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Ozone Impacts of Natural Gas Development in the Haynesville Shale

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The Haynesville Shale is a subsurface rock formation located beneath the Northeast Texas/Northwest Louisiana border near Shreveport. This formation is estimated to contain very large recoverable reserves of natural gas, and during the two years since the drilling of the first highly productive wells in 2008, has been the focus of intensive leasing and exploration activity. The development of natural gas resources within the Haynesville Shale is likely to be economically important but may also generate significant emissions of ozone precursors. Using well production data from state regulatory agencies and a review of the available literature, projections of future year Haynesville Shale natural gas production were derived for 2009−2020 for three scenarios corresponding to limited, moderate, and aggressive development. These production estimates were then used to develop an emission inventory for each of the three scenarios. Photochemical modeling of the year 2012 showed increases in 2012 8-h ozone design values of up to 5 ppb within Northeast Texas and Northwest Louisiana resulting from development in the Haynesville Shale. Ozone increases due to Haynesville Shale emissions can affect regions outside Northeast Texas and Northwest Louisiana due to ozone transport. This study evaluates only near-term ozone impacts, but the emission inventory projections indicate that Haynesville emissions may be expected to increase through 2020.

Introduction

The Haynesville Shale is a rock formation that lies at depths of 10,000 to 13,000 feet below the surface and straddles the border between Northeast Texas and Northwest Louisiana near Shreveport (Figure 1). This formation is estimated to contain very large recoverable reserves of natural gas (*1*, *2*), and during the two years since the drilling of the first highly productive wells in 2008, it has been the focus of intensive exploration and leasing activity (*3*). Despite the economic downturn of 2009 and associated fall in price of natural gas, development of the Haynesville Shale has continued (*4*).

The development of natural gas resources within the Haynesville Shale is likely to be economically important but may also generate significant emissions of ozone precursors. Nitrogen oxides (NOx) are emitted during well drilling and subsequent rock fracturing to stimulate natural gas production as well as from compressor engines that are used to produce and transmit the gas. Volatile organic compounds (VOCs) are emitted from many processes including venting and completion of wells, dehydration of produced natural gas and fugitive emissions from well and pipeline components.

To our knowledge, there have been no published studies of regional air quality impacts of shale gas development, although shale gas is projected to play an increasingly important role in meeting U.S. energy needs (*1*). Emissions resulting from developing the Haynesville Shale would be released in a region that is within and/or frequently immediately upwind of potential ozone nonattainment areas (*5*). Several counties within Northwest Louisiana and Northeast Texas as well as nearby Dallas-Fort Worth have been identified by the U.S. Environmental Protection Agency as areas that do not attain the 2008 ozone standard (*6*) of 75 ppb. In 2010, the EPA proposed a more stringent ozone standard (*7*) which heightens the importance of understanding how development in the Haynesville Shale may impact future ozone air quality in the region.

Methods

Haynesville Shale Emission Inventory. In this section, we describe the development of an emission inventory for sources related to projected natural gas exploration and production of the Haynesville Shale. This inventory does not include other regional sources such as power plants, motor vehicles, or biogenic emissions, nor does it include emissions from development of other oil- and gas-producing formations in the region. These non-Haynesville sources are accounted for in the ozone modeling via a separate emission inventory, as discussed in the Supporting Information.

Exploration and production in the Haynesville Shale began only recently in 2008; therefore, peer-reviewed published data that can be used in emission inventory development are extremely limited. Basic information, such as the geographic extent and recoverable reserves of the Haynesville Shale, is not yet known with certainty. Our strategy in developing estimates of future year activity and emissions was therefore to gather the best available information and cross-check among different sources of data where possible. The Texas Commission on Environmental Quality (TCEQ), Texas Railroad Commission (RRC), and the Louisiana Department of Natural Resources (LDNR) were contacted regarding production and activity within the Haynesville Shale. The RRC and LDNR provided drilling and production data, but recommended that the best source of estimates of future year activity and equipment use would be the energy producers active in the area. A survey was sent out to the producers identified on their company web pages, stockholder reports, or in venture capital firm reports as being major leaseholders in the Haynesville Shale as of March, 2009. Because so few wells had been drilled in the Haynesville Shale at that time, several producers felt that they did not yet have enough information to predict future year activity and production, and all of the producers declined to participate in the survey.

