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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.

IMPLICATIONS

Population growth in the western United States is driving a rapid increase in the generation of electricity and fossil fuel production, leading to higher NO_x emissions and the potential to affect the visibility and air quality of Class I areas in the region. Although total emissions from oil and gas development are small compared with other categories such as coal-fired power plants and automobiles, they occur in remote locations and can have a disproportionate effect on the air quality of national parks and wilderness areas. The following work provides an analysis of these impacts on ozone concentrations using a state-of-the-science photochemical dispersion model.

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,[1] 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[2–4] or changes in the magnitude or distribution of regional emissions.[1]

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.[5]

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.[6]

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.

APPROACH

The modeling system comprises three major components: the Penn State University/National Center for Atmospheric Research Mesoscale Model (known as MM5[10]), a regional weather model; CAMx (Comprehensive Air Quality Model with Extensions[11]), a chemistry transport model; and SMOKE (Sparse Matrix Operator Kernel Emissions[12]), 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

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 O_3.

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

O_3 concentrations predicted by the model are evaluated by comparing the surface layer values with available hourly measurements of ground-level O_3 at 22 sites from the Clean Air Status and Trends Network (CASTNET)[14] 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 O_3 is done in accordance with the EPA's suggested performance guidelines for O_3 modeling.[15,16] 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 O_3 levels range typically between 10 and 25 ppb.[17] Table 1 shows the annual model performance statistics for 1-hr O_3 in the western region of the United States during 2002. In general, CAMx is able to consistently predict the general annual trends for O_3 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 O_3 concentrations during the summer and fall, with the largest biases in August (−15%), whereas it overpredicts O_3 during the winter and spring. Table 1 also shows the

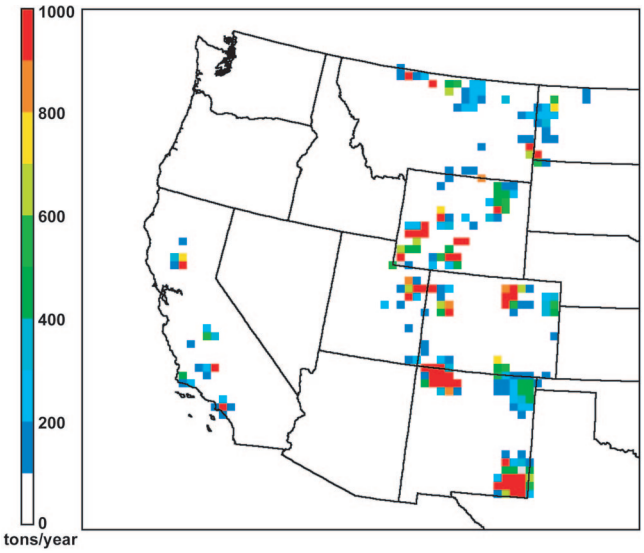

Figure 2. Annual 2002 WRAP NO_x emissions (t/yr) from oil and gas exploration and production activities in the western United States.

Table 1. Annual model performance statistics for 1-hr O_3 calculated with 22 CASTNET sites in the contiguous WRAP region of the western United States.

Statistic	EPA Goal	Mesa Verde National Park	Gunnison National Park	Canyonlands National Park	Fitzpatrick	CASTNET Sites (Western United States)
Mean observation		46	50	48	48	47
Mean estimation		46	52	43	46	44
Standard deviation observations		10	9	10	8	13
Standard deviation estimates		13	10	11	9	12
Mean bias error		−0.02	2.6	−5	−1.5	−3
Mean normalized bias error (%)	< ±15%	0.9	7.3	−8.4	−1.7	−1.6
Mean absolute gross error		8	7	9.6	7.2	10
Mean absolute normalized gross error (%)	<35%	16.9	15.7	19.8	14.9	22.7
Mean fractional error (%)		16.9	14.6	22	15.2	23
Mean fractional bias (%)		−1.4	5.3	−11.9	−3.5	−5.8

Notes: All values in ppb except where indicated.

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 O_3 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.[18–20] 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.

