Environmental Science & Technology

Article

pubs.acs.org/est

Regional Ozone Impacts of Increased Natural Gas Use in the Texas Power Sector and Development in the Eagle Ford Shale

Adam P. Pacsi,* Yosuke Kimura, Gary McGaughey, Elena C. McDonald-Buller, and David T. Allen

Center for Energy and Environmental Resources, The University of Texas at Austin, 10100 Burnet Road, Austin, Texas 78758, United States

Supporting Information

ABSTRACT: The combined emissions and air quality impacts of electricity generation in the Texas grid and natural gas production in the Eagle Ford shale were estimated at various natural gas price points for the power sector. The increased use of natural gas in the power sector, in place of coal-fired power generation, drove reductions in average daily maximum 8 h ozone concentration of 0.6−1.3 ppb in northeastern Texas for a high ozone episode used in air quality planning. The associated increase in Eagle Ford upstream oil and gas production nitrogen oxide (NO_x) emissions caused an estimated local increase, in south Texas, of 0.3−0.7 ppb in the same ozone metric. In addition, the potential ozone impacts of Eagle Ford emissions on nearby urban areas were estimated. On the basis of evidence from this work and a previous study on the Barnett shale, the combined ozone impact of increased natural gas development and use in the power sector is likely to vary regionally and must be analyzed on a case by case basis.

INTRODUCTION

Overall natural gas production in the United States is expected to increase by 56% between 2012 and 2040, and shale gas production is expected to account for 53% of total natural gas production by 2040.[1] Development in shale gas production regions has occurred while its impact on environmental concerns, such as greenhouse gas emissions[2,3] and regional water resources,[4,5] is being examined.

Emissions from natural gas production activities may influence regional ozone concentrations, which are important because of their impacts on human health. Ozone is formed through atmospheric reactions of nitrogen oxides (NO_x) and volatile organic compounds (VOC), and emissions of NO_x and VOC can occur from natural gas production activities. While NO_x emissions from individual natural gas production facilities are generally small, aggregated emissions from the oil and gas sector in counties with extensive production activities can be substantially larger than the threshold for minor point sources.[6] The regional ozone impacts associated with the dispersed NO_x and VOC emissions from natural gas production activities, however, can vary based on the timing and location of the emissions. For example, elevated wintertime ozone concentrations were observed in the Green River Basin in Wyoming during periods with snow cover and stagnant atmospheric conditions[7,8] but not during a winter season with different atmospheric conditions and no snow cover in a nearby basin.[9]

When coupled with lower prices, natural gas production may impact emission levels from the power sector by increasing the utilization of natural-gas-fired generation resources in place of coal-fired power plants[10,11] because of price-based changes in the dispatch order of electricity generating units (EGUs). In comparison to the mix of coal-fired EGUs used nationally in 2007, natural gas EGUs had 84% lower NO_x emissions per MWh,[12] leading to the possibility that some of the NO_x emission increases from natural gas production could be offset by decreased emissions in the power sector. NO_x emissions from the power and natural gas production sectors, however, are not necessarily co-located geographically or temporally. In a photochemical modeling study of the Barnett shale in Texas, Pacsi et al.[11] found that the maximum regional ozone impacts associated with combined changes in the power and production sectors were largely driven by emission changes from coal-fired power plants in northeastern Texas in an area with high biogenic (naturally occurring) VOC emissions rather than emission changes in the production region, which had a relatively unreactive VOC mix.

This study examines the regional ozone impacts associated with increased natural gas production in the Eagle Ford shale in Texas and the increased use of natural gas generation resources in the Electricity Reliability Council of Texas (ERCOT), to determine whether the changes in the power sector are the primary driver of regional ozone concentrations, as was the case with the similar analysis of the Barnett shale.[11] The Eagle Ford shale is an interesting test case because it is a newer shale gas play with rapidly expanding production. The total production

Received: November 10, 2014
Revised: February 20, 2015
Accepted: February 27, 2015
Published: February 27, 2015

DOI: 10.1021/es5055012
Environ. Sci. Technol. 2015, 49, 3966−3973

in the Eagle Ford shale increased from 2 million standard cubic feet per day (MMscf/day) in 2008 to 3800 MMscf/day in 2013.[13] In addition, the Eagle Ford shale is located in a different region than the northeast Texas coal-fired power plants that drove the maximum regional ozone impacts in the study by Pacsi et al.[11] and may have a different local VOC mix than the Barnett shale. This may lead to potentially disparate ozone impacts between the Barnett and Eagle Ford shale regions, which would highlight the need for localized air quality studies with new oil and gas development activities.

■ MATERIALS AND METHODS

The purpose of this work is to assess the combined impacts on regional ozone concentrations of price-based changes in utilization of coal-fired and natural-gas-fired EGUs in ERCOT with changes in the supply chain natural gas production emissions from the Eagle Ford shale in Texas. The following sections discuss the air quality model and the development of emission inventories for ERCOT and the oil and gas production sector in Texas.

Air Quality Model. The air quality model used in this work was developed by the Texas Commission on Environmental Quality (TCEQ)[14] for evaluating air quality management strategies for reducing ozone concentrations in the Dallas−Fort Worth (DFW) area. The original 33 day model was developed using meteorological and emission data for the year 2006 (May 31−July 2), which was a period with several high ozone episodes throughout eastern Texas. Extensive analysis of the original model performance is available through the TCEQ.[14] A 2012 projection of the 2006 episode (which contained estimates for emission changes from many sources, including vehicle emissions) was used in this work, and the 12 × 12 km eastern Texas domain in the model (see Figure S1 of the Supporting Information) was primarily used in the analysis because that was the maximum available resolution for the Eagle Ford shale and Barnett shale at the time this research was undertaken. Recently, the TCEQ has developed a new air quality model[15] that has included these areas at 4 × 4 km resolution, but research into the differences in ozone impacts associated with the finer grid resolution is beyond the scope of this work.

