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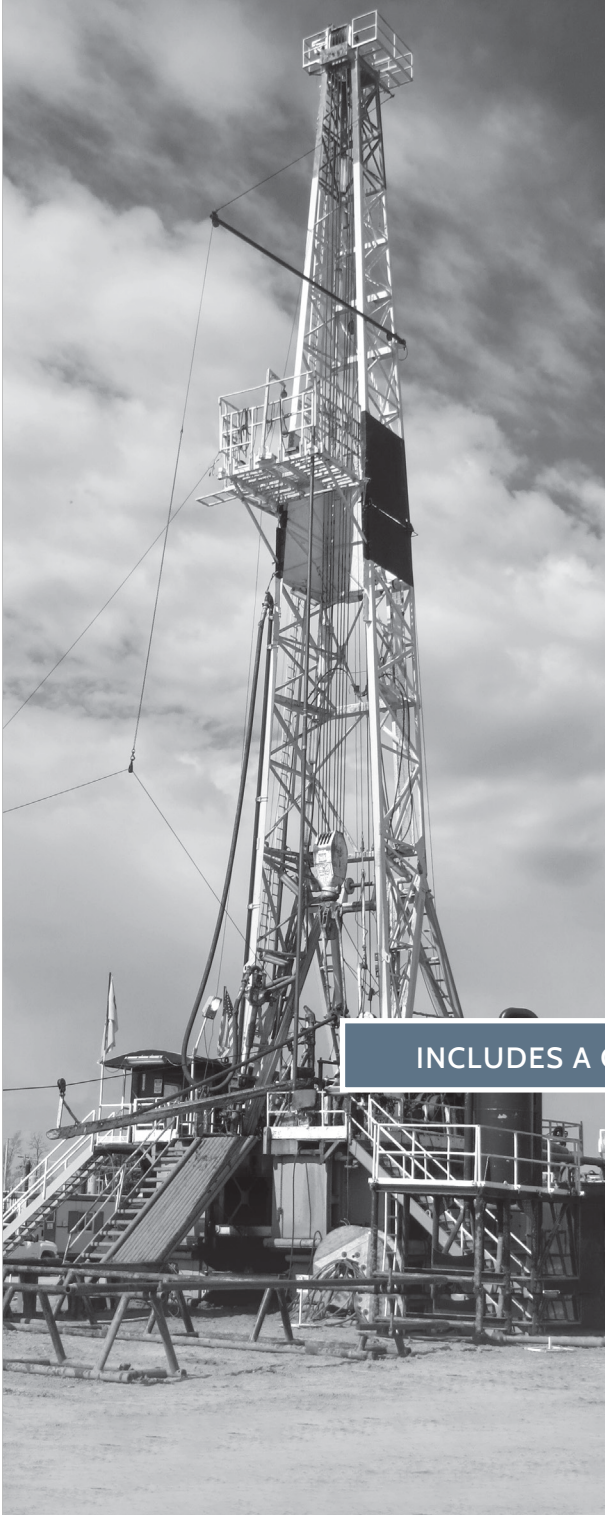
RESEARCH REPORT

Air Quality Trends in Texas and Colorado Associated with Unconventional Oil and Gas Development

Gunnar W. Schade, Detlev Helmig, Katherine Potter, Michel Stahli, and Gabriel Greenberg

INCLUDES A COMMENTARY BY THE HEI ENERGY REVIEW COMMITTEE

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ABOUT HEI ENERGY

The Health Effects Institute's Energy Research program (HEI Energy) was formed to identify and conduct high-priority research on potential population exposures and health effects from the development of oil and natural gas in the United States. Since 2022, HEI Energy has supported population-level exposure research in multiple oil and gas regions. This research followed an extensive planning process that included preparing reviews of the scientific literature, hosting multisector workshops to learn about research priorities, and developing an online curated database and spatial bibliography to advance both public and scientific understanding. The research scope of HEI Energy is expanding beyond oil and gas to other forms of energy development, with an overarching goal of providing impartial knowledge about the benefits and drawbacks associated with various technologies.

The scientific review and research provided by HEI Energy contribute high-quality and credible science to the public debate about unconventional oil and natural gas development and provide needed support for decisions about how best to protect public health. To achieve this goal, HEI Energy has put into place a governance structure that mirrors the one successfully employed for nearly 40 years by its parent organization, the Health Effects Institute (HEI), with several critical features:

- Balanced funding from the US Environmental Protection Agency under a contract that funds HEI Energy exclusively and from the oil and natural gas industry, with other public and private organizations periodically providing support
- An independent Board of Directors consisting of leaders in science and policy who are committed to fostering the public-private partnership that is central to the organization
- A research program governed independently by individuals having no direct ties to or interests in sponsor organizations
- The HEI Energy Research Committee, whose members are internationally recognized experts in one or more subject areas relevant to the Committee's work, has demonstrated its ability to conduct and review scientific research impartially and has been vetted to avoid conflicts of interest
- Research that undergoes rigorous peer review by the HEI Energy Review Committee, which is not involved in the selection and oversight of HEI Energy studies
- Staff and committees that participate in open and extensive stakeholder engagement before, during, and after research and communicate all results in the context of other relevant research

In addition, HEI Energy publicly shares all literature reviews and original research that it funds, along with summaries written for a general audience. Without advocating policy positions, it provides impartial science targeted to make better-informed decisions.

HEI Energy is funded separately from the Health Effects Institute's other research programs (www.healtheffects.org), with financial support from the US Environmental Protection Agency, the oil and gas industry, and private foundations.

ABOUT THIS REPORT

HEI Energy Research Report 242, *Air Quality Trends in Texas and Colorado Associated with Unconventional Oil and Gas Development*, presents a research project funded by HEI Energy and conducted by co-principal investigators Gunnar W. Schade (Texas A&M University) and Detlev Helmig (Boulder AIR) and their colleagues. The report contains three main sections:

The **HEI Statement**, prepared by staff at HEI Energy, is a brief, nontechnical summary of the study and its findings; it also briefly describes the HEI Energy Review Committee's comments on the study.

The **Investigators' Report**, prepared by Schade, Helmig, and colleagues, describes the scientific background, aims, methods, results, and conclusions of the study.

The **Commentary**, prepared by members of the HEI Energy Review Committee with the assistance of HEI staff, places the study in a broader scientific context, points out its strengths and limitations, and discusses the remaining uncertainties and implications of the study's findings for public health and future research.

This report has gone through HEI Energy's rigorous review process. When an HEI Energy-funded study is completed, the investigators submit a draft final report presenting the background and results of the study. Outside technical reviewers first examine this draft report. The report and the reviewers' comments are then evaluated by members of the Review Committee, an independent panel of distinguished scientists who are not involved in selecting or overseeing HEI Energy studies. During the review process, the investigators have an opportunity to exchange comments with the Review Committee and, as necessary, to revise their report. The Commentary reflects the information provided in the final version of the report.

Although this report was produced with partial funding by the United States Environmental Protection Agency under Contract No. 68HERC19D0010 to the Health Effects Institute, it has not been subjected to the Agency's peer and administrative review and may not reflect the views of the Agency; thus, no official endorsement by the Agency should be inferred. This report also has not been reviewed by private party institutions, including those that support HEI Energy, and may not reflect the views or policies of these parties; thus, no endorsement by them should be inferred.

PREFACE

Trends in Air Quality and Community Exposures Associated with Oil and Gas Development

INTRODUCTION

Air Quality and Oil and Gas Development

Emissions from oil and gas development can affect air quality in nearby communities and regionally. The operations emit a complex suite of air pollutants, including hazardous air pollutants (e.g., benzene, toluene, ethylbenzene, xylenes, and formaldehyde), hydrogen sulfide, and criteria air pollutants (e.g., NO₂, PM_{2.5}). Ozone is formed in the atmosphere from reactions of NO_x and volatile organic compounds (VOCs) in the presence of sunlight. Oil and gas operations also directly emit PM_{2.5} and precursor gases (NO_x and some VOCs) that can react to form particulate matter (PM) in the atmosphere.

Much has changed in the oil and gas sector since the shale boom began in the early 2000s. Federal, state, and local regulations and policies have evolved alongside industry practice. Many of these changes have been designed to address concerns about air emissions; to determine whether and why these changes succeeded is at the core of the Health Effects Institute Energy (HEI Energy)'s mission. During this same period, alongside population exposure research funded by HEI Energy under *RFA E20-1*, numerous studies have been conducted to understand human exposures to emissions from oil and gas development and associated health effects, while routine monitoring has continued (e.g., EPA's Photochemical Assessment Monitoring Stations Network), and remote sensing has emerged as an increasingly important tool to understand human exposure.

Rationale for the RFQ

After years of data collection, some researchers have begun to review air quality data for specific regions (e.g., Garcia-Gonzales et al. 2019, Lange et al. 2023, Lim et al. 2019, Long et al. 2019, Lyu et al. 2021, McMullin et al. 2018) and assess trends in air quality (Lange et al. 2023). The HEI Energy Research Committee (the "Committee") recognized that sufficient data might now be available to analyze trends in air quality and population exposure since the early 2000s in one or more US oil- and gas-producing regions. Given the availability of these data, and

based on early progress with the program of population exposure research funded under HEI Energy's *RFA E20-1*, the Committee recommended specific follow-on research to assess trends in air quality and population exposures associated with oil and gas development in one or more US regions.

OBJECTIVES OF THE RFQ

The objective of the RFQ was to identify well-qualified research teams to comprehensively analyze air quality and other data across one or more regions to assess long-term trends in air quality and air pollutant emissions (including, but not limited to, oil and gas development) and their influence on population exposures in various subpopulations since the early 2000s. To the extent feasible, the Committee expressed interest in analyzing the contribution of oil and gas development emissions to the observed trends in air quality and exposure and the effectiveness of evolving policy and industry practice intended to reduce exposures to these emissions.

DESCRIPTION OF THE STUDIES FUNDED UNDER RFQ E23-1

Three studies were funded under RFQ E23-1, and they are summarized below (**Preface Table 1**). The study locations stretch across several major oil and gas-producing regions of the United States (**Preface Figure 1**).

Long-Term Criteria and Toxic Pollutants Trends and Community Exposures Over the Marcellus Shale Region in the United States, Bok H. Baek, George Mason University The research team assessed trends in air quality and population exposures in the Marcellus-Utica shale region and whether any might be explained by changes in oil and gas development-related operations or governance. The research team conducted long-term trend analyses with the bottom-up oil and gas nationwide emissions inventory for criteria and hazardous air pollutants, as well as the ambient measurements of criteria air pollutants (e.g., NO₂, O₃, PM_{2.5}) and selected air toxics (e.g., benzene, toluene, ethylbenzene, xylenes, styrene, and formaldehyde) from the observational

monitoring networks. They performed long-term air quality modeling simulations from 2002 to 2021 to understand the impact of oil and gas development emissions on local and regional air quality over the Marcellus-Utica Shale region.

Trends in Marcellus-Utica Shale Regional Air Quality due to Unconventional Oil and Gas Development (Tri-MAQs), Michael J. Gernand, The Pennsylvania State University The research team aimed to ascertain the contributions of oil and gas development to local and regional air quality, associated population exposures across the multistate Marcellus-Utica Shale region from 2004 to 2023, and how changes in industry and government policy may have affected those contributions. The study involved development of a daily multipollutant (PM_{2.5}, NO₂, SO₂, and VOCs) air quality dataset and a daily dataset of UOGD (unconventional oil and gas development) activity and an inventory of expected emissions across the study region during the 2004–2023 time frame, estimation of population exposures to these pollutants, and estimation of the overall proportion of measured emissions that originate from oil and gas development together with the impact of specific regulatory policies and technical changes in industry processes on air quality in the region.

Air Quality Trends in Texas and Colorado Associated with Unconventional Oil and Gas Development, Gunnar W. Schade (Texas A&M University) and Detlev Helmig (Boulder AIR) The research team investigated the contribution of UOGD to trends in nonmethane hydrocarbon concentrations and associated air quality impacts using long-term datasets from the Northern Colorado Front Range (2008–2024) and various plays in Texas (1997–2023). The team used high-quality data collected by the Texas Commission on Environmental Quality, Boulder AIR, as well as satellite-based measurements. The team also used a form of pattern analysis (non-negative matrix factorization) and tracer compounds (ethane and propane) to separate the possible influence of UOGD and other sources from observed trends in air quality.