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 O_3 formation is illustrated in Figure 5. Figure 5a shows the highest 8-hr O_3 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 O_3 (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 O_3 production. These periods also typically correspond to peak VOC emissions from biogenic and anthropogenic sources. The impact of NO_x and VOC emissions from oil and gas development on O_3 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 O_3

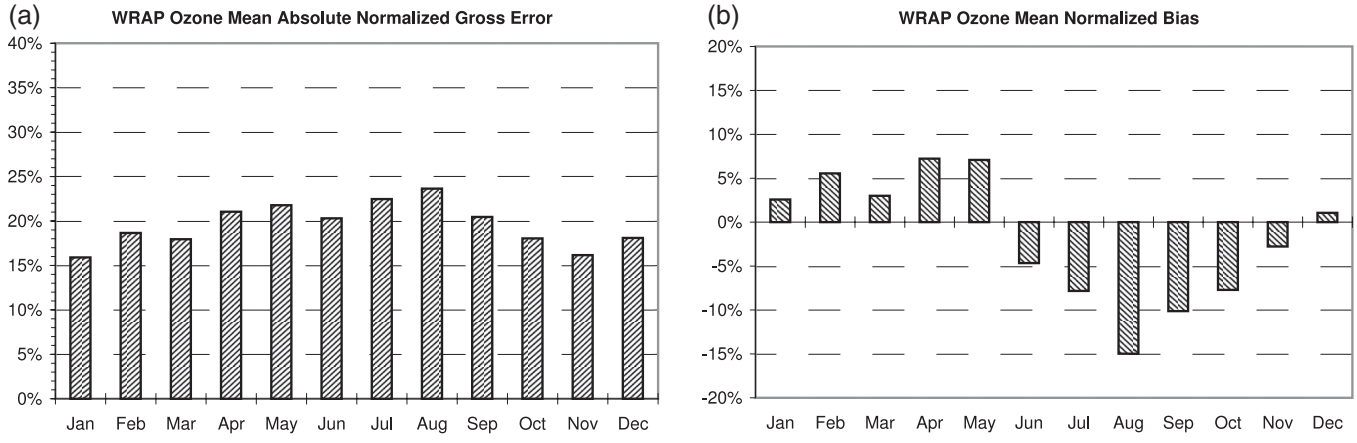

Figure 3. Monthly model performance (a) mean absolute normalized gross error and (b) mean normalized bias bar plots for 1-hr O_3 calculated with 22 CASTNET sites in the WRAP region.

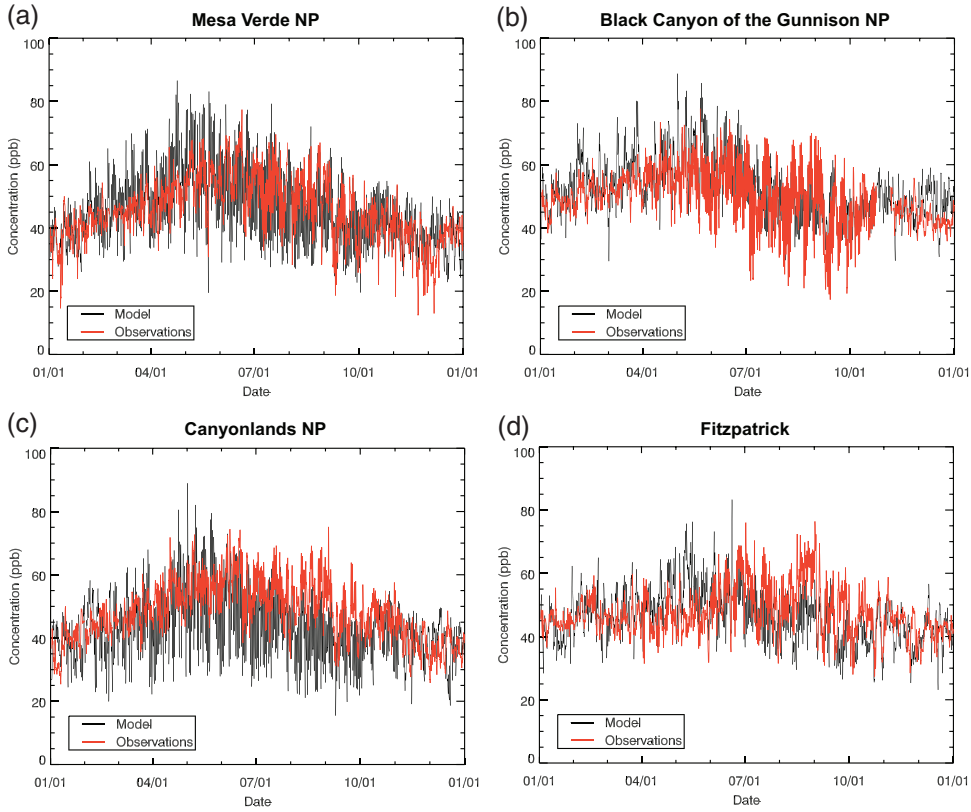

Figure 4. Time series comparison between model (black line) and observed (red line) 8-hr average O_3 (base case) for the CASTNET sites included in Table 1: (a) Mesa Verde National Park, (b) Black Canyon of the Gunnison National Park, (c) Canyonlands National Park, and (d) the Fitzpatrick Class I area included in Table 1.