Power Plant Emissions. The ERCOT PowerWorld simulations that had been developed for previously published analyses for the Barnett shale[11] were used in this study, so that direct comparisons between the results for the Eagle Ford and Barnett shales could be made. Briefly, the hourly generation levels at each EGU in ERCOT required to meet total electricity demand were determined at natural gas prices of \$1.89, \$2.88, \$3.87, and \$7.74 per million British thermal units (MMBTU) using the PowerWorld model. Total ERCOT demand was estimated as the actual hourly demand in ERCOT in 2006[16] with a 2.1% annual growth assumption, which was based on ERCOT planning and growth estimates.[17] The hourly emissions of NO_x from each EGU were determined by scaling the hourly generation from the PowerWorld model by the annual average emission factor (tons per MWh) for the power plant from the eGRID database for the year 2007.[12] The emissions of NO_x were then mapped to specific stack locations in the air quality model. Because the eGRID database does not contain VOC or carbon monoxide (CO) emission rates, the emission rate of these species for each hour was determined by multiplying the hourly NO_x emission rate (as determined by the generation level from the PowerWorld model) by the average ratio of the pollutant emission rate to NO_x emission rate in the original stack entry for the EGU in the TCEQ air quality model.[14]

For this work, the \$2.88 per MMBTU natural gas price simulation was considered the base case because it was based on the average purchase price of natural gas for Texas power producers in early 2012[18] and was, thus, an estimate of the actual power sector operation during the period of the study. The \$7.74 per MMBTU pricing scenario assumed that the natural gas price remained roughly the same as in 2006 and is higher than current projections for natural gas prices in the United States.[1] The \$3.87 per MMBTU case was roughly equivalent to natural gas short-term price projections in the United States during the time that this work was developed.[1] Finally, the \$1.89 per MMBTU was chosen to simulate a scenario in which natural gas price is equal to that of coal on a heat input basis. The \$1.89 per MMBTU price point is less than historic natural gas prices in Texas since the development of shale gas resources.

Eagle Ford Oil and Gas Emissions. The inventory of NO_x, VOC, and CO emissions that had been developed by the TCEQ[14] for the 25 counties (see Figure S2 of the Supporting Information) with Eagle Ford oil and gas activity was removed and replaced with an inventory that was largely based on a study by the Alamo Area Council of Governments (AACOG)[19] for the 2012 ozone season. Descriptions of changes made to the existing AACOG inventory[19] for 2012 and the process of creating the CAMx-ready low-level emission files for Eagle Ford oil and gas sources are documented in detail in the Supporting Information.

For this work, source categories (Figure 1) were aggregated into pre-production and production sources. Pre-production emission source categories (hatched entries in Figure 1) included those related to exploration, pad construction, drilling, hydraulic fracturing, and well completions. Production activities included routine production sources, such as emissions from storage tanks and pneumatic controllers, as well as midstream

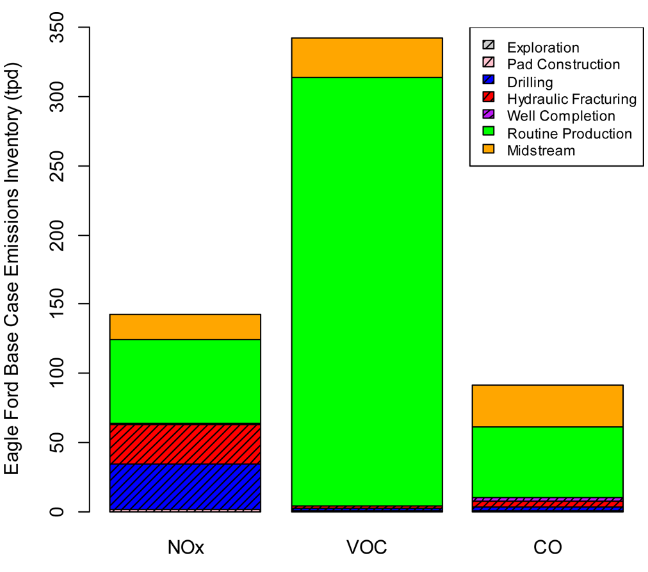

Figure 1. Source categories of total base case (\$2.88 per MMBTU natural gas price) emissions of NO_x, VOC, and CO from oil and gas production sources in the 25 counties containing Eagle Ford shale activity. In this work, emissions are divided into pre-production (shown hatched) and production sources.

DOI: 10.1021/es5055012
Environ. Sci. Technol. 2015, 49, 3966−3973

Table 1. Predicted Emissions [Tons Per Day (tpd)] from ERCOT at Different Natural Gas Prices and Predicted Eagle Ford Area Oil and Gas Emissions Assuming That Production and Emissions Are Increased or Decreased in the Region Based on Change in the Demand for Natural Gas from ERCOT Compared to the Base Case Scenario ($2.88 per MMBTU)[a]

category	$1.89/MMBTU			$2.88/MMBTU			$3.87/MMBTU			$7.74/MMBTU		
	NO_x	CO	VOC	NO_x	CO	VOC	NO_x	CO	VOC	NO_x	CO	VOC
ERCOT EGU emissions (tpd)	307.0	230.6	16.8	362.5	422.7	15.0	423.2	618.1	14.8	483.5	824.8	15.2
Eagle Ford area O&G emissions (tpd)	205.6	131.4	493.6	142.5	91.1	342.0	99.7	63.8	239.4	68.7	43.9	164.9
O&G and ERCOT total emissions (tpd)	512.6	362.0	510.4	505.0	513.8	357.0	522.9	681.9	254.2	552.2	868.7	180.1
net change from base case (tpd)	7.6	−151.7	153.3	0.0	0.0	0.0	18.0	168.1	−102.8	47.2	354.9	−177.0

[a]Note that emissions from ERCOT and oil and gas (O&G) production in the Eagle Ford shale are not necessarily co-located.

sources, including compressor stations. The distinction between pre-production and production sources is highlighted in this work because pre-production sources are concentrated during a small fraction of the well lifetime and would decrease if new well development activities shifted to a different production region. For the base case inventory used in this work (Figure 1), pre-production sources accounted for 45% of NO_x, 1% of VOC, and 11% of CO emissions.