Using drilling and well production data from Texas and Louisiana state regulatory agencies and a review of the available literature, the spatial extent of the Haynesville Shale was defined (Figure 1), and projections of future year Haynesville Shale natural gas production for 2009−2020 were derived for three scenarios corresponding to limited,

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FIGURE 1. Spatial extent of the Haynesville Shale in Texas and Louisiana as defined in this study.

moderate, and aggressive development. The projection scenarios were constructed for each future year using two factors: (1) the number of new wells drilled (spuds) in each year and (2) production estimates for each new active well (derived from existing well decline curves). From these two factors, formation-wide spuds, well counts, and gas production were estimated. This analysis does not attempt to predict future economic conditions but attempts to take future economic variability into account by providing a range of potential future production estimates.

The 2001−2008 historical development in a similar nearby formation, the Barnett Shale near Dallas-Fort Worth, was used as a surrogate for modeling growth in drilling activity in the Haynesville Shale. 2001−2008 was a period of favorable natural gas prices that occurred after the development of the horizontal drilling and rock fracturing techniques that made extraction of shale gas economically feasible. The comparison to the Barnett Shale was made to determine a reasonable growth rate in development activity (determined by drilling counts per year) that can be assumed for the Haynesville Shale. For example, historical data from the Barnett Shale were used to constrain how rapidly drill rigs can be diverted from other regions into a more profitable area as well as indicate how quickly new infrastructure can be built to handle the increased gas production from a newly discovered formation. Further description of the Barnett Shale and the rationale for the use of its development as a surrogate for growth in the Haynesville Shale are provided in the Supporting Information.

Development was initialized with the number of drilling rigs operating in the Haynesville Shale during March 2009; this quantity was estimated through inspection of maps (*8*) of active drilling rigs in the area that were drilling development gas wells at depths between 10,000 and 15,000 ft in the counties shown in Figure 1. Three emissions scenarios were then developed. The "Low scenario" held constant the March 2009 drill rig count of 95 through 2012 until 2020. The "High scenario" grew the number of rigs to from the initial count of 95 in 2009 to 200 at the same growth rate as the 2001−2008 barnett Shale rig count. The "Moderate Scenario" grew the rig count to 200 at 50% of high scenario growth rate. The rig count was capped at 200 in the Moderate and High Scenarios to avoid predicting an unreasonably large number of rigs to be operating in the Haynesville Shale in future years. This number is close to the maximum number of drill rigs that have operated simultaneously in the Barnett Shale and is approximately ten percent of the entire U.S. fleet of drilling rigs (approximately 2000 in March 2009). The High Scenario has 170 rigs active in 2012; the 200 rig cap is reached in 2014, and the number of rigs is held fixed thereafter. The Moderate Scenario has 133 active rigs in 2012 and reaches 200 rigs in 2018. A chart showing the number of drilling rigs active in each year from 2009 to 2020 is shown in the Supporting Information.

The drill rig count for each growth scenario was used to determine the number of new wells drilled per year. Drilling records from the LDNR (*9*) were used to determine an average drilling duration of 63 days for spuds occurring in the Haynesville Shale. This duration includes the time needed to move a drilling rig to a new well site, mobilize the rig for drilling, drill the well, and demobilize the rig for transport to the next well site. Therefore, one drill rig was assumed to be able to drill a total of $365/63 = 5.8$ wells in one year. The current 2009 baseline drilling success factor was determined from the LDNR wells database (*9*) to be 55% for the Haynesville Shale region; this figure was determined to be the percentage of new active wells added to the region relative to the number of recorded spuds. With assumed technological improvements and better definition of the formation boundaries as exploration proceeds, our analysis assumes that the drilling success factor would improve to 100% by 2018 and would increase linearly between 2009 and 2018. In the High Scenario, there are projected to be 2181 active wells in 2012 and 10,714 wells in 2020; in the Low Scenario, 1568 wells are predicted to be active in 2012 and 5632 wells in 2020.

