modeling year” being investigated by WRAP and the latest year in which detailed emissions were readily available. The first step in this analysis is the comparison between predicted $O_3$ concentrations with available observations. Once the model performance of this base-case simulation is deemed adequate, a second CAMx simulation that includes all of the base-case emissions except those from oil...
and gas is used to evaluate their air quality impacts in the western United States. The impacts are determined by looking at the difference between the base case and the “absent oil and gas emissions” simulations.

ANALYSIS

Model Performance Evaluation

O₃ concentrations predicted by the model are evaluated by comparing the surface layer values with available hourly measurements of ground-level O₃ at 22 sites from the Clean Air Status and Trends Network (CASTNET) monitoring network. These sites fall within the western region of the United States and are indicated by circles in Figure 1. An evaluation of CAMx’s skill in predicting O₃ is done in accordance with the EPA’s suggested performance guidelines for O₃ modeling. Observation/prediction pairs are excluded from the analysis when the observed concentration is below a certain cutoff level. The EPA has suggested a cutoff value of 60 ppb; however, most of the sites considered here are located in remote, pristine areas, and thus the cutoff value is set at 20 ppb because natural O₃ levels range typically between 10 and 25 ppb.

Table 1 shows the annual model performance statistics for 1-hr O₃ in the western region of the United States during 2002. In general, CAMx is able to consistently predict the general annual trends for O₃ concentrations, with a mean normalized bias of −1.6% and a mean absolute normalized error of 22.7%, falling well within the EPA’s guidelines for acceptable model performance. Figure 3 shows estimated monthly normalized error and bias bar plots. Throughout the year, the model also performs within EPA goals; for instance, the largest errors are less than 25% during the summer (August). The model seems to show some seasonality in the errors and biases; its performance is better for the winter and fall and slightly worse for the spring and summer. The model has a tendency to underpredict O₃ concentrations during the summer and fall, with the largest biases in August (−15%), whereas it overpredicts O₃ during the winter and spring. Table 1 also shows the

![Figure 1](image1.jpg)

**Figure 1.** Map of the 36-km computational domain used in this study. The shaded area shows the analysis domain and corresponds to those states that are part of the contiguous WRAP region (Alaska and Hawaii are WRAP members, but are not in the modeling domain). The circles in the figure indicate the location of CASTNET sites used in this study for the model performance evaluation of O₃.

![Figure 2](image2.jpg)

**Figure 2.** Annual 2002 WRAP NOₓ emissions (t/yr) from oil and gas exploration and production activities in the western United States.
annual performance statistics for sites located near places for which the impacts from oil and gas emissions will be discussed in the following sections. It is important to notice that for these specific sites the predicted hourly O₃ concentrations also fall within EPA guidelines for acceptable model performance. In general, the performance in most of these sites is better than in the western United States as a whole, with normalized errors ranging from 14.9% (Fitzgerald) to 19.8% (Canyonlands National Park). Many of these sites are located in very complex terrain, so given the coarse resolution of the model, its performance is reasonable and even comparable to that of other studies. Figure 4 shows 8-hr moving averages of predictions and observations for the CASTNET sites presented in Table 1. The figure illustrates that the model does not seem to accurately capture the complex diurnal variations in the observations. However, it shows that throughout the year the model follows the general trends revealed by the observations, particularly on a monthly average basis. In the case of Canyonlands, the model variation is larger than the other sites and the model has a pronounced tendency to underpredict observations during the summer and fall.

### Table 1. Annual model performance statistics for 1-hr O₃ calculated with 22 CASTNET sites in the contiguous WRAP region of the western United States.

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Mesa Verde National Park</th>
<th>Gunnison National Park</th>
<th>Canyonlands National Park</th>
<th>Fitzpatrick</th>
<th>CASTNET Sites (Western United States)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean observation</td>
<td>46</td>
<td>50</td>
<td>48</td>
<td>48</td>
<td>47</td>
</tr>
<tr>
<td>Mean estimation</td>
<td>46</td>
<td>52</td>
<td>43</td>
<td>46</td>
<td>44</td>
</tr>
<tr>
<td>Standard deviation observations</td>
<td>10</td>
<td>9</td>
<td>10</td>
<td>8</td>
<td>13</td>
</tr>
<tr>
<td>Standard deviation estimates</td>
<td>13</td>
<td>10</td>
<td>11</td>
<td>9</td>
<td>12</td>
</tr>
<tr>
<td>Mean bias error</td>
<td>–0.02</td>
<td>2.6</td>
<td>–5</td>
<td>–1.5</td>
<td>–3</td>
</tr>
<tr>
<td>Mean normalized bias error (%)</td>
<td>&lt; ±15%</td>
<td>0.9</td>
<td>–8.4</td>
<td>–1.7</td>
<td>–1.6</td>
</tr>
<tr>
<td>Mean absolute gross error (%)</td>
<td>8</td>
<td>7</td>
<td>9.6</td>
<td>7.2</td>
<td>10</td>
</tr>
<tr>
<td>Mean absolute normalized gross error (%)</td>
<td>16.9</td>
<td>15.7</td>
<td>19.8</td>
<td>14.9</td>
<td>22.7</td>
</tr>
<tr>
<td>Mean fractional error (%)</td>
<td>16.9</td>
<td>14.6</td>
<td>22</td>
<td>15.2</td>
<td>23</td>
</tr>
<tr>
<td>Mean fractional bias (%)</td>
<td>–1.4</td>
<td>5.3</td>
<td>–11.9</td>
<td>–3.5</td>
<td>–5.8</td>
</tr>
</tbody>
</table>