The base case emission scenario for the Eagle Ford shale ($2.88 per MMBTU natural gas price) was developed to be equivalent to actual production levels in the region in early 2012. Additional oil and gas emission scenarios were developed to be consistent with the changes, from the base case, in ERCOT natural gas demand. For the additional scenarios, the difference in ERCOT demand for natural gas between the scenario and the base case was determined and the Eagle Ford production level was assumed to change based on the difference in natural gas demand for ERCOT. For reference, the average daily production for the Eagle Ford shale in 2012 was 2.58 billion standard cubic feet (bcf) per day.[13] For the $1.89 per MMBTU scenario compared to the base case, the additional demand for natural gas in ERCOT was 1.14 bcf/day. For the $1.89 per MMBTU scenario, overall emissions from Eagle Ford shale oil and gas activities were multiplied by a factor of 1.44 to account for the increased demand from ERCOT. For the $7.74 per MMBTU natural gas price scenario, demand for natural gas from ERCOT was 1.34 bcf/day less than demand in the base case and base case emissions from the Eagle Ford shale were scaled by a factor of 0.48 in this scenario. The changes in natural gas production levels in the Eagle Ford shale under these scenarios are not intended to estimate the growth or decline in natural gas production at various price points. For example, at $1.89 per MMBTU, it may not be economical for producers to invest in new natural gas wells in the Eagle Ford shale, and thus, the marginal natural gas production needed for ERCOT electricity generation would not necessarily become available. Determination of these decisions would require an economic model with proprietary data from a variety of natural gas producers, and the development of such an economic model is beyond the scope of this work. Rather, these changes in natural gas production levels (and their associated emissions) are meant to demonstrate the ozone impacts associated with plausible emission levels from the Eagle Ford and ERCOT, and sensitivity scenarios are undertaken to show the overall ozone impacts of changes to oil and gas emissions versus changes to power sector emissions from ERCOT. In this work, the economic decisions are limited to the dispatch order for power plants and associated emission changes from upstream oil and gas sources represent plausible levels of emission changes associated with the change in demand from the power sector, regardless of whether the changes would be economical for producers.

Other Texas Oil and Gas Emissions. Emissions from other natural gas production regions in Texas were estimated in a variety of ways, which are described in detail in the study by Pacsi et al.,[11] but were kept constant between different natural gas pricing scenarios in this work. For the Barnett shale, the base case inventory that was developed in the study by Pacsi et al.[11] for a natural gas price of $2.88 per MMBTU was used in this study, representing an estimate of the actual development (and emissions) from the upstream oil and gas production sector in that region based on the TCEQ Barnett Shale Special Emissions Inventory.[20] For the Haynesville shale in northeastern Texas, the base case assumption used in the study by Pacsi et al.[11] was retained for this study. This meant that emissions from the Texas portion of the Haynesville shale were increased by 51% from the TCEQ SIP Inventory[14] to account for the growth in production in the region between the year 2010, for which the inventory was developed, and 2012, which was the year that was inventoried in this analysis. All other natural gas production emissions in Texas from outside the 25 Eagle Ford counties in the TCEQ SIP Inventory[14] were grown by 10% to account for increased production between 2010 and 2012.

In this work, changes in emissions from lignite (coal) production were assumed to be negligible based on sensitivity analyses in the study by Pacsi et al.[11] and their proximity to larger combustion emission sources at associated coal-fired power plants in Texas.

RESULTS AND DISCUSSION

Overall Emission Changes. Price-based changes in the dispatch order for ERCOT power plants that affect the relative usage of coal-fired and natural-gas-fired power plants have the potential to change ozone precursor emission rates from the power sector. The estimated average daily emissions of NO_x, CO, and VOC from the power sector for the 33 day study episode at different natural gas prices are summarized in Table 1. As the price of natural gas decreases, the emissions of NO_x and CO from ERCOT also decrease. Table 1 also outlines the changes in emissions from oil and gas activities in the 25 county Eagle Ford area assuming that the change in natural gas demand from ERCOT, as compared to the $2.88 per MMBTU base case scenario, is met through increased or decreased production (and thus emissions) in the Eagle Ford. The approach of scaling of all Eagle Ford oil and gas emissions with marginal demand from ERCOT would be considered an upper end estimate of emission changes because it does not include a co-product allocation of emissions for the production of oil and/or natural gas liquids and it assumes that overall production would scale linearly with well count. In reality,