Using the well development estimates for each of the three scenarios and estimates for the typical gas production of a well over its lifetime, total gas production can be calculated for the three development scenarios. This analysis requires deriving estimates of typical well production over the time period 2009−2020, during which a well's production is expected to decline from an initial production peak. Haynesville Shale wells have been producing gas for a very limited time period (approximately 1 year at the time this analysis was conducted); therefore, long-term yearly production rates were unknown. To estimate long-term production rates, eight wells with the longest production were identified, and the production rates from the LDNR database (*9*) were analyzed to derive a representative decline curve for all Haynesville Shale wells (see the Supporting Information). There is significant uncertainty in this estimate, but development of the Haynesville Shale region is so recent that a more robust well decline data set was not available. The decline curve was extrapolated to the year 2020 by finding the best fit power law function for each well and then averaging over the eight wells to calculate a derived decline curve such that yearly well production could be determined for an "average" Haynesville Shale well. The power law function was chosen as a representative fit based on other historical well decline curves.

A separate literature search was conducted to determine the availability of additional published Haynesville Shale well decline curves. Two venture capital reports from Tristone Venture Capital (*2*) and Southern Star (*10*) contained well decline curves for the Haynesville Shale for a number of individual wells. The reported decline curves from venture capital sources were averaged together to develop a single reported well decline curve. The total cumulative per-well production from the reported curves is 5.2 billion cubic feet (bcf), compared to 1.9 bcf for the derived well decline curves. Both decline curves are shown in the Supporting Information. This analysis assumes that the lower, derived well decline curve is representative of the low and moderate development scenarios, and the reported well decline curve obtained from the venture capital reports is representative of the high development scenario.

Total Haynesville Shale production estimates for the period 2009−2020 were obtained by multiplying the number of active wells by the appropriate annual production rate determined from the decline curve and the year that each well was brought online and summing over all active wells. Cumulative gas production for each scenario is shown in the Supporting Information. These production estimates were then used to develop an inventory of potential emissions from future natural gas exploration and production in the Haynesville Shale for all three scenarios. For exploration and production sources, ozone precursor emission rates were estimated based on data gathered from published reports of emission inventories of natural gas production sources in the region (*11*, *12*). "On-the-books" federal or state regulations that would affect the emissions projections (e.g., Federal New Source Performance Standards, off-road engine Tier standards, East Texas Combustion Rule) were applied. A detailed description of the development of the inventory is given elsewhere (*13*).