**Notes:** All values in ppb except where indicated.

**Figure 3.** Monthly model performance (a) mean absolute normalized gross error and (b) mean normalized bias bar plots for 1-hr O₃ calculated with 22 CASTNET sites in the WRAP region.

### Oil and Gas Impacts

As indicated above, this study relies on two separate CAMx simulations to estimate the potential impacts of oil and gas emissions in the western United States. A more regional perspective of O₃ formation is illustrated in Figure 5. Figure 5a shows the highest 8-hr O₃ concentration at each model grid cell that occurred during the 2002 base-case simulation. As expected, there are high concentrations (exceeding 110 ppb) downwind of major urban areas such as Los Angeles, San Francisco, Salt Lake City, and Denver. The figure also demonstrates that for a large region of the southwestern United States that includes remote regions of Nevada, Wyoming, Utah, Arizona, New Mexico, and Colorado, the new 8-hr primary NAAQS-related threshold for ground-level O₃ (75 ppb) is exceeded at least once during 2002 for many Class I areas. Generally, these maxima occur during hot, sunny days with light winds, when the meteorology is most favorable for O₃ production. These periods also typically correspond to peak VOC emissions from biogenic and anthropogenic sources. The impact of NOₓ and VOC emissions from oil and gas development on O₃ in the western United States is shown in Figure 5b. Note that the values for each grid cell in Figure 5b correspond to the dates for which O₃...
maxima occur (Figure 5a), but in this case, the O$_3$ concentration is solely due to emissions from oil and gas development. Although the peak O$_3$ maxima throughout the west are typically quite small, there is a strong signature of 1–2 ppb of O$_3$ throughout New Mexico, Colorado, and Wyoming, with a pattern that approximates the...
emissions shown in Figure 2. However, the maximum possible impacts of oil and gas emissions do not necessarily coincide in time with the maximum possible O₃ concentrations, as illustrated in Figure 6. The maxima 8-hr O₃ enhancement from oil and gas alone shown in Figure 6b demonstrates that significant O₃ concentrations (maximum of 9.6 ppb) could affect southwestern Colorado and northwestern New Mexico. Class I areas in this region that are likely to be impacted by increased O₃ include Mesa Verde National Park and Weminuche Wilderness Area in Colorado and San Pedro Parks Wilderness Area, Bandelier Wilderness Area, Pecos Wilderness Area, and Wheeler Peak Wilderness Area in New Mexico. O₃ concentrations for the base-case simulation during this period (Figure 6a) range from 40 to 70 ppb; thus in some places (e.g., Mesa Verde National Park and Weminuche) oil and gas have the potential to put these places out of compliance with the new EPA O₃ standard. Figure 6b shows that there are three regions where oil and gas have the potential for maximum impacts on Class I areas: southwestern Colorado and northern New Mexico, the southeast corner of New Mexico, and western Wyoming. Table 2 shows the date when the maximum impacts due to oil and gas emissions are achieved and their corresponding base-case concentrations for some of the Class I area sites. In general, these results show that most of the impacts occur during the summer and early fall. However, from this table alone it is not possible to know, for each site, the percentage of time when high impacts are observed in spring and early summer compared with summer and

Table 2. Maximum O₃ impacts due to oil and gas, date the maxima occur, and base-case concentration in some Class I area sites located in the western United States.