DOI: 10.1021/es5055012
Environ. Sci. Technol. 2015, 49, 3966−3973

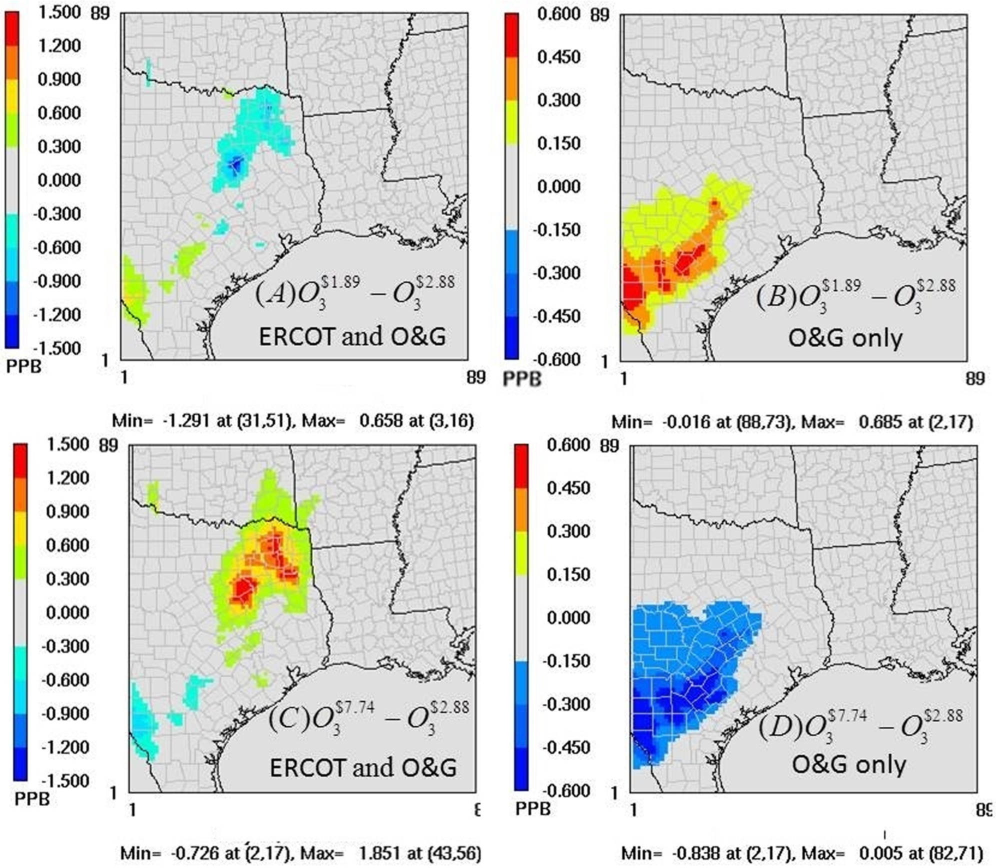

Figure 2. Changes in 33 day episode average daily maximum 8 h ozone concentration compared to the \$2.88 per MMBTU base case for different pricing scenarios. Panels A and C include both ERCOT and Eagle Ford area oil and gas emission changes as outlined in Table 1, while panels B and D included only the changes in oil and gas emissions. Note the difference in scale between the figures on the left and right. Increased ozone concentrations compared to the base case are green to red in color, while decreased ozone concentrations relative to the base case are shown in blue.

production tends to peak early in the lifetime of the well, and thus, newly completed wells may have higher production rates than the average well. The primary focus of this work, however, is to examine the relative ozone impacts of ERCOT and the Eagle Ford production emissions under different natural gas pricing and production scenarios. It is not intended to be an economic analysis of the feasibility of increasing or decreasing production in the Eagle Ford shale based on the price of natural gas.

Base case (\$2.88 per MMBTU) NO_x emissions from ERCOT (362.5 tpd) were substantially higher than daily average emissions from all oil and gas activity throughout the Eagle Ford area (142.5 tpd), although these emission sources are not necessarily co-located. For the \$1.89 per MMBTU natural gas price scenario, the emissions from ERCOT decreased by 15%. However, when Eagle Ford area oil and gas emissions were increased by 44% based on the marginal increase in demand for natural gas from ERCOT compared to the base case, total NO_x emissions from ERCOT and the Eagle Ford increased by 2% (7.6 tpd). For the \$7.74 per MMBTU natural gas pricing scenario, total NO_x emissions increased by 9% (47.2 tpd) compared to the base case, which was driven by a 33% increase in NO_x emissions from ERCOT. The changes in emissions from oil and gas activities in the Eagle Ford region, however, occur at a spatial location that is different from the northeastern Texas coal-fired power plants that drove the largest regional changes in the ozone concentration in the Pacsi et al.[11] analysis of the combined ozone impacts of increased natural gas production in the Barnett shale and use in the Texas power sector.

Impact on Regional Ozone Concentrations. Figure 2 and Figure S5 of the Supporting Information show the impacts of emission changes (Table 1) for the different ERCOT and Eagle Ford area oil and gas emission scenarios on the episode average daily maximum 8 h ozone concentration for each grid cell in the air quality model. For the \$1.89 per MMBTU scenario, the largest change in episode average daily maximum 8 h ozone concentration is a 1.3 ppb decrease compared to the base case in northeastern Texas (Figure 2A). Similarly, the largest changes in episode average daily maximum 8 h ozone concentration for the \$3.87 (see Figure S5A of the Supporting Information) and \$7.74 (Figure 2C) scenarios are increased ozone concentrations in northeastern Texas of 0.9 and 1.8 ppb, respectively. Thus, the largest magnitude of regional ozone changes are located in northeastern Texas near the same coal-fired power generation resources that drove the maximum regional ozone impacts in the study by Pacsi et al.[11]

The regional trends, however, show a difference between the ozone impacts in northeastern Texas and the Eagle Ford shale. Although the magnitude and spatial extent of changes in episode average daily maximum 8 h ozone concentration because of increased emissions from local oil and gas activities in the Eagle Ford were less than in northeastern Texas (Figure 2A), localized increases in the episode average daily maximum 8 h ozone concentration of 0.3−0.7 ppb for the \$1.89 scenario compared to the base case were observed in the region (Figure