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

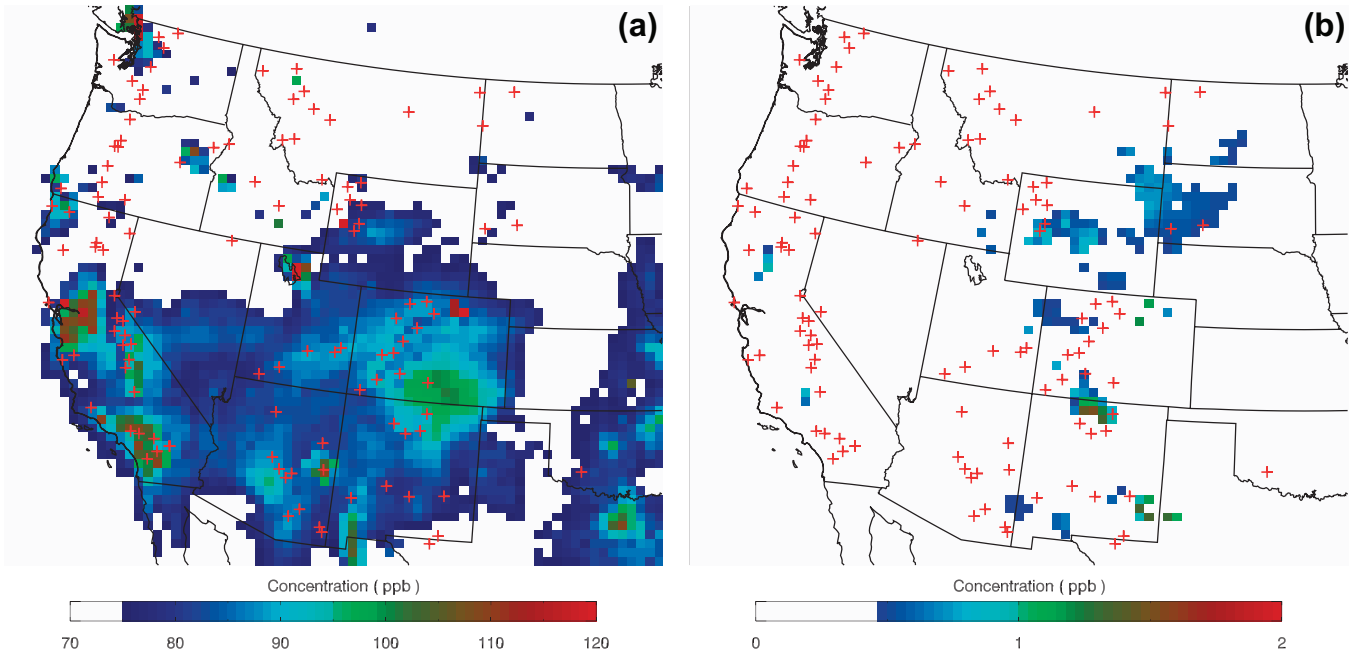

Figure 5. Peak predicted annual O_3 maxima (ppb, 8-hr average) in the western United States from (a) the 2002 base-case simulation and (b) the enhancement from VOC and NO_x emissions from oil and gas development that correspond to the dates and times of O_3 maxima. The locations of all Class I areas in the region are indicated with red crosses.