<table>
<thead>
<tr>
<th>Class I Area</th>
<th>Latitude (°)</th>
<th>Longitude (°)</th>
<th>Base-Case Concentration (ppb)</th>
<th>Maximum Impact Oil and Gas (ppb)</th>
<th>Date Maximum Impact Occurs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weminuche</td>
<td>37.65</td>
<td>−107.80</td>
<td>40</td>
<td>7</td>
<td>August 5</td>
</tr>
<tr>
<td>San Pedro Parks</td>
<td>36.11</td>
<td>−106.81</td>
<td>35</td>
<td>5</td>
<td>September 8</td>
</tr>
<tr>
<td>Carlsbad Caverns</td>
<td>32.14</td>
<td>−104.48</td>
<td>49</td>
<td>4</td>
<td>August 27</td>
</tr>
<tr>
<td>Wheeler Peak</td>
<td>36.57</td>
<td>−105.42</td>
<td>37</td>
<td>3</td>
<td>September 13</td>
</tr>
<tr>
<td>Pecos</td>
<td>35.93</td>
<td>−105.64</td>
<td>40</td>
<td>3</td>
<td>September 13</td>
</tr>
<tr>
<td>Bandelier</td>
<td>35.78</td>
<td>−106.26</td>
<td>61</td>
<td>3</td>
<td>June 30</td>
</tr>
<tr>
<td>Mesa Verde</td>
<td>37.20</td>
<td>−108.48</td>
<td>64</td>
<td>3</td>
<td>July 13</td>
</tr>
<tr>
<td>Saltcreek</td>
<td>33.61</td>
<td>−104.37</td>
<td>49</td>
<td>3</td>
<td>July 29</td>
</tr>
<tr>
<td>Great Sand Dunes</td>
<td>37.72</td>
<td>−105.51</td>
<td>33</td>
<td>2</td>
<td>September 8</td>
</tr>
<tr>
<td>La Garita</td>
<td>37.96</td>
<td>−106.81</td>
<td>38</td>
<td>2</td>
<td>August 6</td>
</tr>
<tr>
<td>Bridger</td>
<td>42.97</td>
<td>−109.75</td>
<td>52</td>
<td>2</td>
<td>April 4</td>
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<tr>
<td>Fitzpatrick</td>
<td>43.27</td>
<td>−109.57</td>
<td>52</td>
<td>2</td>
<td>April 4</td>
</tr>
<tr>
<td>Grand Teton</td>
<td>43.68</td>
<td>−110.73</td>
<td>50</td>
<td>1</td>
<td>April 24</td>
</tr>
<tr>
<td>Washakie</td>
<td>43.95</td>
<td>−109.59</td>
<td>44</td>
<td>1</td>
<td>September 10</td>
</tr>
</tbody>
</table>
early fall. Figure 7 is a much better indicator of this tendency. Figure 7 shows 8-hr moving average time series for the base case and the oil and gas impacts for a few selected sites from Table 2, including Weminuche, where the largest impacts are observed. The other sites represent one of the other two main regions identified as having larger impacts from oil and gas emissions. The general trend of modeled $O_3$ (Figure 7a) is low concentrations during the colder winter months, when limited photochemistry will occur, and higher concentrations during the warmer late spring and summer months, when meteorological conditions are more favorable to $O_3$ production. Additionally, enhanced biogenic VOC emissions that occur during the spring and summer will further influence $O_3$ formation in the region. The dashed lines in Figure 7a show the new EPA standards for $O_3$. It is evident from the figure that there are various instances in which $O_3$ concentrations are higher than the new NAAQS in many of these Class I areas, particularly during the late spring and early summer. Figure 7b shows the resulting changes in predicted $O_3$ concentrations that are attributed solely to emissions from oil and gas development. This estimate was calculated by evaluating two CAMx simulations: the base-case simulation, in which all emission categories are accounted, and a “no oil and gas” simulation, which is similar to the base case except that oil and gas emissions are removed. The difference between these two simulations represents the contribution of oil and gas emissions on regional $O_3$. Notable in Figure 7b is the fact that oil and gas emissions can actually decrease $O_3$ concentrations at various sites through the process of “NOx scavenging,” in which available $O_3$ is consumed by reacting.

Figure 7. Time series of (a) simulated base-case $O_3$ (ppb, 8-hr average) for sites representative of one of the three main regions identified as having larger impacts from oil and gas emissions (Weminuche, Saltcreek, and Fitzpatrick Class I areas). (b) The change in $O_3$ concentration (ppb, 8-hr average) at each site solely due to VOC and NOx emissions from oil and gas development.
with nitric oxide (NO). This effect is most prevalent in the winter, when O₃ concentrations are lower. However, in the summer, the situation is reversed, and warm, stagnant conditions yield an increase in O₃ from oil and gas emissions. Although these impacts appear relatively small (e.g., an increase of a few ppb in the summer), it should be remembered that this period corresponds with seasonally high O₃ concentrations.

CONCLUSIONS

A regional air quality model has been applied to the western United States to investigate the impacts of emissions from oil and gas development on O₃ concentrations. Incremental O₃ increases (8-hr average) ranging from less than 1 to 7 ppb were predicted at several western Class I areas, and a peak incremental O₃ concentration of 10 ppb was simulated in the Four Corners region. This study, although not exhaustive, does indicate a clear potential for oil and gas development to negatively affect regional O₃ concentrations in the western United States, including several treasured national parks and wilderness areas in the Four Corners region. It is likely that accelerated energy development in this part of the country will worsen the existing problem. The formation of O₃ pollution examined here represents a complex phenomenon involving nonlinear physical and chemical processes, uncertain emission inventories, and fine-scale transport in mountainous terrain. These simulations will be refined when updated emission inventories are available from WRAP. Regional air quality modeling requires significant resources but remains the only feasible option for developing emission control strategies that have the potential to reduce O₃ concentrations and protect air quality.

REFERENCES


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