DOI: 10.1021/es5055012
Environ. Sci. Technol. 2015, 49, 3966−3973

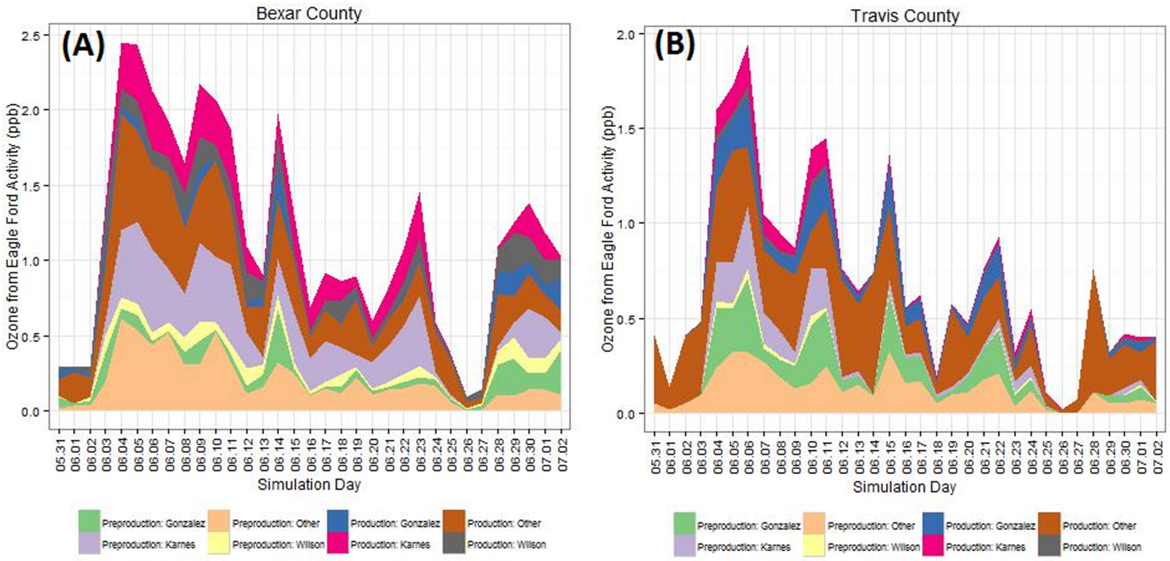

Figure 3. Results from OSAT analysis run for the base case ($2.88 per MMBTU) scenario. For each simulation day, the values indicate the impact (ppb daily maximum 8 h ozone) from Eagle Ford pre-production and production NO_x emissions for (A) Bexar county, which contains San Antonio, and (B) Travis county, which contains Austin.

2A). This result shows the importance of local atmospheric conditions in determining the ozone impacts of increased natural gas production and associated emissions. In the study by Pacsi et al.[11] for the $1.89 per MMBTU scenario, a 20% increase in upstream production emissions from the Barnett shale led to a decrease in the episode average daily maximum 8 h ozone concentration of ~0.2 ppb in the production region (see Figure S6 of the Supporting Information). In this work, the $1.89 per MMBTU scenario required a 44% increase (because of the lower total production in the Eagle Ford shale compared to the Barnett shale in 2012) in emissions from Eagle Ford area oil and gas emission sources, which led to localized increases of up to 0.7 ppb in the episode average daily maximum 8 h ozone concentration in the production region (Figure 2B). As shown in Figure S4 of the Supporting Information, the changes in ozone concentrations in the Eagle Ford production region between scenarios was driven by changes in NO_x emissions rather than VOC emissions, which are largely low-reactivity hydrocarbons from oil and gas sources. The greater presence of local, highly reactive biogenic (natural-occurring) VOC sources in the Eagle Ford compared to the Barnett shale explains the difference in the ozone impacts between those two regions.

The predicted changes in ozone concentrations calculated in this work can be compared to changes in ozone concentrations estimated for the eastern United States as a result of implementation of the Transport Rule,[21] which would have been a major emission reduction program for the electric power sector. In its Regulatory Impact Analysis in Table 4-3, the United States Environmental Protection Agency (U.S. EPA) estimated that the net change in average, population weighted ozone concentration as a result of the rule was 0.09 ppb. Thus, the results from the simulations in this work are of a similar order of magnitude to major proposed emission reduction programs.

Similar trends exist in changes to the episode maximum 8 h ozone concentration, where the largest regional ozone concentration decreases in the $1.89 per MMBTU scenario occur in northeastern Texas (see Figure S7A of the Supporting Information), while smaller magnitude and spatial extent increases in ozone concentration occur in Eagle Ford area and downwind of the region for the simulations when only Eagle Ford emissions were altered and EGU emissions were kept constant (see Figure S8 of the Supporting Information). Thus, it is likely that the combined impacts of emission changes in the power and natural gas production sectors because of changes in natural gas price and availability would need to be examined on a region by region basis.

Implications for Nearby Cities. For the meteorological conditions for the June 2006 episode used in the study, Eagle Ford oil and gas development was frequently located upwind of two urban areas with 8 h ozone design values that are near or above the 75 ppb federal standard. For the Austin area, the preliminary 2014 design value, which is an average of the fourth highest daily maximum 8 h ozone concentration measured in 2012, 2013, and 2014, was 69 ppb.[22] San Antonio had a preliminary 2014 design value of 80 ppb.[22] Therefore, understanding the potential impacts of increased Eagle Ford oil and gas activities on ozone concentrations in the Austin and San Antonio areas is important for regional air quality policy given the increased ozone concentrations in the air quality model in the production region associated with increased oil and gas development.