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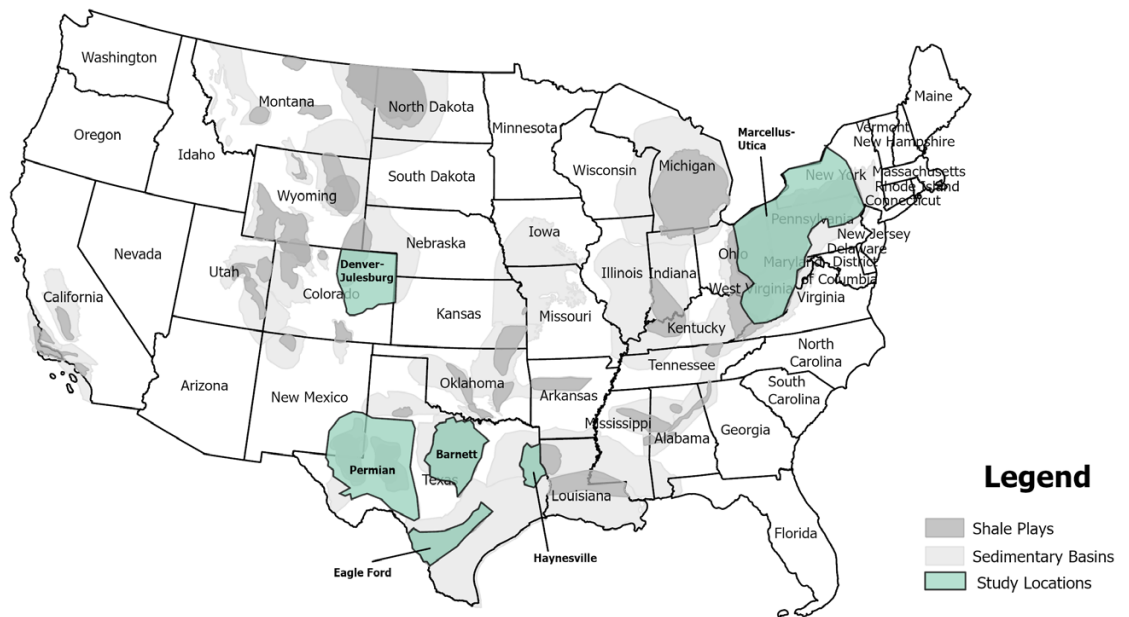
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Preface Table 1. Key Characteristics of HEI’s Research to Assess Trends in Air Quality and Population Exposures Associated with Oil and Gas Development

Principal Investigator	Location	Main Air Pollutants	Emissions Data	Monitoring Data	Exposure Assessment ^a
Baek	Marcellus-Utica Shale region (Ohio, Pennsylvania, and West Virginia)	PM _{2.5} , NO _x , NO ₂ , O ₃ , VOCs (total), benzene, ethylbenzene, formaldehyde, styrene, toluene, xylenes	Existing state- and regional-level data (2002–2021) from the US EPA EQUATES platform, the National Emissions Inventory, and the US EPA 2021 Special Emissions Inventory	Existing state- and regional-level atmospheric monitoring data (2002 to 2021) from the US EPA Air Quality System and Ambient Monitoring Archive	Long-term air quality trends (CAMx using SMOKE emissions modeling), and predictive trend analysis using machine learning-based trends (DeepCTM)
Gernand	Marcellus-Utica Shale region (Ohio, Pennsylvania, and West Virginia)	PM _{2.5} , NO _x , NO ₂ , VOCs (anthropogenic only from modeled source categories), SO ₂	Existing state- and regional-level data (2004–2023) from the US EPA National Emissions Inventory and Clean Air Markets Program Data	Existing state- and regional-level atmospheric monitoring data (2004 to 2023) from the US EPA Air Quality System Satellite monitoring: TROPOMI (2018–2024); OMI (2004–2024); and MODIS (2004–2024)	Pollutant dispersion model using AERMOD; machine learning model (ResDL) trained on remote sensing data, ground station measures, and known emission sources
Schade and Helmig	Texas (parts of the Eagle Ford Shale, Haynesville Shale, Permian Basin, and Barnett Shale), New Mexico (Permian Basin), and Colorado (Denver-Julesburg Basin)	NO _x , NMHC (benzene, ethane, i- and n-pentane, propane), methane, formaldehyde	None used	Existing state- and regional-level atmospheric monitoring data Texas (1997–2023): NMHC, NO _x (NO and NO ₂), and meteorological data Colorado (2008–2024): NMHC, methane, NO _x , and meteorological data Two remote reference sites for (1) methane, (2) ethane, and propane OMI satellite monitoring for formaldehyde in the Permian Basin	Long-term trend analyses in Texas using Natural Cubic Splines and in Colorado using the NOAA Fast Fourier Transform Curve Fitting Tool

AERMOD = American Meteorological Society/Environmental Protection Agency Regulatory Model; CAMx = Comprehensive Air Quality Model with Extensions; DeepCTM = Deep Learning Contaminant Transport Model; MODIS = Moderate Resolution Imaging Spectroradiometer; NMHC = nonmethane hydrocarbons; NO₂ = nitrogen dioxide; NO_x = nitrogen oxides; O₃ = ozone; OMI = Ozone Monitoring Instrument; PM_{2.5} = particulate matter ≤2.5 μm in aerodynamic diameter; SO₂ = sulfur dioxide; ResDEL = Residual Deep Learning; SMOKE = Sparse Matrix Operator Kernel Emissions; TROPOMI = TROPospheric Monitoring Instrument; VOCs = volatile organic compounds.

^a Study population for all research included all subpopulations in the study location.



Preface Figure 1. Study locations in a variety of US shale basins.

HEI STATEMENT

Synopsis of Research Report 242

Long-Term Trends in Air Quality in Unconventional Oil and Gas Development Regions in the United States

BACKGROUND

Over the past two decades, unconventional oil and gas development (UOGD)* has led to a significant increase in oil and gas production across the United States.

Emissions associated with UOGD can affect local and regional air quality. UOGD processes emit a mix of pollutants that are relevant to health, including methane, nonmethane hydrocarbons (such as ethane, propane, and benzene), and nitrogen oxides (NO_x). These air pollutants may affect air quality directly (e.g., benzene is a hazardous air pollutant) or by reacting with other air pollutants to form, for example, fine particles and ozone in the lower atmosphere (e.g., nonmethane hydrocarbons and NO_x may react to form ozone). Assessing exposure to such pollutants is difficult because the amount of pollution in the air depends on several factors that often vary by local conditions, such as proximity, topography, or meteorological conditions.

Simultaneously, operations and regulation have evolved alongside UOGD expansion. Many changes in regulations and operations have been designed to address concerns over potential population-level air pollution exposures and associated health effects. Nonetheless, questions remain regarding the effect of air pollutants associated with UOGD on air quality, how exposures vary among populations, and whether evolving industry practice, regulation, and governance, and other local and regional factors have indeed led to the intended changes in emissions.

Studies have now begun using historical air quality monitoring data to assess trends in air quality (and potential population exposures and links to source emissions) in UOGD regions in the United States.

What This Study Adds

- This study evaluates long-term air quality trends across UOGD regions in the United States, primarily in Texas (1997–2023) and Colorado (2008–2024).
- The investigators compiled publicly available data on methane, nonmethane hydrocarbons, and NO_x concentrations from air quality monitoring stations in each state. They then evaluated long-term air quality trends associated with UOGD in both states using statistical techniques for analyzing time series data.
- Long-term trends in nonmethane hydrocarbon and NO_x concentrations increased and then stabilized over time in Texas, generally correlating with regional UOGD production volumes in the state.
- In contrast, long-term trends in nonmethane hydrocarbon and NO_x concentrations declined over time in Colorado, and methane growth was slower than the global background, while UOGD production continued to increase.
- These findings suggest that emissions levels near UOGD are likely declining in Colorado but not noticeably in Texas.
- This study demonstrated differences in long-term trends in air pollutant concentrations near UOGD in Texas and Colorado that likely reflect differences in a mix of local and regional factors in each state.

Drs. Gunnar W. Schade (Texas A&M University) and Detlev Helmig (Boulder AIR) and colleagues sought to evaluate long-term trends in air quality across two large UOGD regions with different regulatory frameworks (Texas and Colorado) and to assess whether emissions associated with UOGD might be changing over time. Their study was funded through HEI Energy's

This Statement, prepared by HEI Energy, summarizes a research project funded by HEI Energy and conducted by co-principal investigators Gunnar W. Schade (Texas A&M University) and Detlev Helmig (Boulder AIR) and their colleagues. Research Report 242 contains the detailed Investigators' Report and a Commentary on the study prepared by the HEI Energy Review Committee.

* A list of abbreviations and other terms appears at the end of this report.

Request for Qualifications (RFQ) E23-1: Trends in Air Quality and Community Exposures Associated with Oil and Gas Development.

APPROACH

The overarching objective of their study was to use air quality data collected in UOGD regions in Texas and Colorado (**Statement Figure**) to determine any identifiable trends in emissions of nonmethane hydrocarbons and NO_x (Aim 1). The investigators also used satellite-derived data to assess trends in formaldehyde vertical column densities, which can be used as a marker for nonmethane hydrocarbons, near UOGD in Texas and New Mexico (Aim 2).

For Aim 1, the investigators gathered data on ethane, propane, benzene, and NO_x, known emissions from UOGD activities, from air quality monitoring stations located near the Barnett Shale, Eagle Ford Shale, Haynesville Shale, and the eastern Permian Basin in Texas. Helmig and colleagues collected data on the same pollutants, as well as methane, from air quality monitoring stations near the Denver–Julesburg Basin in Colorado. The data spanned the 1997–2023 period for Texas and 2008–2024 for Colorado. The differences in study times were the result of data availability. For Texas data, investigators also assessed correlations of UOGD production volumes with long-term trends in air pollutant concentrations in each study basin.

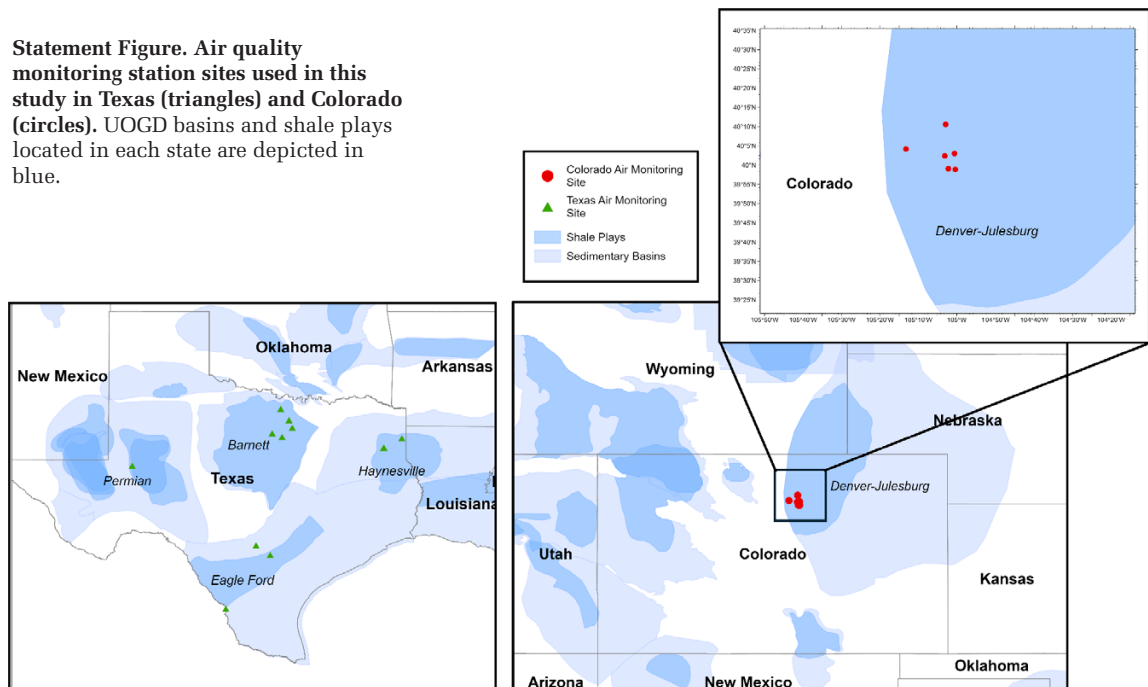
The investigators then used statistical methods for analyzing time series data (referred to as trend analysis) to evaluate trends in air pollutant concentrations over time. They used separate statistical techniques for the Texas (fitting natural cubic spline curves) versus Colorado (NOAA’s FFT curve-fitting tool) analysis. To assess whether the use of two different statistical techniques notably affected the long-term air quality trends found in both states, the investigators qualitatively compared the long-term trends found for ethane from data for one site in Texas and one site in Colorado.

For Aim 2, the investigators obtained satellite-derived data on atmospheric formaldehyde vertical column densities from 2004 to 2022 across the Permian Basin, which spans both Texas and New Mexico. They averaged the data across space and time to generate regional monthly averages. They then conducted a trend analysis to evaluate changes in formaldehyde vertical column densities over time.

KEY RESULTS

The investigators found that, in general, long-term trends in nonmethane hydrocarbon and NO_x concentrations across air quality monitoring sites in UOGD regions of Texas increased during the years of production growth in each area, which then stabilized or declined over time. Those trends largely correlated with UOGD production volumes in the different

Statement Figure. Air quality monitoring station sites used in this study in Texas (triangles) and Colorado (circles). UOGD basins and shale plays located in each state are depicted in blue.



regions. For example, trends in benzene concentrations at one air quality monitoring site in the Permian Basin demonstrated a correlation of 0.82 with gas production volumes. At a different site in the Barnett Basin, trends in benzene concentrations showed a correlation of 0.91 with gas production volumes.

In contrast, Helmig and colleagues found that non-methane hydrocarbon and NO_x concentrations generally exhibited decreasing long-term trends in Colorado, despite increasing UOGD production in the state. For example, slopes of long-term trend lines (indicating the rate of change) in ethane and propane demonstrated concentration decreases ranging from -0.2 to -0.8 ppb per year across air quality monitoring sites. They additionally found elevated concentrations and an upward trend in methane across sites in Colorado. This trend was smaller in magnitude when compared with methane data from a more remote reference location in North America, indicating that the rate of atmospheric methane accumulation in Colorado is slower than in background air, which the investigators attribute to a declining contribution of methane from the oil and gas sector.