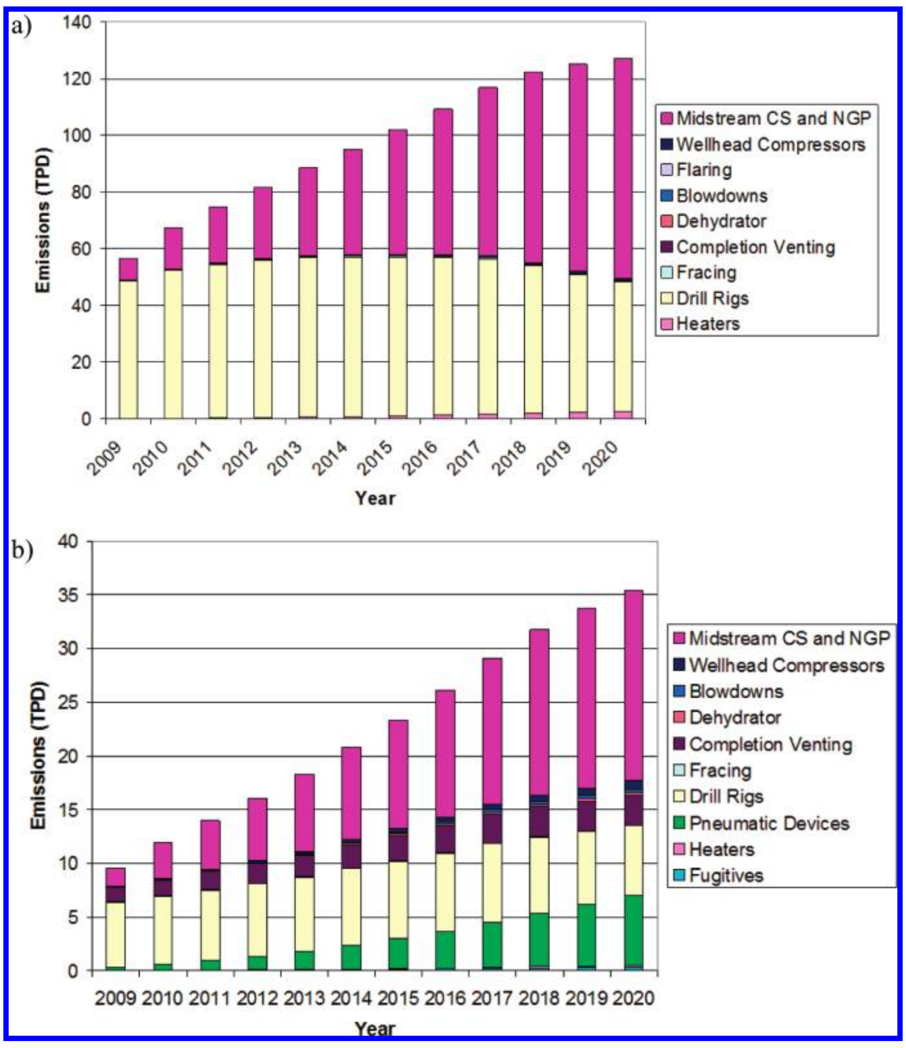

FIGURE 2. a) 2009 to 2020 moderate scenario Haynesville Shale formation-wide NOx emissions by source category and b) 2009 to 2020 moderate scenario Haynesville Shale formation-wide VOC emissions by source category. Midstream CS and NGP refer to central compressor stations (CS) and natural gas processing (NGP) facilities which transmit and process produced gas.