To understand the potential ozone impacts of Eagle Ford emissions on air quality in Austin and San Antonio during this episode, sensitivity runs for the base case ($2.88 per MMBTU natural gas pricing scenario) were undertaken using Decoupled Direct Method (DDM) and Ozone Source Apportionment Technology (OSAT) that are available with CAMx. More information on these tools is available in existing literature.[23] Briefly, the OSAT tool was used to quantify the base case ozone formation contributions (ppb) of NO_x and VOC emissions from Eagle Ford pre-production and production sources in each of the 25 counties for each day in the simulation, while the DDM tool was used to calculate the average marginal increase in ozone formation per ton of additional NO_x emissions from pre-production and production sources in each of the 25 counties throughout the 33 day episode. For this study, the

DOI: 10.1021/es5055012
Environ. Sci. Technol. 2015, 49, 3966−3973

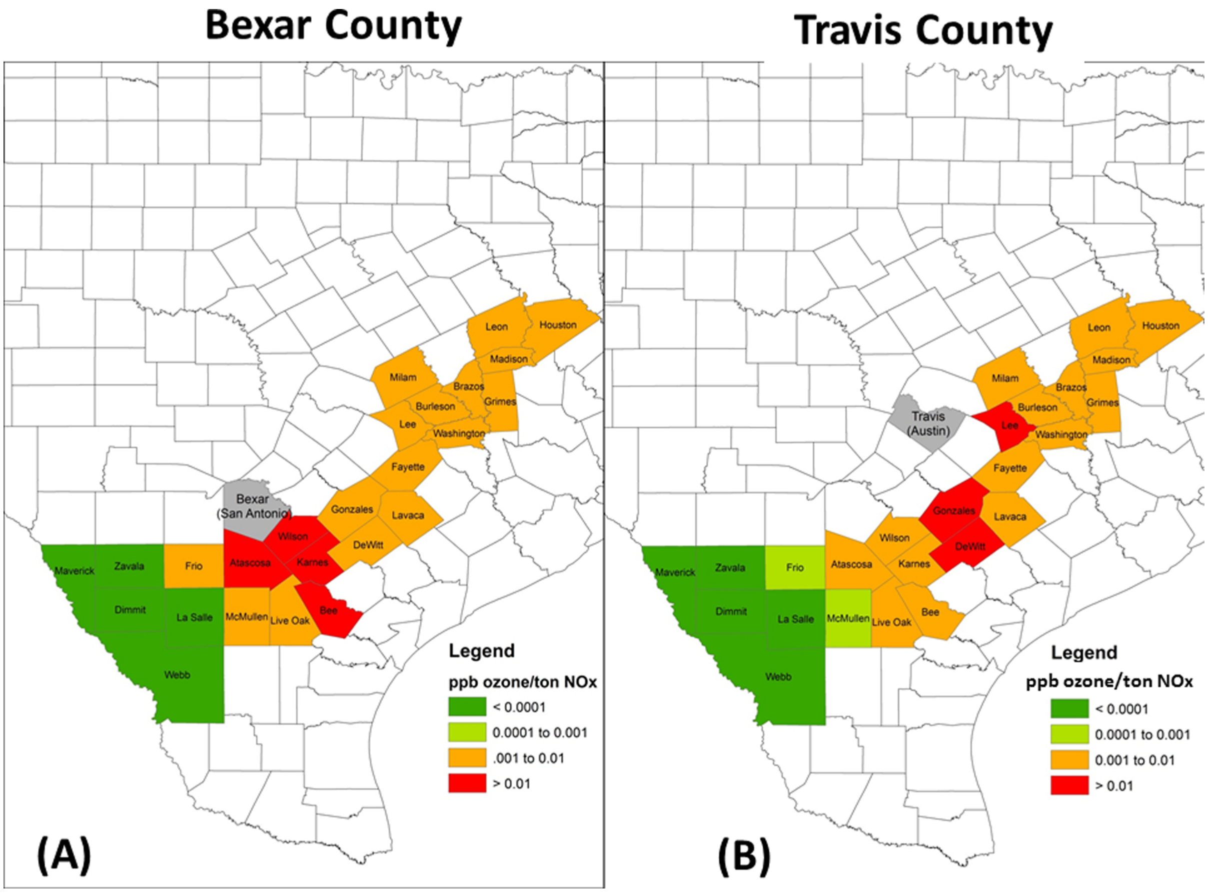

Figure 4. Results for a DDM run focus on (A) Bexar and (B) Travis counties in which NO_x emissions from Eagle Ford oil and gas activities were doubled. Colors indicate the additional ppb of ozone formation in Bexar or Travis county per ton of additional NO_x emissions in the colored county from Eagle Ford oil and gas activities.

average county-wide changes in daily maximum 8 h ozone concentration were examined for Travis (Austin) and Bexar (San Antonio) counties. While the San Antonio and Austin air quality planning areas both include additional surrounding counties, the OSAT (Figure 3) and DDM (Figure 4) results centered on the effects on the urban core of the air quality planning area during the 33 day episode examined in this study.

Figure 3 shows the portion of the daily maximum 8 h ozone concentration for Bexar (Figure 3A) and Travis (Figure 3B) counties in the base case ($2.88 per MMBTU scenario) simulation that was a result of NO_x emissions from Eagle Ford pre-production and production activities for each day in the episode. In this graphic, the ozone formation impacts of select contributing counties are emphasized. For both counties, the ozone impact of Eagle Ford oil and gas emissions was variable during the episode with Bexar county ranging between 0.1 and 2.5 ppb and Travis county ranging between 0.0 and 1.9 ppb. The daily maximum 8 h ozone concentration results for Bexar county from the OSAT simulation (Figure 3A) are directionally consistent with the results of an AACOG photochemical modeling study,[24] in that 2012 levels of emissions from the Eagle Ford shale were predicted to increase ozone concentrations in Bexar county.

In addition to presenting the overall daily maximum 8 h ozone concentration impact of oil and gas emissions from the Eagle Ford shale area, Figure 3 also makes the distinction between the effects of pre-production and production (including mid-stream sources) emissions and between the emission impacts from several counties. Over the 33 day study period, 48 and 42% of the ozone formation in Bexar and Travis counties, respectively, that was attributed to Eagle Ford oil and gas activities were from pre-production NO_x sources. This is important to note because the spatial location of pre-production emissions would be expected to change over time based on the location of wells being drilled and hydraulically fractured. The overall ozone trends for Bexar and Travis counties tend to follow the trends in ozone impacts from specific counties during the episode examined in this work. For example, the pattern in the overall ozone impacts on Bexar county (Figure 3A) tend to have a similar shape as the ozone impacts in Bexar county from pre-production (purple color) and production (pink color) emissions from Karnes county, which is located to the southeast of Bexar county (Figure 4A). The overall ozone trend for Travis county (Figure 3B) also tended to have a similar pattern to the ozone effects in Travis county from emissions in Gonzalez and Karnes counties, which are located to the south of Travis county (Figure 4B). However, on June 28, the 0.7 ppb ozone concentration increase in Travis county was predominately attributed to production emissions from counties to the east (Lee, Burleson, and Milam).