In comparing long-term trend curves from ethane data at one site in each state, the investigators noted no major differences between the long-term trend curves that were found using two different statistical techniques.

In assessing long-term trends in formaldehyde vertical column densities as a proxy for nonmethane hydrocarbon emissions in the Permian basin, the investigators found a small, increasing trend until 2020 that coincided with increasing UOGD in this basin. However, they reported slightly decreasing concentrations throughout 2021 and 2022, which diverged from continued increases in UOGD during those years, though the investigators note uncertainty in the results reported due to the aging of the satellite instrument, leading to increased error bands on the formaldehyde measurements.

INTERPRETATION AND CONCLUSIONS

The investigators found that long-term trends in air pollutant concentrations decreased over time in Colorado despite increased UOGD production volumes, whereas trends in air pollutant concentrations generally correlated with UOGD production in Texas. The investigators indicated that their findings suggested that emissions per quantity of oil and gas produced near UOGD in Colorado were likely declining, but had not improved in Texas. They also suggested that these findings may be driven by differences in regulatory frameworks in each state, noting that Texas relies on

federal regulation while Colorado has state-specific measures, but they did not conduct formal analyses to assess such conclusions. The investigators could not draw strong conclusions that were based on the long-term trends in formaldehyde in the Permian Basin, given the uncertainties associated with the data and subsequent observed trends.

In its independent review of the study, the HEI Energy Review Committee identified as a key strength of this work the comparison of long-term trends in air pollutants associated with UOGD in Colorado and Texas, each with varying local and regional contexts and different regulatory frameworks. The Committee also highlighted the importance of evaluating ambient air pollutant concentrations using long historical records of air quality data from multiple air quality monitoring sites, which was an improvement from prior research.

The observed differences in long-term trends in air quality in UOGD regions in both states and their relationship to UOGD production volumes were instructive, indicating that some UOGD operations were able to reduce emissions while simultaneously increasing production. However, the Committee noted that the investigators' interpretation of their findings seemed to overemphasize the influence of differences in regulatory frameworks in each state, given that no formal analysis was done.

The Committee appreciated the value of comparing long-term ethane air quality trends at a single site in each state. However, it questioned whether the use of two different statistical methods may have influenced the findings between states, particularly given the lack of a comprehensive quantitative comparison of the methods. Although overall differences in trends between the approaches were minor, the rationale for using two methods was not clearly justified, leading the Committee to question the potential effect of method choice on the results.

In addition, the Committee appreciated the use of long-term satellite-derived records of formaldehyde vertical column density. However, it was determined that this analysis of long-term formaldehyde trends in the Permian Basin did not contribute strongly to the overall study given the many limitations associated with the satellite-derived data.

In summary, this study contributed to our knowledge about long-term trends in air quality near UOGD in Texas and Colorado. It demonstrated that long-term trends in ethane, propane, benzene, and NO_x near UOGD basins differed between these two large oil and gas regions. This work enhances previous research on long-term air quality trends near UOGD by analyzing a long historical record of air quality monitoring data

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among multiple sites in different states. The Committee generally agreed with the reported results, although it underscored that the results likely reflect differences in a combination of local and regional factors in each state and emphasized that the unique effect of regulation remains difficult to disentangle from many other factors.

Air Quality Trends in Texas and Colorado Associated with Unconventional Oil and Gas Development

Gunnar W. Schade^{1*}, Detlev Helmig^{2*}, Katherine Potter¹, Michel Stahli², and Gabriel Greenberg²

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ABSTRACT

Introduction The shale oil and gas (O&G)[†] production boom has led to increasing air pollutant emissions, mostly in the form of volatile hydrocarbons and nitrogen oxides (NO_x). Because most of these emissions have emerged in rural areas and air quality monitoring (AQM) had historically been concentrated in metropolitan areas, very few AQM locations were operating in the late 2000s that could provide insights into emissions development. New AQM stations were deployed in the 2010s in or downwind of shale O&G production areas, but most have historically limited data records that do not fully capture the production boom. In this project, we analyzed existing air quality records from AQM stations in Texas and the Northern Colorado Front Range to determine whether they recorded identifiable trends in methane and selected nonmethane hydrocarbon emissions associated with O&G development. We also analyzed satellite-based formaldehyde abundance trends in the Permian Basin in Texas and New Mexico.

Methods After additional data quality assurance, we applied two types of trend analyses to the data: (1) a local, stepwise least-squares fitting method known as cubic splines, and (2) a fitting algorithm developed by the National Oceanic and Atmospheric Administration to analyze its greenhouse gas time series, which decomposes the data into a set of periodic and polynomial functions. Both routines allow user-defined settings and provide a long-term (multiyear) nonlinear trend function with uncertainty estimates as output. Permian Basin formaldehyde trends, which were temporally and spatially

averaged, were also estimated from Ozone Monitoring Instrument Level 3 satellite data. The trends were compared with auxiliary data at both the regional (shale basin) and local (county) levels to assess whether changes in production could be driving emissions. Furthermore, derived trends were scrutinized in light of federal and state regulations passed to limit O&G development-related air pollutant emissions.

Results Observed long-term trends varied significantly among the Texas sites. Barnett Shale AQM station data showed mostly flat to slightly decreasing long-term trends for the O&G emissions tracers ethane and propane, consistent with a gas production peak in 2011–2012, followed by an extended decline of 10%/yr. Air quality downwind of the Haynesville Shale was affected most during the initial boom years from 2006 to 2011 and then improved remarkably. Eagle Ford Shale AQM station data also correlated with O&G production data, showing that the highest ambient ethane and propane levels occurred during the peak production years of 2014–2015 and 2019, whereas the lowest levels were encountered during the lull in production in 2016–2017 and after 2020. Lastly, Permian-Midland Basin data showed a steady increase in ambient hydrocarbon levels throughout the production growth phase since 2016, also detectable via the satellite data–derived formaldehyde proxy, a trend that has been leveling in recent years. In both the Eagle Ford and Permian, casinghead gas production, related to gas flaring, correlated best with ambient ethane data. Similar to Texas, the Northern Colorado Front Range showed significantly higher ambient hydrocarbon levels, including methane, in air advected from the Denver–Julesburg Basin (DJ Basin) O&G region compared with the background air. However, Colorado ambient air quality data did not closely follow O&G production volume trends, but instead showed declining concentration trends. Atmospheric methane has continued to rise in step with global background levels, but at a slower rate. Over time, the difference between concentrations in polluted and clean air has narrowed, indicating that regional methane emissions are declining. For hydrocarbons, sites located closer to the shale basin showed higher concentrations overall, but the trend analyses reveal a steady decline of the petroleum hydrocarbon enhancement in outflow from the DJ Basin. The agreement between the methane and hydrocarbon trend behavior increases confidence in the finding of overall declining emissions from hydrocarbon production in the DJ Basin.

Conclusions Long-term trends in the concentrations of selected hydrocarbons associated with O&G production have differed markedly between the states of Texas and Colorado.

This Investigators' Report is one part of Health Effects Institute Research Report 242, which also includes a Commentary by the HEI Energy Review Committee and an HEI Statement about the research project. Correspondence concerning the Investigators' Report may be addressed to Dr. Gunnar W. Schade, Department of Atmospheric Sciences, Texas A&M University, 3150 TAMU, College Station, TX 77843-3150; email: gws@geos.tamu.edu. No potential conflicts of interest were reported by the authors.

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[†] A list of abbreviations and other terms appears at the end of this report.

Air Quality Trends in Texas and Colorado Associated with Unconventional Oil and Gas Development

In Texas, these trends generally mirrored changes in O&G production volumes, whereas in Colorado, they declined slowly but steadily. Unlike Texas, where only federal rules are in place to regulate emissions, Colorado passed several state-level rules targeting O&G emissions reductions that may have contributed to its air quality improvements.

CHAPTER 1: INTRODUCTION

Unconventional oil and gas development (UOGD) in the United States has pronounced effects on air pollutant emissions (Allen 2016). US oil and gas (O&G) production has increased significantly since the late 2000s, driven by the introduction of horizontal drilling and hydraulic fracturing that uses slickwater formulations. Gas production from deep shale rocks, such as the Marcellus in Pennsylvania, increased first. Increased oil production (“tight oil”) followed from less deep belowground shales, such as the Eagle Ford and Permian in Texas and the Denver–Julesburg Basin (DJ Basin) in Colorado.

This “shale boom” has resulted in increased air pollutant emissions, with the most concerning emissions stemming from venting and leakage of petroleum hydrocarbons (i.e., methane and nonmethane hydrocarbons [NMHCs]), as well as from emissions of nitrogen oxides (NO_x) and the sulfur compounds hydrogen sulfide (H_2S) and sulfur dioxide (SO_2). Volatile NMHCs are vented or emitted as fugitive emissions; NO_x is emitted from heavy equipment usage, truck traffic to and from well pads, and gas flares; and sulfur compounds are emitted from the products (outgassing of H_2S) or from waste treatment (SO_2 from gas flares).

Several prior works have investigated the regional effects of NMHC emissions from the O&G industry (Helmig 2020a; Lange et al. 2023; Lyu et al. 2021; McKenzie et al. 2018; Pétron et al. 2014; Pozzer et al. 2020; Schade and Roest 2016; Tzompa-Sosa et al. 2019), but few have focused on long-term data series to identify trends in emissions (Angot et al. 2021; Helmig et al. 2016; Oltmans et al. 2021; Schade and Roest 2015; Simpson et al. 2012) and determine how O&G emissions may have changed in response to newly enacted regulations. Furthermore, O&G NMHC and NO_x emissions contribute to boundary layer

photochemical ozone production, and some areas are now in nonattainment of the ozone National Ambient Air Quality Standard (NAAQS) as a result of UOGD emissions (Edwards et al. 2014; Edwards et al. 2013; Marsavin et al. 2024; Pollack et al. 2023; Pozzer et al. 2020; Schnell et al. 2016).

Figure 1 highlights the United States’ tight oil production trends, with most shale-produced oil in the Permian and Eagle Ford Shale regions of Texas, as well as in the Bakken Shale in North Dakota. Clearly noticeable are four major periods: the rapid increase in shale production through the 2010s up to 2015; the drop in production during the following years in response to price manipulations of the Organization of the Petroleum Exporting Countries (OPEC); the recovery from 2017 up to the end of 2019 (the maximum); and finally, the pandemic crash, recovery, and regrowth in the Permian Basin. How large was the influence of these developments on local and regional air quality in and downwind of the mostly rural shale production regions? What subsequent effect did any regulations passed at the federal or state levels have on reducing these emissions? And can we use in situ and satellite-based observations to determine any of these trends?

Our focus in this project to address these questions was on NMHC measurements and monitoring, and particularly on ethane, propane, and benzene because their relatively long atmospheric lifetimes allow atmospheric concentration changes to manifest even at significant distances from emission sites. Ethane and propane, in particular, are highly valuable tracers for O&G petroleum hydrocarbon emissions, having only a few or minor non-O&G sources, and low natural background concentrations. Ambient air monitoring data can therefore serve as proxies for O&G emissions, including for higher hydrocarbons, and the likely changes in exposure to a whole suite of O&G exploration–related emissions (Helmig et al. 2016; Kort et al. 2016; Pozzer et al. 2010; Simpson et al. 2012).

Monthly US tight oil production by formation
million barrels per day

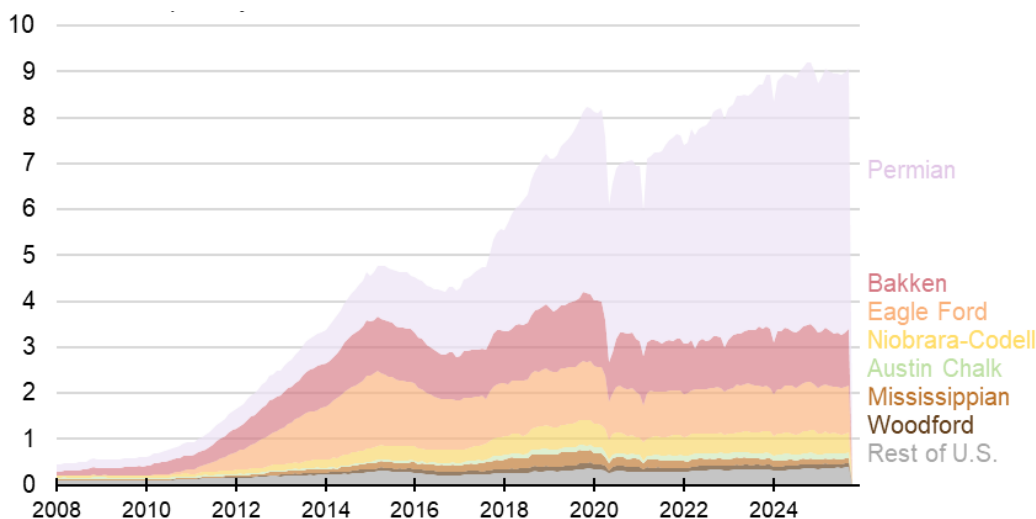


Figure 1. Monthly US tight oil production since 2007, highlighting shale oil–producing regions. Source: US Energy Information Administration, <https://www.eia.gov/outlooks/steo/images/Fig42.png>.