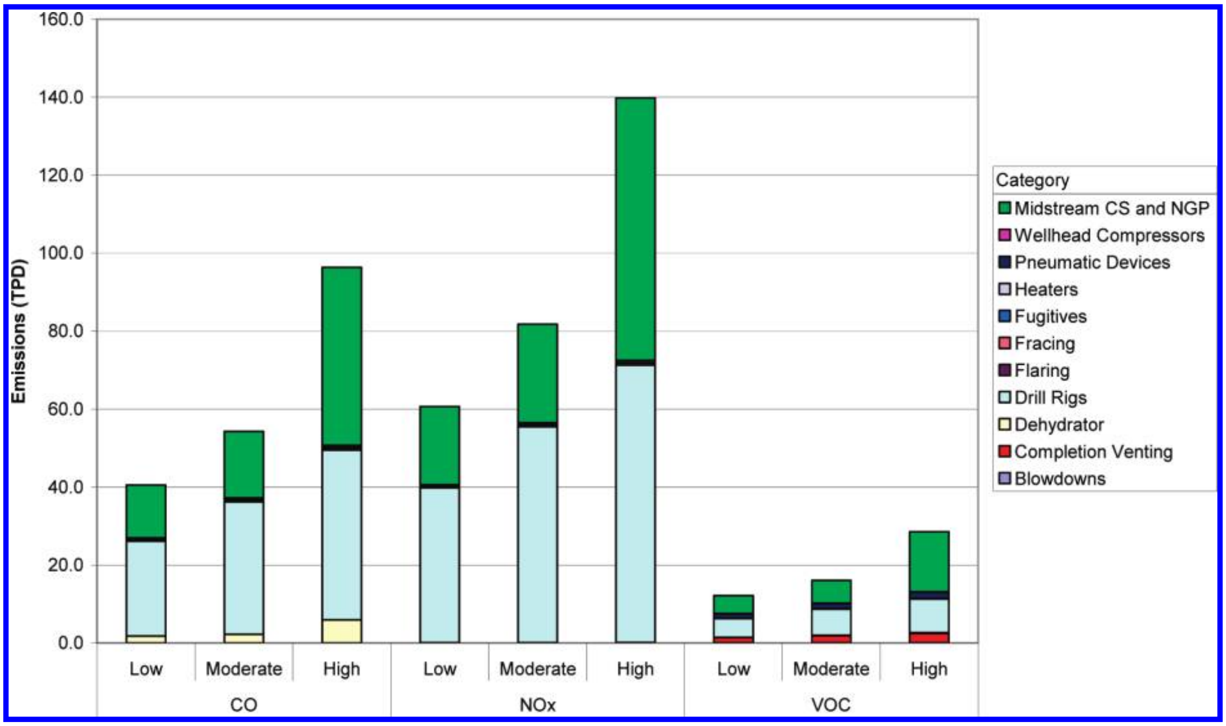

FIGURE 3. 2012 Haynesville Shale formation emissions of NOx, VOC, and CO by scenario and source category. Midstream CS and NGP refer to central compressor stations (CS) and natural gas processing (NGP) facilities which transmit and process produced gas.

Figure 2a shows the formation-wide NOx emissions for 2009−2020 for the moderate scenario. NOx emissions are projected to increase by 124% from 2009 to 2020. By 2020, development in the Haynesville Shale results in more than 120 tons/day of NOx emitted in northeast Texas and northwest Louisiana. Notably, drill rig NOx emissions remain relatively constant, while midstream compressor station and natural gas processing plant NOx emissions account for most of the increase. For the moderate scenario, the number of rigs in the Haynesville Shale region increases from 2009 to 2017, but the drill rig emissions flatten out and eventually decrease because of turnover in the drill rig engine fleet that results in replacement of older engines with higher Tier, cleaner-burning engines. Figure 2b shows that moderate scenario VOC emissions are projected to increase by 271% from 2009 to 2020. VOC emissions increases are primarily due to increases in midstream compressor station and natural gas processing plant VOC emissions, though pneumatic devices, drill rigs, and completion venting among other categories also contribute significantly to VOC emission increases.

Emissions of the ozone precursors NOx, VOC, and carbon monoxide (CO) for the entire Haynesville Shale formation for the 2012 modeling year are shown in Figure 3. Estimates of 2012 NOx emissions ranged from 61 tons/day in the low development scenario to 82 tons/day in the moderate scenario to 140 tons/day in the high scenario. These emissions increases are sufficiently large that it is necessary to evaluate their ozone impacts.

Ozone Modeling. The Comprehensive Air-quality Model with extensions (CAMx) (*14*) was used to model the eastern half of the United States using nested 36, 12, and 4 km resolution grids with the 4 km grid located over the Haynesville Shale region (Figure S1). CAMx is a three-dimensional, chemical-transport grid model used for tropospheric ozone, aerosols, air toxics, and related air-pollutants and is used for air-quality planning in Texas (*15, 16*) and Louisiana (*17*). CAMx was used here to estimate the near-term ozone impacts due to projected Haynesville Shale emissions during 2012.

The model's vertical resolution is finest near the ground (33 m surface layer) and extends to the lower stratosphere in 44 layers. The CAMx modeling databases were originally developed for current regulatory modeling of ozone in Houston and Northeast Texas. Meteorological input data for CAMx were developed using the PSU/NCAR Mesoscale Model version 5 (MM5) (*18*). The MM5 provides CAMx with hourly, gridded data for wind vectors, pressure, temperature, diffusivity, humidity, clouds, and rainfall. Emissions of VOCs, NOx, and CO from the TCEQ's 2005 emission inventory (*15*) were used. Boundary conditions for the outermost (36 km) grid were derived from a continental-scale CAMx run that was itself driven with data from a GEOS-Chem model (*19*) global simulation of 2005. The continental-scale CAMx run included the effects of episode-specific fire emissions derived from satellite observations. Large NOx sources were treated with the CAMx plume-in-grid submodel, and the model was run using a dry deposition algorithm (*20, 21*) developed for Environment Canada's AURAMS air quality forecasting model (*22*) that was newly implemented in CAMx.