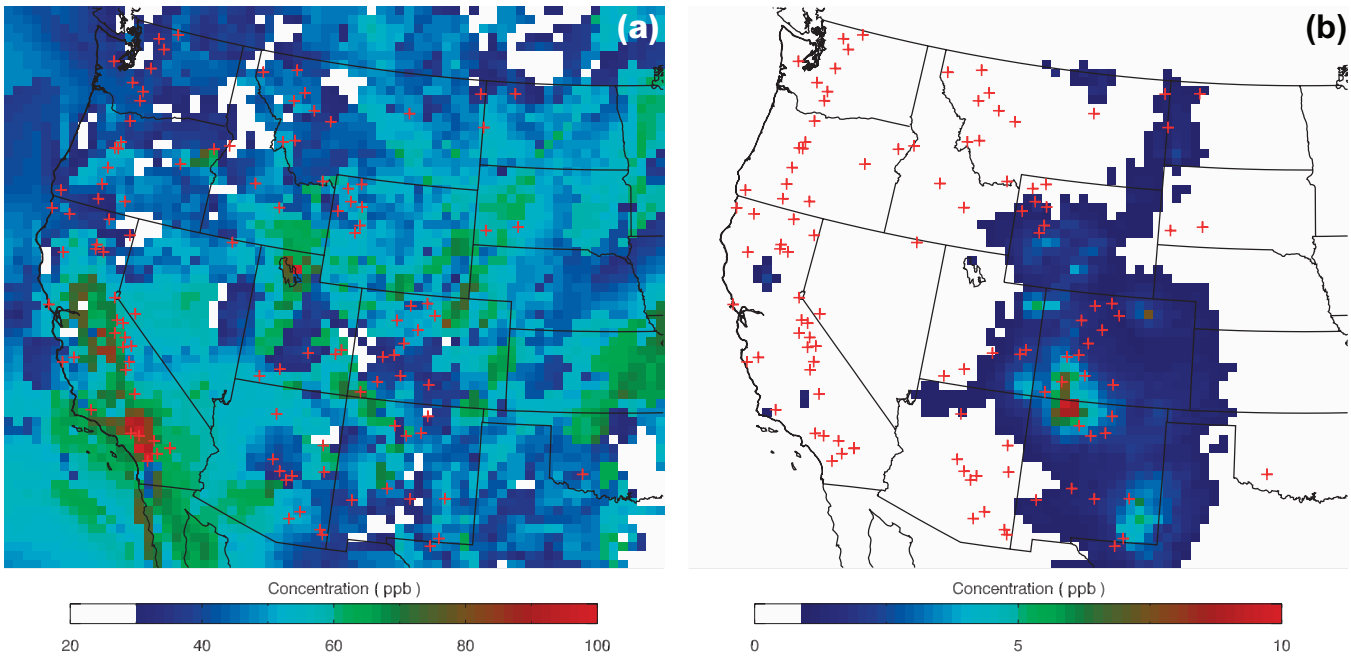

Figure 6. Peak predicted annual O_3 (ppb, 8-hr average) enhancement from VOC and NO_x emissions from (b) oil and gas development in the western United States and (a) corresponding O_3 concentrations from the 2002 base-case simulation. The locations of all Class I areas in the region are indicated with red crosses.

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 O_3 concentrations, as illustrated in Figure 6. The maxima 8-hr O_3 enhancement from oil and gas alone shown in Figure 6b demonstrates that significant O_3 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 O_3 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. O_3 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 O_3 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 O_3 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.

Class I Area	Latitude (°)	Longitude (°)	Base-Case Concentration (ppb)	Maximum Impact Oil and Gas (ppb)	Date Maximum Impact Occurs
Weminuche	37.65	−107.80	40	7	August 5
San Pedro Parks	36.11	−106.81	35	5	September 8
Carlsbad Caverns	32.14	−104.48	49	4	August 27
Wheeler Peak	36.57	−105.42	37	3	August 24
Pecos	35.93	−105.64	40	3	September 13
Bandelier	35.78	−106.26	61	3	June 30
Mesa Verde	37.20	−108.48	64	3	July 13
Saltcreek	33.61	−104.37	49	3	July 29
Great Sand Dunes	37.72	−105.51	33	2	September 8
La Garita	37.96	−106.81	38	2	August 6
Bridger	42.97	−109.75	52	2	April 4
Fitzpatrick	43.27	−109.57	52	2	April 4
Grand Teton	43.68	−110.73	50	1	April 24
Washakie	43.95	−109.59	44	1	September 10