CHAPTER 2: SPECIFIC AIMS AND OVERARCHING APPROACH

In this project, we acquired and analyzed various data products for the determination of air quality trends. Our specific aims were to evaluate the following:

1. Surface ambient air composition data collected within, in proximity to, and downwind of shale O&G production basins in Texas and Colorado, with a focus on atmospheric composition changes of selected NMHCs and NO_x.
2. Satellite-based formaldehyde (HCHO) measurements (tropospheric vertical column densities [VCDs]) above the Permian Basin as a proxy for NMHC emissions in the last 20 years.

Aim 1 was investigated using state air quality monitoring (AQM) station data from the Texas Commission on Environmental Quality (TCEQ) from stations in proximity to shale areas in Texas, namely the Eagle Ford Shale, the Barnett Shale, the Haynesville Shale, and the eastern Permian Basin (Permian-Midland Shale). For Colorado, the investigations used surface monitoring data from Boulder Atmosphere Innovation Research (AIR) AQM stations in the Northern Colorado Front Range ([NCFR]; funded by Front Range communities), from a tall tower that was operated by the National Oceanic and Atmospheric Administration (NOAA) before the tower's decommissioning in 2016, and from a site operated by the Colorado Department of Public Health and Environment (CDPHE). In addition, the ethane vertical column density data acquired by the National Center for Atmospheric Research (NCAR) in Boulder were investigated. These data sources included both AQM stations with hourly measurements and AQM stations with discrete 24-hour sampling every 6 days. Eleven AQM stations were included from Texas, and seven were included from Colorado. Trends were analyzed using two independent statistical tools.

Aim 2 was investigated using historical data from the Ozone Monitoring Instrument (OMI) on the Aura satellite, as provided by the National Aeronautics and Space Administration (NASA). Level 3 gridded data were used spanning the 2002–2022 period. HCHO, a mostly secondary product of atmospheric hydrocarbon oxidation, can serve as a proxy for NMHC emissions in the Permian Basin because of the absence of isoprene-emitting vegetation in this region, with isoprene being the dominant precursor of atmospheric HCHO in most of the troposphere.

HISTORICAL CONTEXT, GENERAL CAVEAT

Most AQM stations in the United States have been set up in urban areas. As on-road mobile sources, such as passenger cars and utility vehicles, are a dominant source of primary air pollution, urban areas where on-road traffic is most dense

RESEARCH ROADMAP

Aims and Research Conducted	Methods Description
Aim 1	
Evaluate air quality trends in Texas using TCEQ data from 11 AQM sites	Methods are described in Chapter 3 and Appendix A1; results and discussion are in Chapter 3 subsections; and additional results are in Appendix C1.
Evaluate air quality trends in the NCFR using observations from seven AQM sites operated by Boulder AIR, NCAR, CDPHE, and NOAA	Methods are described in Chapter 3 and Appendix A2; results and discussion are in Chapter 3 subsections; and additional results are in Appendix C2.
Aim 2	
Evaluate air quality trends in the Permian Basin of Texas and New Mexico using satellite-based HCHO column measurements as a proxy for surface NMHC emissions	Methods are described in Chapter 4 and Appendix B; results and discussion are in Chapter 4 subsections.

have historically been the dominant locations of monitoring. Metropolitan areas have historically had worse air quality than rural areas, and long-term urban AQM has demonstrated that air quality has improved substantially in most urban areas over the decades since the passing of the first US Clean Air Act in the 1970s and its major amendment in the early 1990s (https://gispub.epa.gov/air/trendsreport/2024/#air_trends). The latter, for instance, reformed how we evaluate how ozone and particulate matter affect air quality, but also how we assess changes to “background” air quality in rural areas (Chameides et al. 1997). Rural areas have always been affected by tropospheric ozone, a secondary pollutant formed during the transport of primary pollutants, mostly emitted in urban areas, to the countryside. However, rural ozone — as exemplified during the second Texas Air Quality Study (Parrish et al. 2009; Wilczak et al. 2009) — would typically remain below maximum values observed in suburban areas because low precursor emissions in rural areas cannot sustain high ozone abundances. The onset of widely distributed O&G production in rural areas changed this picture (Schade and Roest 2015).

Since the onset of shale O&G exploration in the United States, emissions of both hydrocarbons and NO_x have increased (Allen 2016; Dix et al. 2020; Gorchoy Negron et al. 2018), mostly in rural areas. This increase has already had a substantial influence on secondary ozone formation, documented for both Texas and Colorado, where ozone monitored at urban locations

is affected by precursor emissions not associated with typical urban sources, such as car traffic (Evans and Helmig 2017; Pozzer et al. 2020).

When air pollutant emissions from shale O&G exploration first became an issue — because of nuisance impacts on nearby residents — citizens called on their local and regional representatives to require some mitigation, such as through emissions regulations. In response, both the US Environmental Protection Agency (EPA) and several states passed rules affecting O&G exploration activities. **Table 1** below provides a summary of these rulemaking activities from the EPA and the two states considered in this report.

In Texas, the legislature dedicated funds to its environmental agency, the TCEQ, to deploy AQM stations first into the Barnett Shale region in northern Texas in 2010, to the Eagle Ford Shale in south-central Texas in 2013, and to the Midland-Permian Basin in 2020. However, Texas passed no associated statewide regulatory rules to limit air pollutant emissions in its jurisdiction. The only relevant rule changes in Texas were made to a statewide rule on gas flaring adjudicated by the Texas Railroad Commission (TxRRC). The amendments to collect better data and entice reductions in the practice of flaring may have affected associated gas production-related emissions.

In Colorado, several environmental groups have inspired citizen-led groups in advocating for stricter O&G emissions rulemaking, particularly in light of the NCFR's continuing exceedances of the ozone NAAQS, recognizing major O&G operation contributions to summertime photochemical ozone production in the region (McDuffie et al. 2016). This activism led to a state ballot initiative, Proposition 112, which would have increased the minimum distance between new O&G

development and occupied buildings to 2,500 feet (Colorado General Assembly 2018). While that initiative, strongly opposed by the Colorado O&G industry, was narrowly defeated, it triggered a series of Colorado House and Senate bills that have since imposed stricter emission controls and limits. The most significant recent changes stemmed from Senate Bill 19-181, which led to a 2,000-foot setback rule and gave more power to local governments in restricting O&G development within their jurisdiction.

Table 1 lists the progression of EPA New Source Performance Standard regulations, known as the *Quad-O* rules, which are implemented and overseen by the TCEQ in Texas; two minor changes to the Texas Railroad Commission flaring rules; and the diverse rules implemented in Colorado since 2009.

Our research, as described in this report, focused on air quality changes over time against the backdrop of increasing shale O&G production in the United States, and the associated air quality regulations listed in Table 1. We used ambient air quality measurements of production-specific hydrocarbons, specifically the hydrocarbon oxidation proxy HCHO, in conjunction with these production data and regulations to determine whether and which emissions changes may have occurred over time. Because we are using ambient air data, rather than emissions data directly, the general caveat remains that concentration changes can only accurately reflect emissions changes if no substantial changes to meteorological conditions, and chemical removal rates from the atmosphere, have occurred over the periods investigated. Thus, our analyses reflect (1) an accounting for seasonal changes, which do affect both meteorological and chemical removal conditions, and (2) consideration of potential long-term, interannual changes to weather conditions.

Table 1. EPA, TCEQ/TxRRC, and Colorado State Rules Affecting Oil and Gas Exploration-Related Air Pollutant Emissions

Regulation or Rule	Year	Summary of Action
EPA Rulemaking		
New Source Performance Standards (NSPS) Subpart OOOO	2012	Phased in between 2012 and 2015 to address volatile organic compound (VOC) and SO ₂ emissions from the oil and natural gas industries; includes requirements for sources of pollution not previously regulated (e.g., hydraulically fractured gas wells)
OOOOa	2016	Updated NSPS to address CH ₄ , VOC, and toxic air pollutants such as benzene from new, reconstructed, and modified O&G sources
OOOO/OOOOa amendments	2020	Eliminate or reduce certain monitoring obligations; remove regulations applicable to transmission and storage; remove methane requirements for the industry's production and processing segments

continued next page

Table 1. (continued)

Regulation or Rule	Year	Summary of Action
OOOOb	2022, final rule 2024	Limitations on methane emissions from O&G facilities that began construction, modification, or reconstruction after December 2022 Emissions standards and compliance schedules for VOC and SO ₂ that began construction, modification, or reconstruction after December 2022
OOOOc	2022, final rule 2024	Emissions guidelines and compliance for methane from oil and natural gas facilities that began construction, modification, or reconstruction before December 2022
TCEQ and TxRRC Rulemaking		
Rule 32 §3.32; 16 Texas Administrative Code	Nov 2020	A change was made to <i>Form R-32, Application for Exception to Rule 32</i> , requiring more detailed operator documentation of why flaring is required
Rule 32 §3.32; 16 Texas Administrative Code	Sep 2021	A change was made to <i>Form PR</i> , the monthly production report, requiring the separate allocation of gas vented versus flared
State of Colorado Rulemaking^a		
HB07-1341	2007	Reconstructed the COGCC to have more representation from outside the O&G industry
HB07-1298	2009	A suite of new regulations was passed that included requirements for emission control devices on certain equipment near communities
COGCC	2012	Hydraulic fracturing sites must disclose all chemicals used in a public database
SB 13-202	2014	Requires a greater frequency of inspections at O&G wellheads, prioritized according to the risk level of a wellhead experiencing excess emissions, depending on its phase of development
COGCC	2013	Setbacks for drilling increased to 500 feet for homes and 1,000 feet for high occupancy buildings such as schools and hospitals
CDPHE Air Quality Control Commission (AQCC)	2014	Colorado AQCC adopts a series of policies to reduce methane emissions, making Colorado the first state to do so
COGCC	2015	Penalties increased for all emission violations
HB19-1261	2019	Colorado implements a goal to reduce greenhouse gas emissions by 26% and 50% of what was observed in 2005, by 2025 and 2030, respectively
SB19-181	2021	Enables local governments to have HB1041 powers over O&G extraction areas without restriction, including the ability to inspect any facility; setbacks increased from 500 to 2,000 feet
SB22-193	2022	Clean Air Grant Program funds public and private entities \$25 million for projects to reduce industry-related air pollution
HB21-1189	2023	Fenceline monitoring requirement implemented for hydrogen sulfide, hydrogen cyanide, and benzene for covered facilities; community monitoring is also now required
HB22-1244	2023	Allows the Colorado AQCC to designate “toxic air contaminants” to be regulated more stringently than the Clean Air Act and requires these emissions to be reported

^aThe Colorado Oil and Gas Conservation Commission (COGCC) was renamed the Energy and Carbon Management Commission (ECMC) in 2023.

CHAPTER 3: TEXAS AND COLORADO AIR QUALITY TRENDS FROM SURFACE DATA

INTRODUCTION

In this chapter, we first describe our selected data sources and then the quality assurance performed on these data. We focus on three hydrocarbons — ethane, propane, and benzene — because of their comparatively long atmospheric lifetimes, minimizing the effect of changing chemical removal rates. We present ambient hydrocarbon data trends over time and relate them to production data where appropriate.

TEXAS DATA

Eleven TCEQ-operated atmospheric monitoring sites were chosen for this study. Of these, three provided hourly non-methane hydrocarbon (NMHC) measurements made in situ (site code – site name):

- FLV – Floresville
- DCT – Decatur Thompson
- EML – Eagle Mountain Lake

The other eight sites provided canister NMHC samples collected over 24-hour windows (aligned with the 24-hour day starting at 00:00 CST) every 6 days, and were analyzed centrally (the canister samples were either analyzed at a TCEQ laboratory or at a TCEQ-accredited laboratory (e.g., GD Air Testing, <https://gdair.com/>), each site consistently using the same laboratory):

- OLN – Old Highway 90
- LRB – Laredo Bridge
- WFD – Weatherford
- BWP – Bowie Patterson
- MWL – Mineral Wells
- OHE – Odessa–Hays Elementary (school)
- KNK – Karnack
- LGV – Longview

Four of the TCEQ monitoring sites in this study also have hourly NO_x (sum of nitric oxide [NO] and nitrogen dioxide [NO_2]) data: FLV, EML, KNK, and LGV. All sites provided meteorological data. A site map is provided below (Figure 2). Data were obtained from the earliest starting date available for each station and compound through December 31, 2023. For NMHC and NO_x data, the starting dates range from 1997 to 2015. No station in Texas measures methane.

The sites were selected because of their location in or near (downwind of) O&G production areas (Figure 2) in Texas while considering the region’s dominant wind climatology of southeasterlies. While additional sites were available within the network of AQM stations in Texas, either their records were deemed too short or their locations were less representative for this study.

None of the analyzed sites in Texas can be considered a clean air reference site, or “background” site. A background site would need to regularly measure air masses that are representative of those advecting toward any AQM station affected by the emissions of interest driving its observations, whenever said background is not observed.