The model was first applied for a historical episode during May 20-June 30, 2005 to evaluate its performance in simulating observed ozone and precursors. This analysis is described in (*23*) as well as in the Supporting Information. The model was found to reproduce observed ozone with good accuracy within the Texas-Louisiana-Arkansas-Oklahoma region. Projections of future year emissions for all regional sources unrelated to the Haynesville Shale were made for the year 2012 (*24*). A baseline 2012 model simulation was carried out in which the model was configured exactly as for the May-June 2005 simulation, except that the emission inventory of anthropogenic sources for 2005 was replaced with the 2012 anthropogenic emission inventory excluding emissions from the Haynesville Shale. This simulation is referred to as the 2012 baseline. Then, the 2012 simulation was repeated three times with emissions from the three (low, moderate, and high) Haynesville Shale emissions scenarios added to the 2012 emission inventory. The processing of the Haynesville emissions for use in CAMx, including spatial allocation of emissions, is discussed in the Supporting

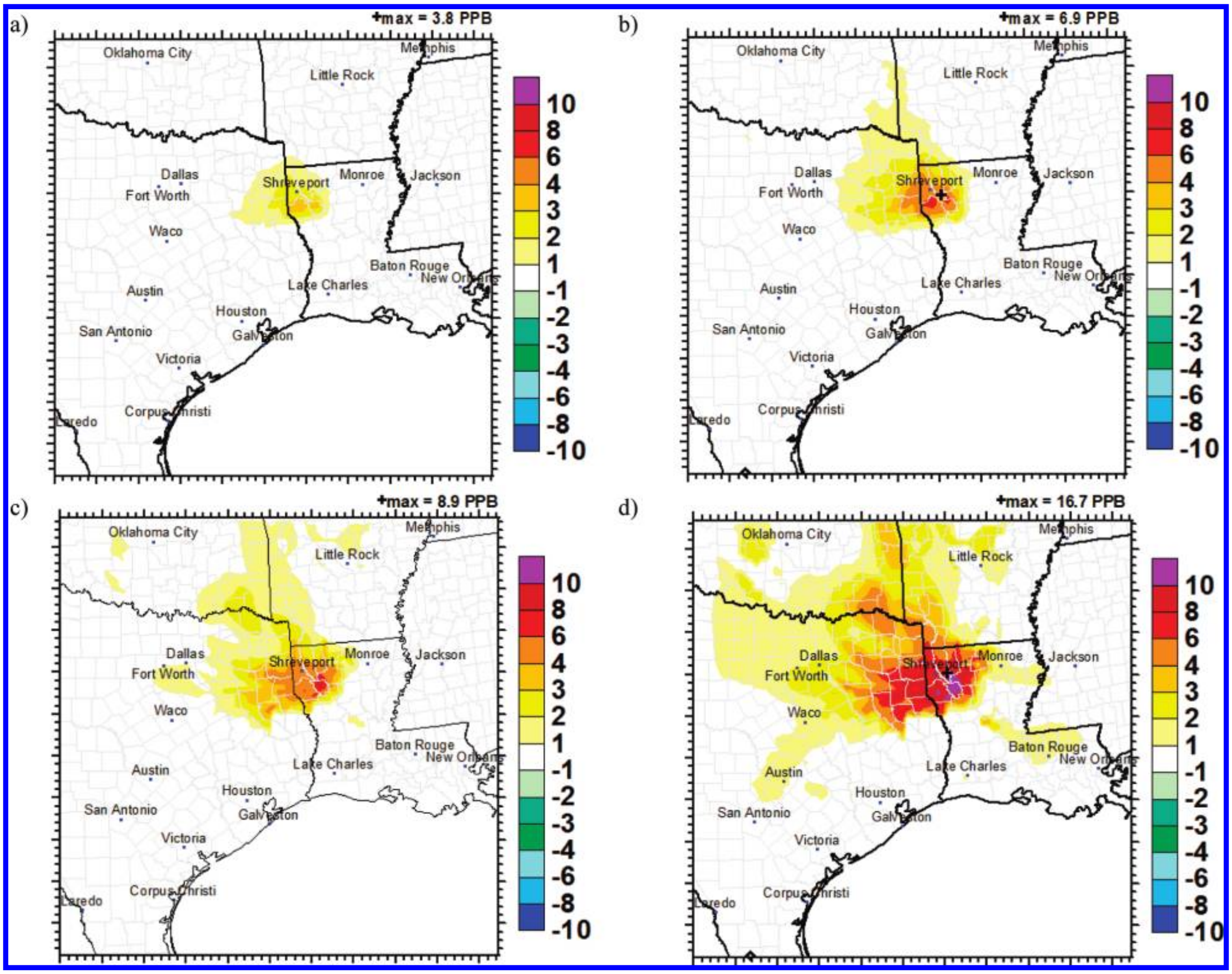

FIGURE 4. Twelve km grid ozone modeling results: a) Episode average difference in daily maximum 8-h ozone (ppb): Haynesville Low Secenario-2012 Baseline and b) Episode average difference in daily maximum 8-h ozone (ppb): Haynesville High Scenario-2012 Baseline and c) Episode maximum difference in daily maximum 8-h ozone (ppb): Haynesville Low Scenario-2012 Baseline and d) Episode maximum difference in daily maximum 8-h ozone (ppb): Haynesville High Scenario-2012 Baseline.

Information. The modeled ozone from each of these three scenarios is compared below to the 2012 baseline simulation ozone to isolate the ozone impacts of the Haynesville Shale for each emissions scenario.

Results and Discussion

Ozone Impacts. In presenting the ozone impacts of the Haynesville Shale, we focus on its effects on regional 8-h average ozone because of the relevance of this quantity to the National Ambient Air Quality Standard (NAAQS) for ozone (1-h ozone impacts are presented in the Supporting Information). We compute the difference in the daily maximum 8-h average ozone between the baseline 2012 run and each of the three Haynesville Shale runs in turn for each day of the May-June episode for all grid cells within the modeling domain. The average difference in the 8-h daily maximum ozone between each pair of runs is calculated for all times when the modeled 8-h ozone was greater than 60 ppb for at least one of the pair of runs. This restricts the analysis to periods of modeled high ozone within the May-June episode (i.e., nighttime and clean periods are removed from consideration). We look at the average difference across the entire May-June episode between the baseline 2012 run and each Haynesville emissions scenario run as well as the maximum difference between the pair of runs during the episode.