Figure 4 shows the episode average daily maximum ozone concentration increase (ppb) in Bexar (Figure 4A) and Travis (Figure 4B) counties per ton of NO_x emitted from Eagle Ford oil and gas activities in surrounding counties based on DDM simulations. For Bexar county, NO_x emissions from neighbor-

DOI: 10.1021/es5055012
Environ. Sci. Technol. 2015, 49, 3966−3973

ing southern counties (Wilson and Atacosa) and non-bordering counties to the southeast (Karnes and Bee) had the largest ozone impact (red color) during the 33 day episode examined in this study. For Travis county, NO_x emissions from Lee county (on the eastern border) and counties to the south (Gonzalez and Dewitt) had a proportionally larger impact on ozone concentrations (red color). Conversely, NO_x emissions from Eagle Ford oil and gas activities in counties near the border with Mexico (dark green colors in panels A and B of Figure 4) have the lowest ozone impacts per ton of emissions in both Travis and Bexar counties during the study period.

The variability of the ozone impacts in Austin and San Antonio based on the location of the NO_x emissions from Eagle Ford activities has important potential implications for oil and gas development in the region. Eagle Ford shale activity is present over a large geographic region in south Texas (50 miles wide by 400 miles in length[13]), and it is important to understand the extent to which emissions from different parts of the shale may impact air quality in Austin and San Antonio. If a goal in developing the Eagle Ford shale resources were to minimize the ozone impacts in the Austin and San Antonio areas, NO_x emission control requirements on oil and gas activities might be concentrated in counties with disproportionately high ozone impacts per ton of NO_x emitted. For the June 2006 episode used in this work, the counties with disproportionately high ozone formation per ton of NO_x emitted in the model are shown in Figure 4; however, future work should analyze longer term ozone trends for Austin and San Antonio as well as meteorological conditions during high ozone episodes to determine the extent to which the prevalent meteorology in this episode is representative of the range of ozone formation conditions in the region.

Implications. The disparate ozone impacts in the Barnett and Eagle Ford shales in Texas as a result of increased production of natural gas and utilization of natural gas generation resources highlight the need for localized modeling and studies of the air quality impacts of new oil and gas development. Furthermore, emissions within the same production region (the Eagle Ford) can have spatially disparate impacts on ozone concentrations at specific downwind sites of interest (Austin and San Antonio). A cost-effective air quality program with control requirements for a production region, whether in Texas or other states, would likely need to account for the spatial discrepancy in the ozone formation potential of NO_x and VOC emission sources within it. Such programs may require the development or refinement of local air quality models to supplement life-cycle tools that have been developed for the natural gas supply chain and greenhouse-gas emission analyses.[2,4,10]

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Additional figures, tables, and text as noted in the text. This material is available free of charge via the Internet at http://pubs.acs.org.

■ AUTHOR INFORMATION

Corresponding Author

*Telephone: 512-471-0049. Fax: 512-471-1720. E-mail: adam.pacsi@gmail.com.

Notes

The authors declare the following competing financial interests: David T. Allen has research support from a consortium of the Environmental Defense Fund and 11 natural gas producers to measure methane emissions from natural gas production activities. That research is independent of this work. Adam P. Pacsi, who was a graduate student at the University of Texas at Austin at the time that the work in this paper was performed, has accepted a position at Chevron Energy Technology Company.

■ ACKNOWLEDGMENTS

This material is based on work supported by the National Science Foundation under Grant EFRI-0835414.

■ REFERENCES

(1) United States Energy Information Administration (EIA). *Annual Energy Outlook 2014*; EIA: Washington, D.C., 2014; http://www.eia.gov/forecasts/aeo/ (accessed June 27, 2014).

(2) Allen, D. T.; Torres, V. M.; Thomas, J.; Sullivan, D. W.; Harrison, M.; Hendler, A.; Herndon, S. C.; Kolb, C. E.; Fraser, M. P.; Hill, A. D.; Lamb, B. K.; Miskimins, J.; Sawyer, R. F.; Seinfeld, J. H. Measurements of methane emissions at natural gas production sites in the United States. *Proc. Natl. Acad. Sci. U. S. A.* **2013**, *110* (44), 17768−17773 DOI: 10.1073/pnas.1304880110.

(3) Brandt, A. R.; Heath, G. A.; Kort, E. A.; O'Sullivan, F.; Petron, G.; Jordaan, S. M.; Tans, P.; Wilcox, J.; Gopstein, A. M.; Arent, D.; Wofsy, S.; Brown, N. J.; Bradley, R.; Stucky, G. D.; Eardley, D.; Hariss, R. Methane leaks from North American natural gas systems. *Science* **2014**, *343*, 733−735.

(4) Laurenzi, I. J.; Jersey, G. R. Life cycle greenhouse gas emissions and freshwater consumption of Marcellus shale gas. *Environ. Sci. Technol.* **2013**, *47* (9), 4896−4903.

(5) Nicot, J. P.; Scanlon, B. R. Water use for shale gas production in Texas, U.S. *Environ. Sci. Technol.* **2012**, *7*, 3580−3586.

(6) Litovitz, A.; Curtright, A.; Abramzon, S.; Burger, N.; Samaras, C. Estimation of regional air-quality damages from Marcellus shale natural gas extraction in Pennsylvania. *Environ. Res. Lett.* **2013**, *8*, 014017 DOI: 10.1088/1748-9326/8/1/014017.