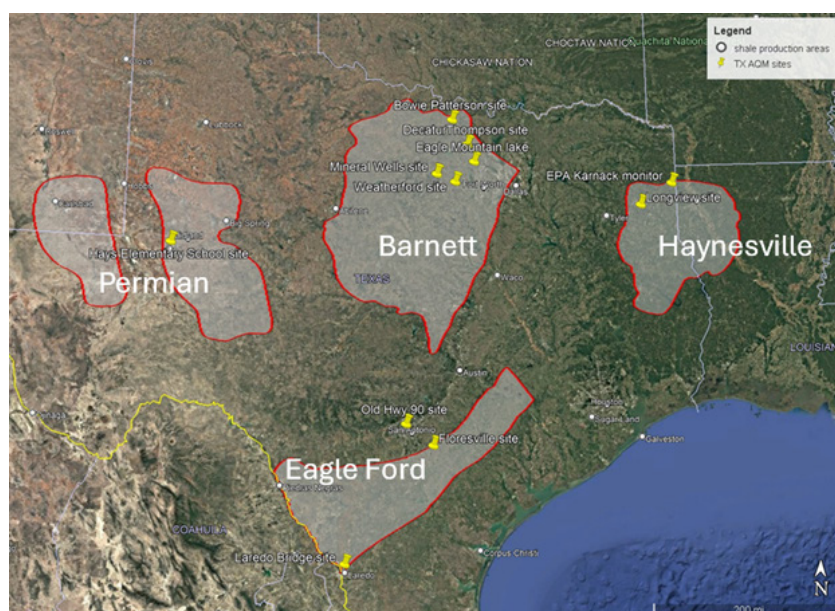


Figure 2. Site map showing all Texas air monitoring stations from which data were analyzed, as well as shale area boundaries provided as Keyhole Markup Language (KML) files by the US Energy Information Administration.

COLORADO DATA

A total of six Colorado sites were chosen for this study. Four of these sites are operated by Boulder AIR under contract with regional governments (Boulder County, City of Longmont, Town and City of Broomfield, and Town of Erie). Monitoring data from these sites includes hourly NMHC data (representing the mean of the first 10 minutes of every hour) as well as 1–10-minute resolution methane, 1–5-minute resolution NO_x , and 1-minute meteorology data. Details of the considered data are as follows:

- BRZ – Boulder Reservoir, methane one sample every 10–15 minutes, NO_x every 5 minutes (April 2017–December 2024)
- LUR – Longmont Union Reservoir, methane and NO_x at the minute level (December 2019–December 2024)
- BSE – Broomfield Soaring Eagle Park, methane and NO_x at the minute level (April 2020–December 2024)
- BNP – Broomfield North Pecos, methane at the minute level (June 2021–December 2024)
- ECC – Erie Community Center, methane and NO_x at the minute level (September 2021–December 2024)

The Colorado sites that are not operated by Boulder AIR include three regional sites with different record periods:

- BAO – Boulder Atmospheric Observatory, flask samples (one to two 5-minute samples a day) (August 2007–July 2017) (BAO NMHC data were ultimately not analyzed for trends because the sampling period covered less than 1.5 years)
- PVCO – Platteville Middle School (one to two integrated 3-hour samples every 6 days collected from 6:00 to 9:00 a.m. local time) (January 2013–December 2023)
- NCAR – National Center for Atmospheric Research site in Boulder, Fourier Transform Infrared Spectroscopy (FTIR) ethane column data (April 2010–January 2020)

For comparison of NCFR data with ambient background levels, two remote background datasets were chosen for reference:

- MLO – Mauna Loa Observatory, hourly methane measurements (April 1987–April 2024)
- CVAO – Cape Verde Atmospheric Observatory, hourly ethane and propane measurements (October 2006–August 2024)

Figure 3 shows an overview of the locations of the NCFR measurement sites on the backdrop of the DJ Basin O&G production area. Figure A2-1 shows the two reference station locations in the Northern Hemisphere, both remote oceanic locations.

We considered data spanning the time window from 2008 to 2024. Considered records cover different portions of this time, with periods of overlap, and an increasing number of records have just become available in the most recent years.

STUDY DESIGN AND METHODS

DATA QUALITY ASSURANCE

Texas NMHC Data

Data sources and acquisition procedures are described in Appendix A1. Quality assurance of NMHC data, previously validated by TCEQ, included the following: NMHC data were reported with a minimum detection limit (MDL) for each species. For benzene, i- and n-pentane, any “0” values were replaced by half the MDL. Ethane and propane should always be present in the atmosphere at levels above the detection limit, even in clean background air; therefore, any reported “0” values in the TCEQ data were excluded from the analysis and have been set to “NA” in the quality-assured “cleaned data” (referred to here as a “Level 1” or “L1” dataset). For canister data, the TCEQ-reported MDL was used. For hourly data, TCEQ did not report an MDL, and therefore, the generic MDL given

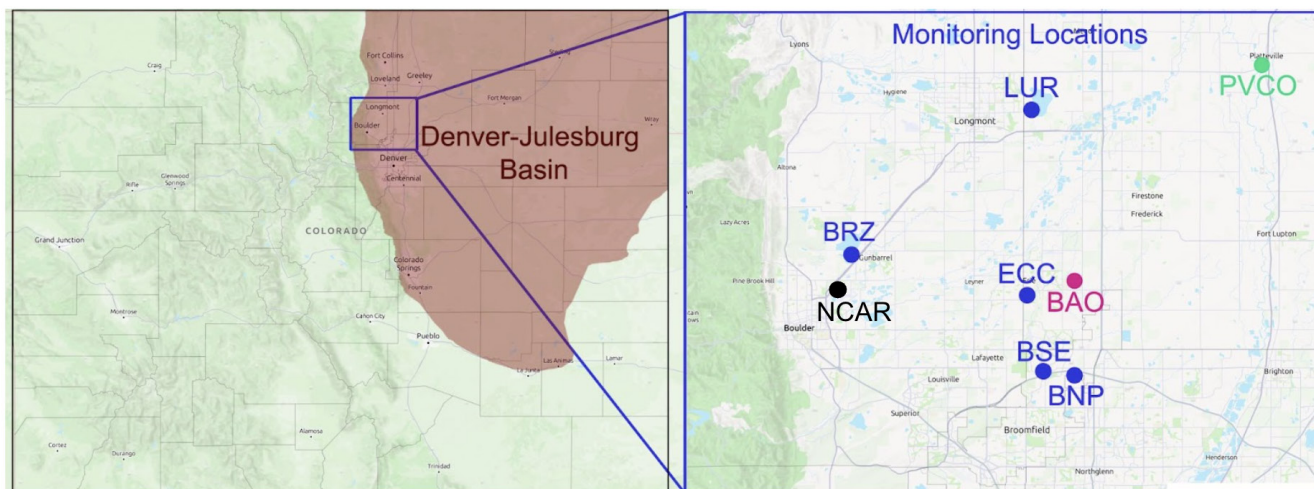


Figure 3. DJ Basin production area boundary in Colorado (left) and associated NCFR-based AQM station locations investigated for this report.

in the EPA Air Quality System database for that measurement method was used instead.

Additionally, the following curation steps were taken. From known atmospheric ethane background levels, any value <0.4 ppb from a “Level 0” (L0, or source data) dataset was excluded from the L1 dataset. The i-/n-pentane ratio in ambient air should be within a certain range, and here bounds were conservatively set from 0.35 to 4, so for any samples with an i-/n-pentane ratio outside of that range, both i- and n-pentane were removed from L1 data. Data from TCEQ contains a “Qualifiers” column for each compound. Most of these qualifiers were inconsequential in terms of data removal. However, a case existed for the only three canister sites measured at the GD Air lab (WFD, MWL, BWP), for which the benzene qualifiers were marked with blank issues coinciding with an extended period of high benzene levels. These benzene data were removed from the L1 datasets. Furthermore, singular, high-concentration outliers for any species at the start of the dataset were taken to be measurement errors and removed from L1 data.

Texas NO_x Data

Four of the TCEQ monitoring sites that were considered in this study also provided hourly NO_x (sum of NO and NO₂) data: FLV, EML, KNK, and LGV. Unfortunately, much of TCEQ’s NO_x data contains numerous negative values in both NO and NO₂ data, which are not physically possible. To clean these datasets, most of the negative values were removed from the L1 data used for analysis. In some cases, the negative values were larger and clearly delineated via step changes, suggestive of a calibration or zeroing error (Schade and Roest 2018). In these cases, all of the NO or NO₂ data from the step-change period were offset upward in relation to the size of the negative step. Throughout the quality assurance process, spline trends were fit to both L0 and L1 data to assess the effect of these quality assurance protocols on trend outcomes and to evaluate potential bias effects from our procedures.

Colorado Methane, NMHC, and NO_x Data

Monitoring data from NCFR programs, including mole fraction data of NMHC, methane, and NO_x data that were acquired by Boulder AIR, have undergone extensive quality control and assurance and are considered finalized through 2024. For monitoring results below the detection limit, values of half the MDLs are reported.

Calibration protocols rely on EPA-certified and Global Atmosphere Watch Programme gases. For the BRZ data, calibration intervals, sources, and protocols are detailed in the supplement of Helmig and colleagues (2025). Other sites follow similar protocols, listed on individual program websites in the respective Methods sections:

- BNP and BSE: <https://www.bouldair.com/broomfield.htm>
- LUR: <https://www.bouldair.com/longmont.htm>
- ECC: <https://www.bouldair.com/erie.htm>

NO_x Monitoring uses federal equivalent method (FEM) regulatory equipment and follows regulatory protocols and calibration gases. Postcollection data quality assurance protocols included reviewing diagnostic and calibration data, filtering anomalies, and analyzing occurrences near the lower detection limit. Further information is available in Boulder AIR standard operating procedures (SOPs) available at <https://drive.google.com/drive/folders/1stbK1djspt7sfgD-dg8ZkC8LOE3uU4v4O?usp=sharing>.

Methane Postcollection data quality assurance protocols included reviewing diagnostic and calibration data, filtering anomalies, and correcting for instrument drift. Further information is available in the Boulder AIR SOPs.

NMHC Data quality assurance procedures included reviewing detailed time series, evaluating extreme values and events, assessing for lower detection limit issues (such as undetected peaks) and missing values by compound, reviewing high mole fraction responses, and verifying compound ratios (e.g., i-/n-pentane, i-/n-butane) for consistency. Data corrections, when necessary, involved rare data omissions and chromatogram reintegration. Boulder AIR site sector selection was based on data collected through the first half of 2024 before the finalization of data from the third and fourth quarters. Newly finalized Boulder AIR data up to December 31, 2024, were incorporated into all trend plots.

BAO Data NOAA data included flags/codes within data files that were used for filtering erroneous samples (e.g., gas chromatography co-elution). After visual inspection of the time series graphs, no samples were omitted.

NCAR Data Ethane vertical column density (VCD) data were provided by James Hannigan and considered fully quality assured; no data filtering was done.

PVCO Data Data were provided by Alicia Fraser at CDPHE through email exchange and were considered quality assured by CDPHE. The data files included flags/codes that were used for filtering erroneous samples (e.g., co-elution). VOC data were further quality controlled by omitting samples with unexpected ratios of compounds (e.g., ethane/propane ratios above 10 and i-/n-pentane ratios below 0.5), and several samples were excluded on this basis. Inspection of the methane time series data revealed several unexpected step changes and values that were well below the atmospheric methane background at the time of sample collection. The trend determination of the PVCO data resulted in much higher mole fraction values and a steep increase in surface methane that deviated strongly from results from other sites. Similar issues were found for the ethane data. A more detailed summary of the PVCO data quality findings is provided in Appendix C. We concluded that these data were of insufficient quality for consideration in this work and omitted them from further analyses.

Remote Site Reference Data

MLO Data NOAA (methane) data files included flags/codes that were used for filtering known erroneous samples (e.g., co-elution). After visual inspection, only one low value below 1,850 ppb in early 2024 was additionally excluded.

CVAO Data Preliminary NMHC data were provided by the University of York (Prof. Alistair Lewis); ethane data were visually inspected and quality assured based on ratios of compounds. No samples were omitted.

These reference data were used and shown in this report alongside data from Colorado. They apply equally to the Texas data because they constitute estimates of northern hemispheric background levels.

TEXAS TREND ANALYSIS: NATURAL CUBIC SPLINES

Data fitting and trend analysis for the Texas data have been carried out using *cubic splines* implemented with the R *splines2* package (Version 0.5.3). By fitting piecewise cubic polynomials, cubic splines can model complex patterns while avoiding overfitting or fitting oscillations associated with higher-degree polynomials. For time series trends, the “wiggleness” or smoothness of the fit can be controlled by the number of *knots* between the piecewise cubic polynomials, thus allowing the assessment of trends on shorter (more knots) or longer (fewer knots) timescales. Additionally, seasonal patterns captured by the splines can vary from year to year.

Both B-splines and natural splines were tested, which yielded nearly identical curves in the central part of the data. However, the B-splines had more erratic or extreme behavior at the data boundaries, the dataset’s start and end dates. Natural splines produce more consistent behavior at the boundaries, leading to smoother transitions there, which is why they were selected.