Comparisons of the differences in the May-June 2012 episode average daily maximum 8-h ozone are shown for the low and high Haynesville Shale scenarios in Figure 4 for the 12 km grid; we present the results on the 12 km grid to show impacts at the regional rather than local scale but note that the 4 km grid and 12 km grid were consistent in the magnitude of ozone impacts (not shown; see ref *24*). The ozone impacts from the moderate emissions scenario fall between the low and high cases and are not shown here for the sake of brevity.

Figure 4a shows that the episode average ozone impact of the emissions from the Haynesville Shale in the low scenario is largest in northwestern Louisiana, with peak increase of 4 ppb in southern Bossier Parrish. The area in which the episode average increase in daily maximum 8-h average ozone is larger than 1 ppb is mainly confined to northeast Texas and northwest Louisiana. In the high emissions scenario (Figure 4b), the episode average increase in daily maximum 8-h ozone has a similar pattern, but the increases are larger, with a peak of 7 ppb. There are areas of De Soto, Caddo, Bienville, Red River, and Bossier Parishes in Louisiana with episode average increases in the 6−8 ppb range. Texas counties Harrison, Panola, Rusk, Marion, and Shelby all experience average increases in the 4−6 ppb range, and Gregg and Cass Counties have regions where the average increase falls in the 3−4 ppb range. The region with episode average impacts greater than 1 ppb is larger in the high scenario than in the low scenario, extending eastward to the edge of Dallas-Fort Worth and northward into Oklahoma and Arkansas.

Figure 4c and 4d show the maximum differences in the daily maximum 8-h ozone between the Haynesville Shale and 2012 baseline runs for the low and high scenarios, respectively. In the high scenario, the peak increase is 17 ppb in southern Bossier Parish, and the area of increases greater than 6 ppb covers a broad swath of counties in northeast Texas and northwest Louisiana. The region of impacts greater than 4 ppb extends northward into Oklahoma and Arkansas, and the region of impacts between 2−3 ppb extends westward into the Dallas-Fort Worth area. The region of impacts ranging from 1−2 ppb includes McLennan, Travis, Hays, and Bexar Counties in Texas and the Baton Rouge area in Louisiana including Pointe Coupee, East and West Baton Rouge, and Livingston Parishes. The pattern of impacts is similar but less intense in the low scenario. These results show that the impacts of development in the Haynesville Shale may extend well outside the immediate vicinity of the Haynesville Shale into other regions of Texas and Louisiana and affect areas that may not attain the new 2010 ozone standard.