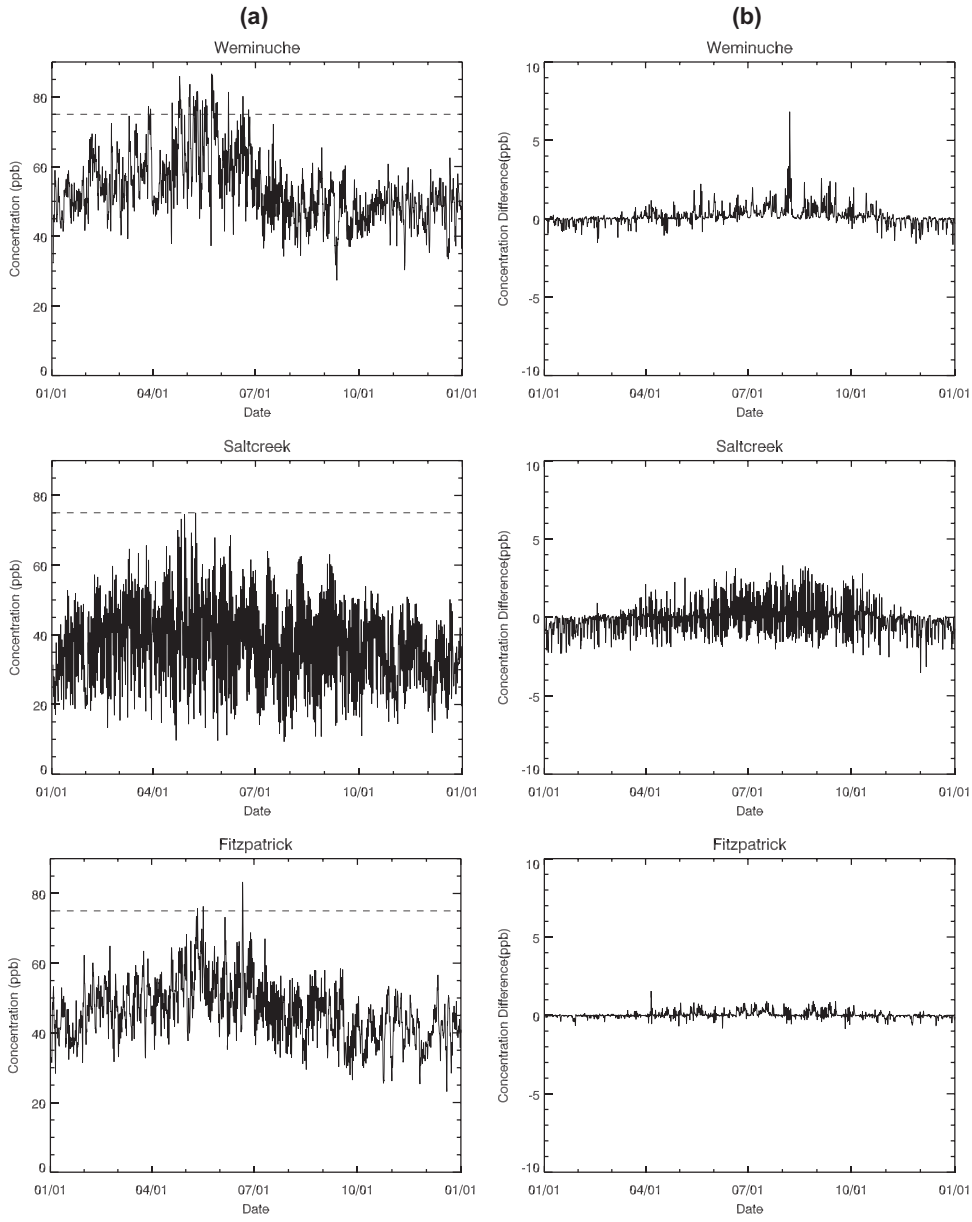

Figure 7. Time series of (a) simulated base-case O_3 (ppb, 8-hr average) for sites representative of one of the three main regions identified as having larger impacts from oil and gas emissions (Weminuche, Saltcreek, and Fitzpatrick Class I areas). (b) The change in O_3 concentration (ppb, 8-hr average) at each site solely due to VOC and NO_x emissions from oil and gas development.

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 "NO_x scavenging," in which available O_3 is consumed by reacting

with nitric oxide (NO). This effect is most prevalent in the winter, when O_3 concentrations are lower. However, in the summer, the situation is reversed, and warm, stagnant conditions yield an increase in O_3 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 O_3 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 O_3 concentrations. Incremental O_3 increases (8-hr average) ranging from less than 1 to 7 ppb were predicted at several western Class I areas, and a peak incremental O_3 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 O_3 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 O_3 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 O_3 concentrations and protect air quality.

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