We used three gradations of curve variability (smoothness) to fit the data to account for various timescales of influence: the “fine fit” captures shorter-term intra-annual variations; the “seasonal fit” captures the seasonality and variations between the seasonality in different years; and the “trend fit” captures longer-term changes. The difference in smoothness in each of the curves we present is controlled by the location and frequency of the spline *knots*. Because spline knots are the junction between piecewise polynomials, they are placed at the junctions where behavior might be expected to change or where changes in behavior are to be captured (de Boor 2001). *Knots* were spaced evenly throughout the dataset. The “fine” trend had either 12 (hourly data) or 8 (canister data) knots/yr. The “seasonal” trend had 4 knots/yr. The “trend” fit used 1 knot/yr. After testing knots at 1-, 1.5-, and 2-year intervals, the greater variation captured with the 1 knot/yr interval appeared most appropriate given the timescales of changes in the O&G industry and any regulatory effects.

Although natural splines were chosen for their extra constraints at the boundaries (start and end of data), even the

smoothest “trend” fits can be influenced by data behavior at these points, potentially leading to misinterpretation of trends immediately before or after the dataset time range. To eliminate such exaggerated boundary effects, the defined spline boundary for the “trend” spline fitting was inset by one-quarter year, softening any extreme trend behavior at the start and end of the datasets. Despite this adjustment, extrapolation of the curve outside the dataset should be interpreted with caution. Testing with deseasonalized data (Appendix A1) showed that the seasonal cycle did not cause anomalous behavior in the “trend” estimate, including at the boundaries, as spline fits using deseasonalized data were nearly the same as those using the original data with a seasonal cycle.

The Texas NMHC data, as with most such data, display a log-normal distribution. Therefore, the spline “trend” fit was also assessed on a log scale and for different quantiles as detailed in Appendix A1. Fitting the “trend” to the data on a log scale and for different quantiles had little effect on the overall trend behavior and supports the conclusion that the trend lines presented here are representative of the overall data trend.

In contrast to Colorado (see below), a linear regression slope analysis was not performed for any of the Texas data because no consistent, monotonic trend was present, as observed in the generally shorter Colorado datasets.

COLORADO TREND ANALYSIS: NOAA FAST FOURIER TRANSFORM CURVE-FITTING TOOL

We utilized NOAA’s Fast Fourier Transform (FFT) curve-fitting routine, which was specifically developed to analyze continuous monitoring data that exhibit seasonal cycles, for the Colorado trend analysis. The NOAA FFT trend analysis routine is a well-established method, originating with Thoning and colleagues (1989), and has been steadily refined since its introduction. The tool provides outputs that separate long-term growth, seasonality, and short-term variability in greenhouse gas records. The implementation used here follows the version maintained by NOAA’s Global Monitoring Laboratory and has been widely adopted for analyzing changes in atmospheric composition over the past three decades (Angot et al. 2021; Helmig et al. 2016, 2025).

For numerical analysis of deseasonalized trends, the FFT trend analysis tool has been applied to the individual site data. Input data were first approximated by a generalized least-squares fit (purple “Fit” line in the example shown in **Figure 4**) that combines three polynomial terms (i.e., quadratic) with two annual harmonics, thereby capturing both long-term growth and the mean seasonal cycle. Residuals from this fit are transformed to the frequency domain, multiplied by two Gaussian low-pass filters — one with a full width at half-maximum of 667 days to isolate multiyear variability and another with a 50-day full width at half-maximum to retain the seasonal signal while suppressing subseasonal noise — and then returned to the time domain through an inverse FFT. Adding the 50-day-filtered residuals back to the

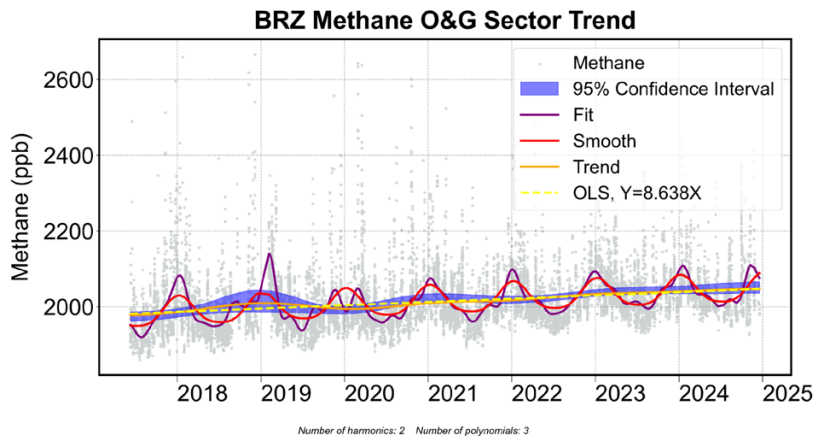


Figure 4. Original data (gray) with NOAA tool outputs fit (purple), smooth (red), trend (orange), and trend bounds (blue shading). In addition, an ordinary least-squares regression line fit (dashed yellow) to the long-term trend is shown. The Y-axis is restricted to highlight trend behaviors. The shaded blue area depicts a Monte Carlo simulation–determined uncertainty in the NOAA trend output (see description in the text).

full fit yields the “Smooth” curve (red “Smooth” line in Figure 4), which removes short-term oscillations yet preserves seasonality, whereas combining the 667-day-filtered residuals with only the polynomial component produces the “trend” curve (orange “Trend” line in Figure 4) that tracks long-term changes and is accompanied by its 95% confidence envelope (blue shading in Figure 4). Figures with blue confidence intervals (Figure 4) used a simulation-based method for confidence interval determination, whereas trends using orange confidence intervals (e.g., Figure 35) were produced using a generalized approach, leading to a constant confidence interval over the entire data record. Blue confidence intervals were computed for species for which the generalized method significantly overestimated the error range of the model and **where pointwise error estimation was relevant to the figure’s interpretation.** Because the FFT requires equally spaced data, running the program results in gaps being filled by linear interpolation at the user-specified sampling interval before the transform is applied. Further details can be found at <https://gml.noaa.gov/ccgg/mbf/crvfit/crvfit.html>. To produce the tool outputs, the NOAA trend tool scripts CCGCRV (Carbon Cycle Group curve-fitting routine) were downloaded locally. A Python script was constructed to run the tool using command-line prompts, save solutions, and load outputs into Python (Version 3.12.0) for analysis. The driver program (ccg-crv.py) was prompted using arguments detailed in the ccgcrv.pdf file found on the CCGCRV-dedicated NOAA GML web page (<https://gml.noaa.gov/aftp/user/thoning/ccgcrv/>), along with all other relevant script files (retrieved 2023).

The program outputs the following solutions in numerical format:

- **Function Fit:** The function fit approximates both the long-term growth and the annual cyclical variations in the data. This fit serves as a baseline from which other variations are extracted.
- **Smooth Curve:** The smooth curve represents the original data after removing short-term, transient fluctuations (such as daily or weekly variability). It combines the *function fit* and the residuals filtered using the short-term cutoff

frequency — with a default of 50 days — to preserve major seasonal signals while clearly highlighting interseasonal variations.

- **Trend Curve:** The trend curve isolates the long-term growth in species mole fractions, excluding both seasonal cycles and short-term variations. It consists of the polynomial portion of the *function fit* combined with residuals filtered at the long-term cutoff frequency — a default of 667 days. This component best approximates the underlying long-term increase or decrease in atmospheric concentrations over multiple years.

The 95% confidence interval around the trend function was estimated using a block-bootstrapped Monte Carlo simulation. An autocorrelation function analysis, which quantifies the correlation between sequential observations in a time series, indicated that residuals remained temporally correlated over approximately 4 days, thereby defining the bootstrap block length. In addition, monthly and yearly heteroskedasticity observed in the time series required that random variance be sampled within month-year bins. Heteroskedasticity refers to nonconstant variance over time. In this case, the residual variance tended to decrease over successive years while also exhibiting seasonal (monthly) fluctuations driven by natural meteorological and chemical cycles.

Synthetic datasets were generated by appending randomly selected, month-year–standardized residuals in 4-day blocks to the fit function produced by the NOAA trend analysis tool. Residuals were computed as the difference between the fit function and the raw observations, then standardized by their corresponding month-year variance. This procedure produced synthetic datasets with variance distributions comparable to those of the observed data.

A total of 1,000 randomized datasets were generated and re-fit using the NOAA tool. For each iteration, the resulting trend component was stored. Finally, for each time step, the 2.5 and 97.5 percentiles of the ensemble of 1,000 trend estimates were used to construct a pointwise 95% confidence interval around the estimated trend.

We expanded these output solutions with an ordinary least-squares (OLS) regression line; a linear fit (yellow dashed line in Figure 4) was applied to the NOAA *trend curve* to calculate a single slope estimate for the rate of concentration change over time for each monitored compound. All OLS regression lines for the Colorado analyses were calculated using the NOAA *trend curve* output as the response variable and time as the predictor. We note that concentration changes are not constant from year to year but vary depending on actual changes in emissions and air transport, meteorology, and chemistry. Thus, the regression line is a simplification of the actual year-to-year increase/decrease in concentration. It was found to be a useful tool, however, for comparing data from different sites and for gauging averaged, long-term changes in atmospheric concentrations over selected time windows.

Uncertainty of the OLS trend determination results from contributions to the monitoring data uncertainty, the NOAA trend outputs, and the OLS calculation. Uncertainty in the OLS slope estimates is given as 95% confidence intervals on some individual site trend graphs, and in selected regression data tables in the Results section of this chapter.

OIL AND GAS SECTOR SUBSETTING

Texas Sites

Subsetting NMHC data into O&G and non-O&G “clean” air mass origin sectors was attempted for the Eagle Ford and Haynesville Shale regions. The Permian and Barnett Shale region sites are surrounded by O&G activity, making it impossible to delineate a “clean” sector. O&G and non-O&G wind sectors for each site were defined, given the relative location of the shale and the presence of O&G wells. Further data visualization and trend-fitting refined these sectors.

As done for the Colorado sites, hourly NMHC data at FLV (Eagle Ford Shale) were subsetting into an O&G and non-O&G “clean” sector using concurrent hourly FLV wind direction and speed data. Sector sizes were tested to avoid excluding data

to an extent not amenable to trend analysis, and to maximize differences between the O&G and “clean” sectors. The latter, however, are ill-defined for the Eagle Ford and Haynesville shales in Texas, as air masses nearly always advect from either urban areas or another, more distant shale oil and gas production region.

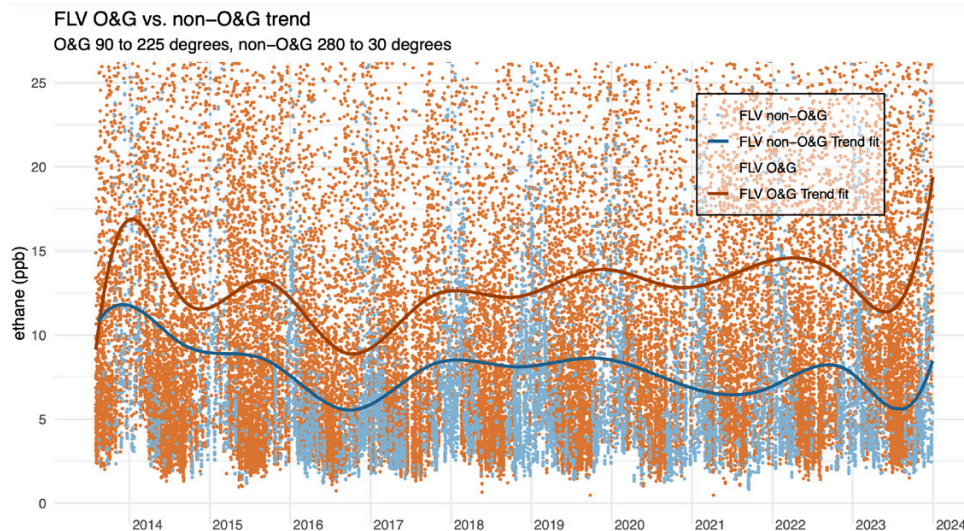
As an example, **Figure 5** shows the raw data and trends for the FLV site. Although clear abundance differences between sectors are visible, the long-term trends are similar. Subsetting for canister sites (one 24-hour canister every 6 days) was attempted for the Karnack (KNK), and Longview (LGV; both Haynesville), Old Highway 90 (OLN), and Laredo (LRB; both Eagle Ford) sites. Because samples at those sites were collected over 24 hours, the coinciding 24 hours of locally measured 1-hour wind data were used. Canister samples with 75% or more of 1-hour winds over the 24-hour sample period from a given shale production sector were categorized as “O&G.” For some sites or sectors, this criterion was dropped to 70% or 60% to retain a critical number of data points to allow for trend analysis.

Because the samples were collected for 24 hours, over which the air mass origin can vary, and because of the prevalence of O&G activity in Texas and around these sites, we generally found that the canister sites showed little difference between attempts at selecting “O&G sector days” and “non-O&G sector days.” Only for the Karnack site shown in **Figure 6** did we find differences between the defined sectors, mostly during the period of its increased high NMHC events from 2004 to 2011.

Colorado Sites

For each site, data were investigated for characteristic air mass signatures by generating pollution roses, bivariate plots, and O&G well maps. Examples of bivariate plot results for ethane are presented in **Figure 7**. These analyses yielded initial sector definitions categorizing an NCFR site’s wind sector as either “clean” (i.e., background or non-O&G, western air mass origin indicating little or no O&G exploration influence) or

Figure 5. “Clean” versus “O&G” sector differences and trends for the FLV site. Note that wind directions tend to be seasonal (almost exclusively southerly during summers). In addition, the described boundary effect at the start and end of the time series shows in both trends. All wind speeds >1 m/s.