An ozone monitor's compliance with the NAAQS is reckoned using its design value, which is the three-year average of the fourth highest daily maximum 8-h ozone concentration. Changes in the ozone design value due to Hayneville Shale development relative to the baseline 2012 run were calculated for the low and high Haynesville scenarios. The design value analysis was carried out for currently active ozone monitors within the 4 km grid using EPA's Modeled Attainment Test Software (MATS (*25*)). MATS allows the model results to be used in a relative sense, scaling observed base year (2005) ozone design values with a ratio of model results for a base (2005) and a future year (2012) to project future year design values . This method is designed to reduce the uncertainty in future year projections due to any model bias that may be present, and is a standard technique in regulatory ozone modeling (*27*). Additional description of the method is provided in the Supporting Information.

Design values were calculated for three future cases: the baseline 2012 run, the 2012 Haynesville low scenario, and the 2012 Haynesville high scenario; the difference between the Haynesville scenario design values and the 2012 baseline design values was calculated to show the impact on the local design values of the additional emissions from Haynesville Shale development. The MATS results show 2012 design value increases for ozone monitors located within the Haynesville Shale counties of Harrison (TX), Bossier (LA), and Caddo (LA) of 2 ppb in the low scenario and 4−5 ppb in the high scenario. For the Gregg (TX) and Smith (TX) county monitors, which lie west of the Haynesville Shale, design value increases are smaller, ranging from 1 ppb for both monitors in the low scenario to 1−2 ppb in the high scenario.

Implications and Future Work. The magnitude of projected emissions and modeled 8-h ozone impacts described above indicate that development of the Haynesville Shale provides cause for concern about future ozone air quality in Texas and Louisiana. This analysis suggests that if the development of the Haynesville Shale proceeds at even a relatively slow pace, emissions from exploration and production activities will be sufficiently large that their potential impacts on ozone levels in Northeast Texas and Northwest Louisiana may affect the ozone attainment status of these areas. For example, the observed 2007−2009 design value at the Harrison County, TX monitor is 68 ppb, which complies with the 2008 NAAQS. The 4 ppb increase in the design value predicted for the high scenario would cause this monitor to fail to attain the full range of the 2010 NAAQS proposed by the EPA (60−70 ppb). The monitors in Gregg and Smith County have 2007−2009 design values of 75 and 74 ppb, respectively. They attain the 2008 NAAQS but are higher than the 60−70 ppb range of the proposed 2010 standard. The predicted increases in their design values due to Haynesville development would drive them further from attainment. Note that this study only evaluates near-term ozone impacts of development, but the emission inventory indicates that emissions may be expected to increase beyond 2012.

Additional study is required to refine the emission inventories used in this analysis. There is significant uncertainty associated with the emissions estimates since development in the Haynesville Shale is still in its early stages. This study forecasts emissions from development whose pace depends on a wide variety of factors that are subject to change. However, it is important to gain an understanding of the potential effects of this development and their impact on regional air quality; therefore, we account for uncertainty in the ozone model results by developing a range of emissions scenarios and presenting ozone impacts for the high and low scenarios as a method for bounding the uncertainty. The assumptions used in the development of the inventories - particularly the apparent limited need for wellhead compressors - indicate that these inventories could tend toward lower bound estimates. On the other hand, it is also possible that some source categories may be overestimated - for example, improvements in drilling technology could reduce future drilling times and therefore, NOx emissions associated with drilling. New controls or standards could also have a significant effect on future emissions and only on-the-books regulations were applied to the Haynesville inventory. Figure 2 shows that drill rigs and compressor stations and gas plants make the most significant contributions to the NOx emission inventory; additional controls on these sources would therefore be beneficial in reducing future year emissions from the Haynesville Shale. Future work will focus on enhancing the inventory with additional data regarding well site compression, well decline curves, and drill rig use.

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Supporting Information Available

Details describing the emissions estimation methodology, CAMx model, and model performance evaluation. This material is available free of charge via the Internet at http://pubs.acs.org.

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