(7) Schnell, R. C.; Oltmans, S. J.; Neely, R. R.; Endres, M. S.; Molenar, J. V.; White, A. B. Rapid photochemical production of ozone at high concentrations in a rural site during winter. *Nat. Geosci.* **2009**, *2*, 120−122.

(8) Carter, W. P. L.; Seinfeld, J. H. Winter ozone formation and VOC incremental reactivities in the Upper Green River Basin of Wyoming. *Atmos. Environ.* **2012**, *50*, 255−266.

(9) Edwards, P. M.; Young, C. J.; Aikin, K.; deGouw, J.; Dube, W. P.; Geiger, F.; Gilman, J.; Helmig, D.; Holloway, J. S.; Kercher, J.; Lerner, B.; Martin, R.; McLaren, R.; Parish, D. D.; Peischl, J.; Roberts, J. M.; Ryerson, T. B.; Thorton, J.; Warnecke, C.; Williams, E. J.; Brown, S. S. Ozone photochemistry in an oil and natural gas extraction region during winter: Simulations of a snow-free season in the Uintah Basin, Utah. *Atmos. Chem. Phys.* **2013**, *13*, 8955−8971.

(10) Venkatesh, A.; Jaramillo, P.; Griffin, W. M.; Matthews, H. S. Implications of changing natural gas prices in the United States electricity sector for SO_2, NO_x, and life cycle GHG emissions. *Environ. Res. Lett.* **2012**, *7*, 034018 DOI: 10.1088/1748-9326/7/3/034018.

(11) Pacsi, A. P.; Alhajeri, N. S.; Zavala-Araiza, D.; Webster, M. D.; Allen, D. T. Regional air quality impacts of increased natural gas production and use in Texas. *Envrion. Sci. Technol.* **2013**, *47*, 3521−3527.

(12) United States Environmental Protection Agency (U.S. EPA). *2007 Emissions & Generation Resource Integrated Database*; U.S. EPA: Washington, D.C., 2012; http://www.epa.gov/cleanenergy/energy-resources/egrid/ (accessed June 3, 2014).

DOI: 10.1021/es5055012
Environ. Sci. Technol. 2015, 49, 3966−3973

(13) Texas Railroad Commission (TXRRC). *Eagle Ford Information*; TXRRC: Austin, TX, 2014; http://www.rrc.state.tx.us/oil-gas/major-oil-gas-formations/eagle-ford-shale/ (accessed Jan 20, 2014).
(14) Texas Commission on Environmental Quality (TCEQ). *Dallas–Fort Worth Attainment Demonstration State Implementation Plan Revision for the 1997 Eight-Hour Ozone Standard*; TCEQ: Austin, TX, 2010; http://www.tceq.texas.gov/airquality/sip/dfw_revisions.html (accessed June 3, 2014).
(15) Texas Commission on Environmental Quality (TCEQ). *Texas State and Local Air Quality Planning Program: Modeling Files and Information*; TCEQ: Austin, TX, 2013; https://www.tceq.texas.gov/airquality/airmod/rider8/rider8Modeling (accessed Oct 31, 2014).
(16) Electricity Reliability Council of Texas (ERCOT). *Balancing Energy Services Daily Report Archive*; ERCOT: Austin, TX, 2006; http://www.ercot.com/gridinfo/zonal_archives (accessed June 3, 2014).
(17) Electricity Reliability Council of Texas (ERCOT). *Report of Existing and Potential Electric System Constraints and Needs*; ERCOT: Austin, TX, 2006; http://www.ercot.com/content/news/presentations2006/2006_ERCOT_Reports_Transmission_Constraints_and_Needs.pdf (accessed June 3, 2014).
(18) United States Energy Information Administration (EIA). *Natural Gas Prices*; EIA: Washington, D.C., 2014; http://www.eia.gov/dnav/ng/ng_pri_sum_dcu_nus_m.htm (accessed June 3, 2014).
(19) Alamo Area Council of Governments (AACOG). *Oil and Gas Emissions Inventory, Eagle Ford Shale, Technical Report*; AACOG: San Antonio, TX, 2013; http://www.aacog.com/DocumentCenter/View/19069 (accessed June 28, 2014).
(20) Texas Commission on Environmental Quality (TCEQ). *Barnett Shale Special Emissions Inventory Phase 2*; TCEQ: Austin, TX, 2011; https://www.tceq.texas.gov/airquality/point-source-ei/psei.html#barnett (accessed June 3, 2014).
(21) United States Environmental Protection Agency (U.S. EPA). *Regulatory Impact Analysis for the Federal Implementation Plans To Reduce Interstate Transport of Fine Particulate Matter and Ozone in 27 States; Correction of SIP Approvals for 22 States*; Office of Air and Radiation (OAR), U.S. EPA: Washington, D.C., 2011; EPA-HQ-OAR-2009-0491.
(22) Texas Commission on Environmental Quality (TCEQ). *Compliance with Eight-Hour Ozone Standard*; TCEQ: Austin, TX, 2014; http://www.tceq.state.tx.us/cgi-bin/compliance/monops/8hr_attainment.pl (accessed July 30, 2014).
(23) Arunachalam, S. *Peer Review of Source Apportionment Tools in CAMx and CMAQ*; Office of Air Quality Planning and Standards (OAQPS), United States Environmental Protection Agency (U.S. EPA): Research Triangle Park, NC, 2009; http://www.epa.gov/scram001/reports/SourceApportionmentPeerReview.pdf (accessed July 30, 2014).
(24) Alamo Area Council of Governments (AACOG). *Development of the Extended June 2006 Photochemical Modeling Episode*; AACOG: San Antonio, TX, 2013; http://www.aacog.com/DocumentCenter/View/19262 (accessed June 28, 2014).

DOI: 10.1021/es5055012
Environ. Sci. Technol. 2015, 49, 3966–3973