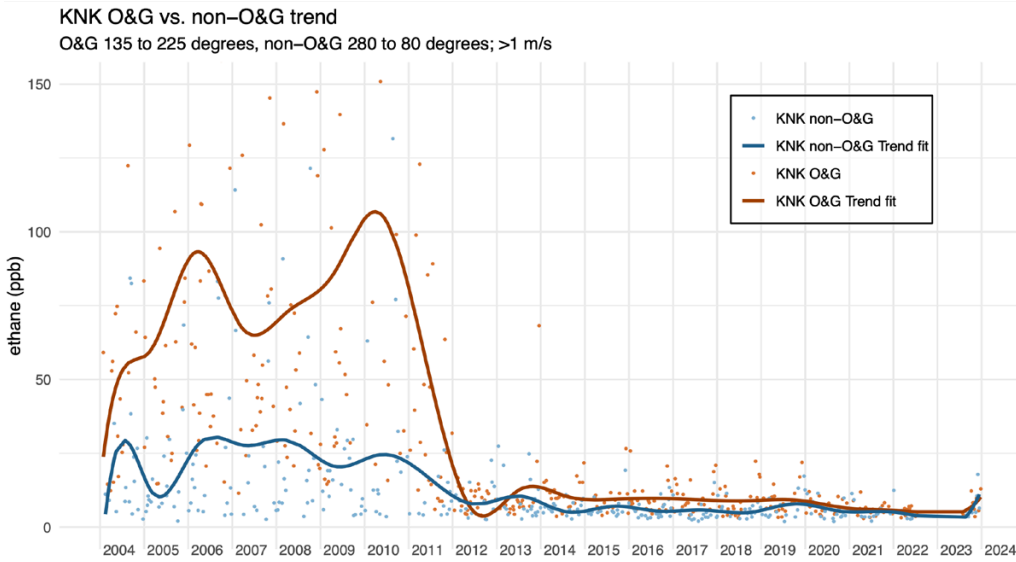


Figure 6. Ethane data and their long-term trends at the KNK site when subsetted by air mass origin sectors (see text).

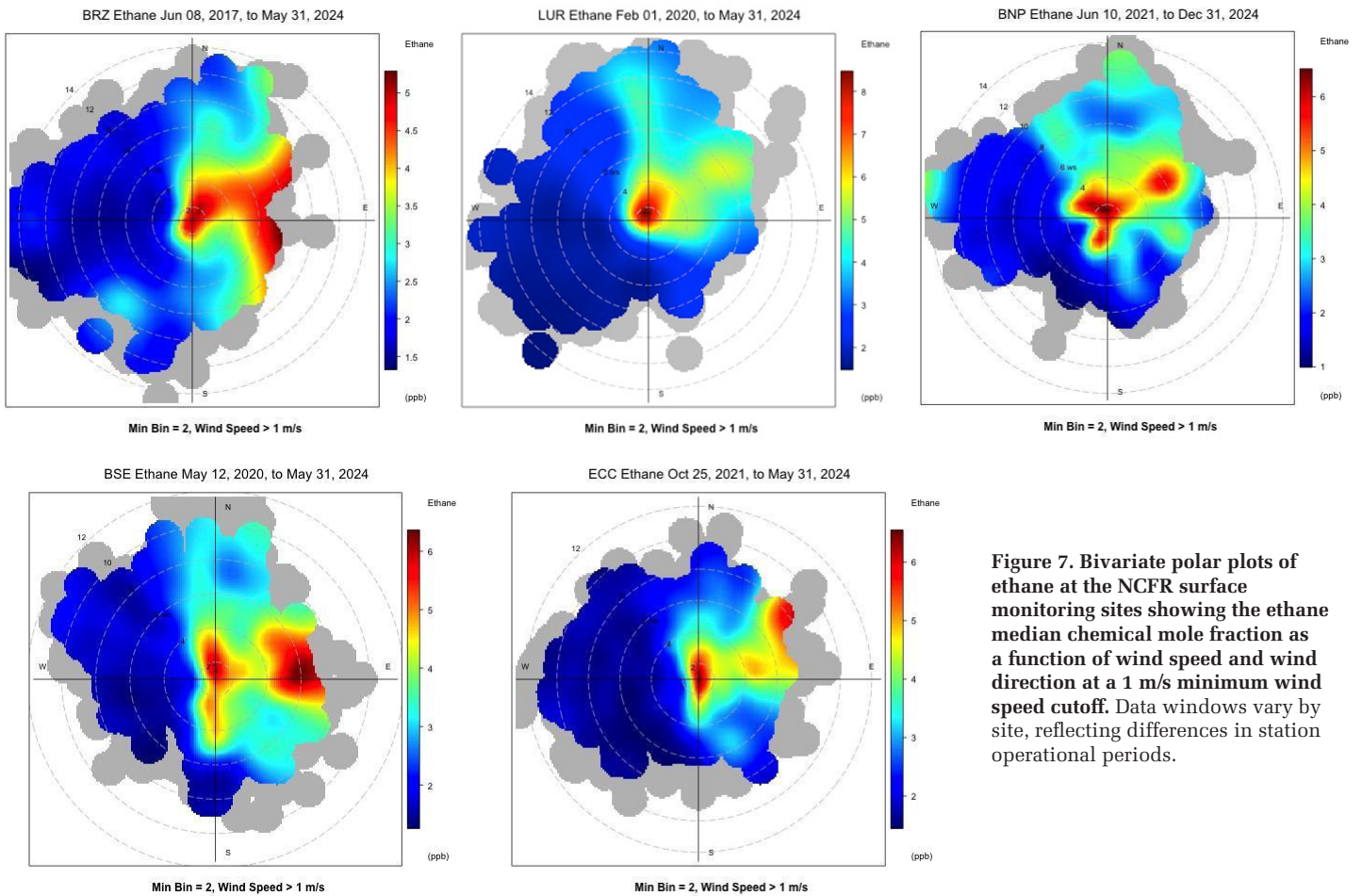


Figure 7. Bivariate polar plots of ethane at the NCFR surface monitoring sites showing the ethane median chemical mole fraction as a function of wind speed and wind direction at a 1 m/s minimum wind speed cutoff. Data windows vary by site, reflecting differences in station operational periods.

“O&G” (indicating strong O&G exploration influence). Across all sites, ethane mole fractions showed a clear dependence on wind speed and wind directions, with average values 2 to 5 times higher in air transported from the northeast sector than in air from other wind directions. Results for the five monitoring sites considered were similar, albeit with subtle differences in the sector boundaries. The highest enhancements were always seen at lower wind speeds, although the wind sectors were ill-defined under those conditions. These initial sector assumptions were evaluated with plots of monthly median ethane mole fractions by sector. Small variations in sector size and shifts in wind direction often produced slightly different results, and western clean sector choices were not consistently immune from high pollutant (e.g., ethane) levels, especially at lower wind speeds. Further details are discussed in Appendix A2, with results shown in Appendix C2.

To more robustly define sectors beyond visual examination, two algorithms were developed and modified for each site: (1) a simple optimization algorithm to maximize the difference between the monthly median ethane values between non-O&G and O&G sectors, and (2) a Monte Carlo-style algorithm to incorporate the *i*-*n*-pentane ratio as a cutoff filter, ranking the best options, to confirm final sector choices (details in Appendix A2). The final sector boundaries subsequently applied to segregate the data are summarized in **Table 2**.

Table 2. Final Sector Boundary Selections

Site	Western	Oil and Gas
BSE	190°–290°	330°–110°
BRZ	200°–320°	350°–90°
ECC	200°–290°	350°–90°
LUR	190°–280°	350°–90°
BNP	170°–270°	300°–60°

Our analyses demonstrated that sector choices for all Boulder AIR site data exhibited clear distinctions in O&G indicators. Ethane and *i*-*n*-pentane ratio sector comparison plots (**Figure 8**) showed the distinct differences between wind sectors, especially as wind speed minima were increased, allowing for a more robust directional signal. For instance, for ethane at the LUR site, any monthly median maxima in the western sector (red lines in Figure 8) became consistently smaller once minimum wind speeds above 2–3 m/s were used. For the BRZ site’s *i*-*n*-pentane ratio, minimum wind speed cutoffs did not significantly affect the western sector’s monthly median ratios; however, the O&G sector’s medians consistently increased with higher cutoffs (**Figure 9**).

Wind sector differences in benzene and NO_x data were less well defined compared with methane, ethane, and propane. Therefore, the data of these two gases were not differentiated by wind direction.

The suitability of local meteorological data for identifying wind direction sectors and air transport was further investigated by comparing these analyses with NOAA’s HYSPLIT (HYbrid Single-Particle Lagrangian Integrated Trajectory, version win64U 5.0.0b) air trajectory model outputs, a well-established tool in the meteorological community. Detailed results are available in Appendix A. The exercise provided further evidence in support of the use of locally measured wind data for wind sector determination.

Trend Method Comparison: Spline Curve-Fitting Versus NOAA Trend Tool

Two trend-fitting methods were used in this analysis that could potentially lead to differences in trend output. The NOAA trend tool represents the long-term trend by a third-degree polynomial function and the seasonal oscillation by a harmonic on an annual cycle, and additional harmonics for any subseasonal cycles. In contrast, spline curve fitting uses piecewise third-degree polynomials, with varying knots between the polynomials to represent the long-term and seasonal trends. When the seasonal cycle is represented with a harmonic component, it repeats identically from year to year rather than allowing for interannual variation, thus assuming a uniform cycle and not accounting for existing interannual changes in the variable driving atmospheric abundance. In comparison, the spline method does not make such an assumption about a fixed seasonal cycle. Both trend determination methods may struggle with shorter time series as the polynomial term of the function can be unduly influenced by seasonality; however, for the spline method, this effect occurs primarily at the boundaries. For both methods, the complexity of the fit is influenced by the degree of the polynomial and the number of harmonics or, respectively, the number and location of knots. However, while splines can fit varying complexity over the time series (cf., e.g., Figure 22), extraneous oscillations can occur when using higher-degree polynomials (de Boor 2001).

To evaluate the methods’ performance, we directly inter-compared their outputs to assess the agreement and fidelity of trend results obtained using the hourly ethane datasets from the Texas FLV site and the Colorado LUR site (Appendix A). **Figure 10a** shows the NOAA trend tool results, whereas **Figure 10b** shows the results using the natural cubic spline fit. **Figure 10c** shows the long-term trend results from both methodologies. The similarities between the results are evident, with respect to the fine trend, the seasonal (periodic) smooth trend line (red in Figure 10a, orange in 10b), and the long-term trends (orange in Figure 10a, blue in Figure 10b). Apparent differences manifest in a fixed seasonal cycle using the NOAA tool versus a year-to-year variation in seasonality using splines. Only slightly different are the “fine” fits (purple in Figure 10a vs. green in Figure 10b), with similar amplitudes generated. Slight differences in the long-term trend (Figure 10c) also exist; however, the overall trend is very similar.

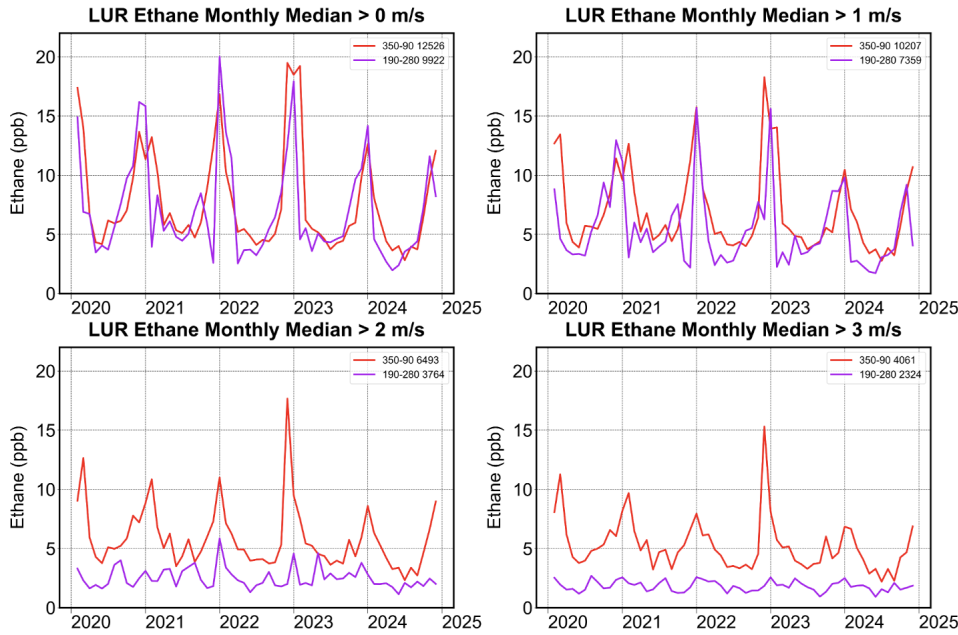


Figure 8. Western non-O&G (190°–280°) versus O&G (350°–90°) sector comparisons for monthly median ethane at the LUR site when locally measured winds exceed different thresholds, including the number of observations available for each sector’s bounds.

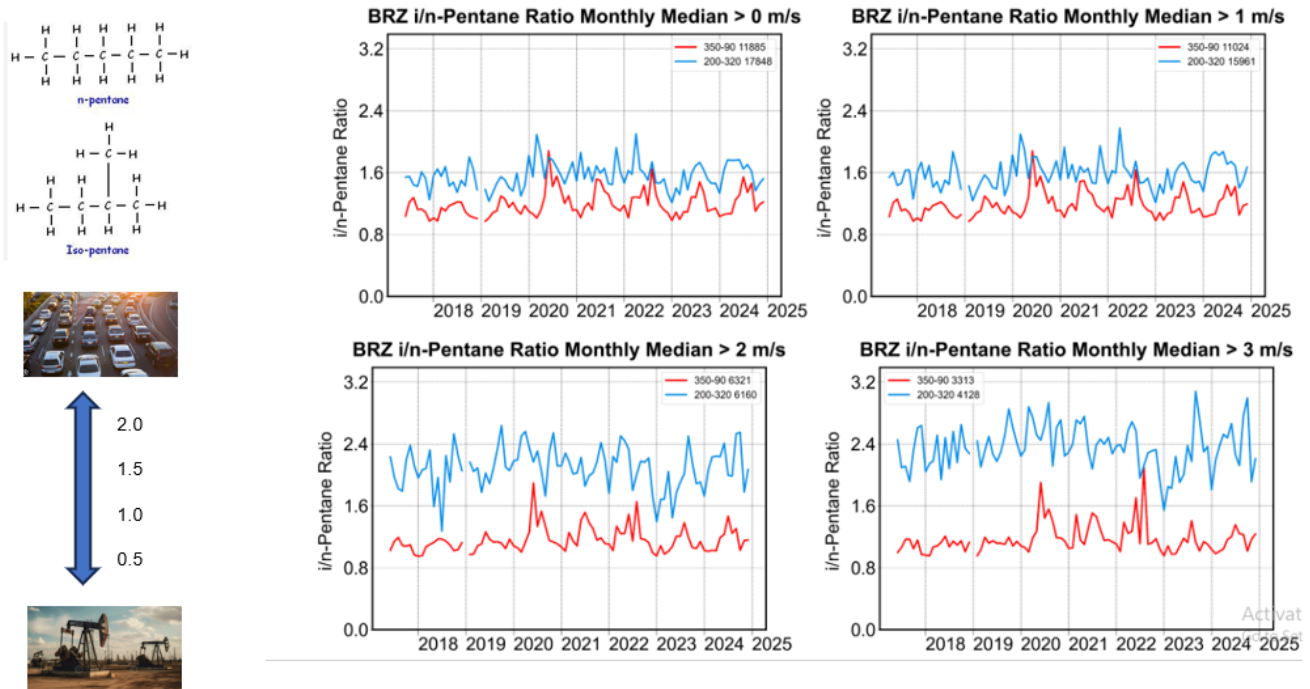


Figure 9. West sector (non-O&G) “background” air (200°–320°) versus east, O&G (350°–90°) comparison for monthly median i/n-pentane ratios at the BRZ site, filtered by increasing wind speed cutoff. The number of observations available for each sector’s bounds is indicated in the figures’ legends. The left side of the figure shows the two pentane isomers and a scale of observed ratios depending on the emissions source.

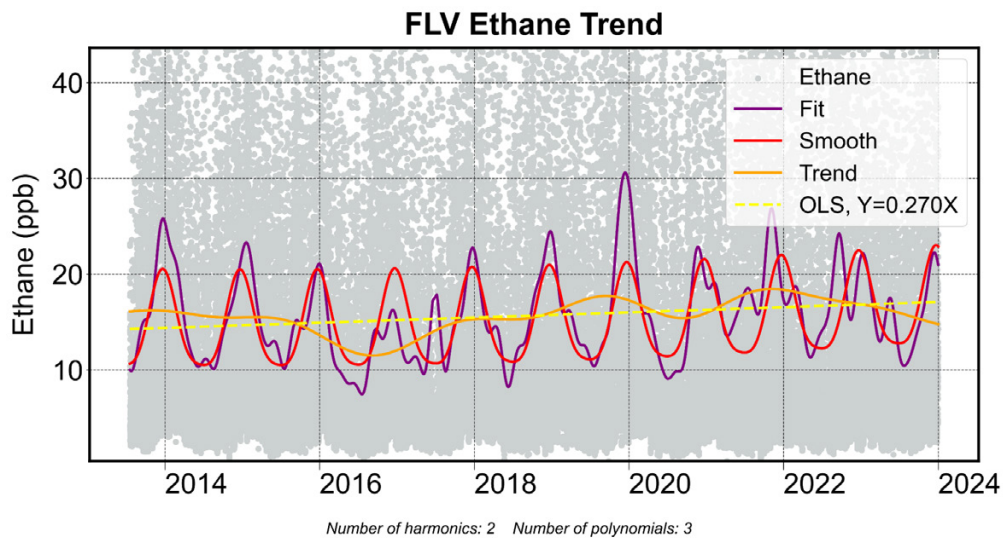


Figure 10a. NOAA trends tool applied to FLV site ethane data (gray dots).

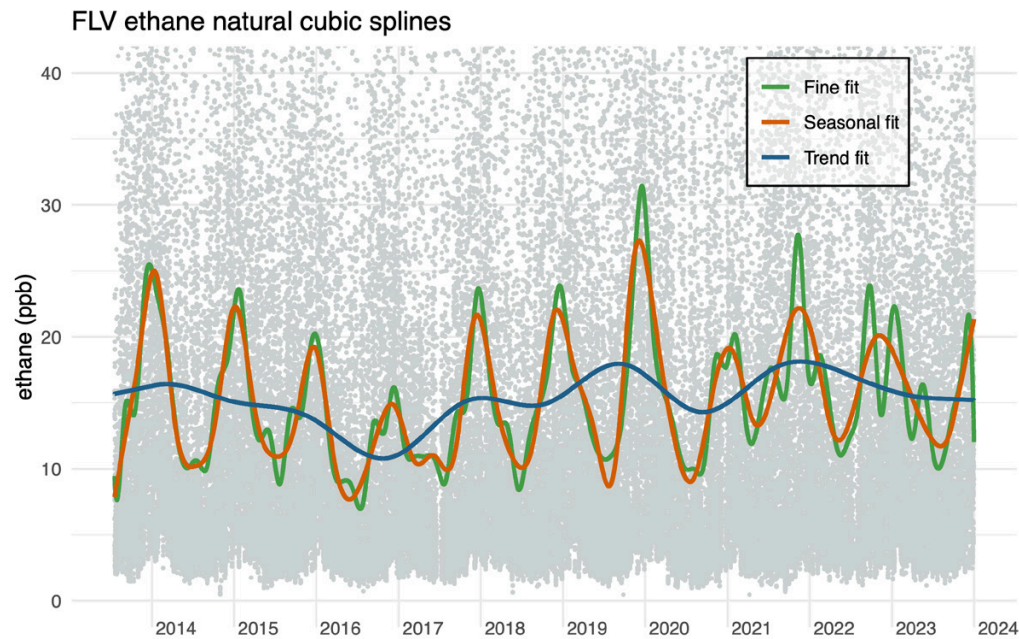


Figure 10b. Natural splines trends fit tool applied to same FLV site ethane data (gray dots).

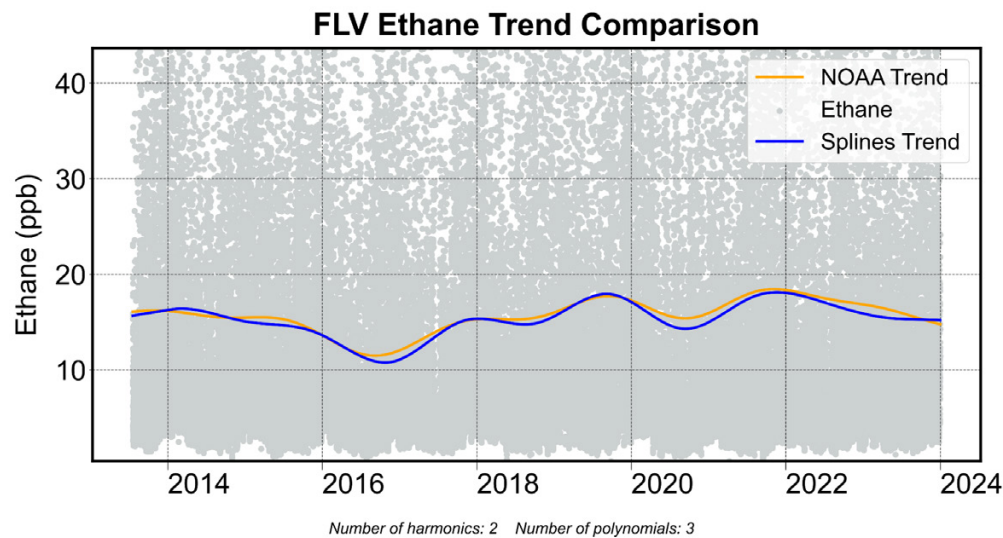


Figure 10c. NOAA long-term trend fit (orange line) compared with the natural splines trends fit (blue line) over the hourly ethane data (gray dots).

NON-NEGATIVE MATRIX FACTORIZATION ANALYSIS

For several Texas sites for which the wind sector analysis was not a successful tool, we carried out a Non-negative Matrix Factorization (NMF) analysis using the NMF package in *R* (Gaujoux and Seoighe 2010), version 4.4.2. NMF is a widely used mathematical tool to decompose data (in our case, the time series data) into its underlying *factors*. NMF has been used in air quality analyses to provide a source apportionment, which both identifies air pollutant sources and provides semi-quantitative source contributions (Begum et al. 2005; Guha et al. 2015; Schade and Roest 2018).

NMF decomposes the air pollutant time series dataset (a matrix, typically denoted \mathbf{X}) into a set of source profiles (the *factors*) and their respective contributions while ensuring that all values remain non-negative, a physical constraint. Generally, \mathbf{V} is an approximation of the product of a basis matrix \mathbf{W} , which consists of the source profiles, and a coefficient matrix \mathbf{H} , which defines the source contributions: $\mathbf{X} \cong \mathbf{V} = \mathbf{W} \times \mathbf{H}$. Through NMF, we minimize a loss function to find \mathbf{W} and \mathbf{H} such that their product (\mathbf{V}) best approximates \mathbf{X} while ensuring all elements remain non-negative. The NMF operator chooses the number of factors, called the rank k , a priori to represent the number of emission sources to extract. For a given k , if \mathbf{V} has dimension mn , then \mathbf{W} is mk and \mathbf{H} is kn .

NMF has been used by air quality researchers examining chemical speciation of particulate matter concentrations to extract source signatures such as traffic emissions, industrial activities, or biomass burning (Chan et al. 2008; Guha et al. 2015). In the context of studying O&G activity-related air pollution, our previous work using NMF on 2015 data collected in the Eagle Ford Shale revealed six consistent source factors, of which two were associated with preexisting local sources from car traffic and industry, three with regional O&G exploration, and one with diesel combustion emissions (Schade and Roest 2018).

For this study, we conducted NMF on data from several canister sites. The canister datasets for these Texas sites are described by Ethridge and colleagues (2015). We chose a subset of the more than 60 measured compounds, including several chlorinated species such as chlorofluorocarbons, in each set, making the following modifications:

1. Compounds with few data above their detection limits were removed (e.g., ketones).
2. Isomers with many nondetect observations were combined into a single species with fewer nondetect observations (i.e., ethyl-toluenes and trimethylbenzenes).
3. All nondetect observations were replaced with one-half the compound's detection limit.
4. Outliers for individual compounds were reduced by a factor of 2, and occasionally missing data in a time series were replaced by the time series' median, both to avoid individual observations dominating a compound's variance.

More details are provided in Appendix A. The goal of these modifications was to create a consistent set of nonzero data that would allow us to apply the NMF to extract a factor representing the O&G source present at the site. As this dataset still consisted of compounds with widely different abundances, variances, and measurement uncertainties, we further applied a normalization (Guha et al. 2015; Schade and Roest 2018):

5. Each component of \mathbf{X} was normalized using its minimum and maximum values through $X_{\text{norm}} = (X - X_{\text{min}})/(X_{\text{max}} - X_{\text{min}})$, which removes the background and results in all concentrations falling into the range $[0,1]$ while ensuring no negative values.

After this preprocessing, we applied NMF using both random and non-negative double singular value decomposition seeding with standard Kullback-Leibler (KL) divergence as the loss function. We also applied a least-squares-based loss function including uncertainty-based weighting of the data. Both methods provided similar outcomes in all cases, but factor relevance (and order) was often different depending on the loss function, and in some cases, a factor identified by one method (KL) was absent in the results from the other method (least-squares).

We report results from runs using $k = 5,6$ on 47–60 compounds, depending on site (Appendix A). Uncertainty was gauged using evaluations of (1) how much of the original dataset's (\mathbf{X}) variance was explained by the estimate (\mathbf{V}) and its factors, and (2) how much of the "background" factor, which in all \mathbf{H} consisted of the set of chlorinated species maintained in \mathbf{X} , consisted of nonbackground factor species.

RESULTS

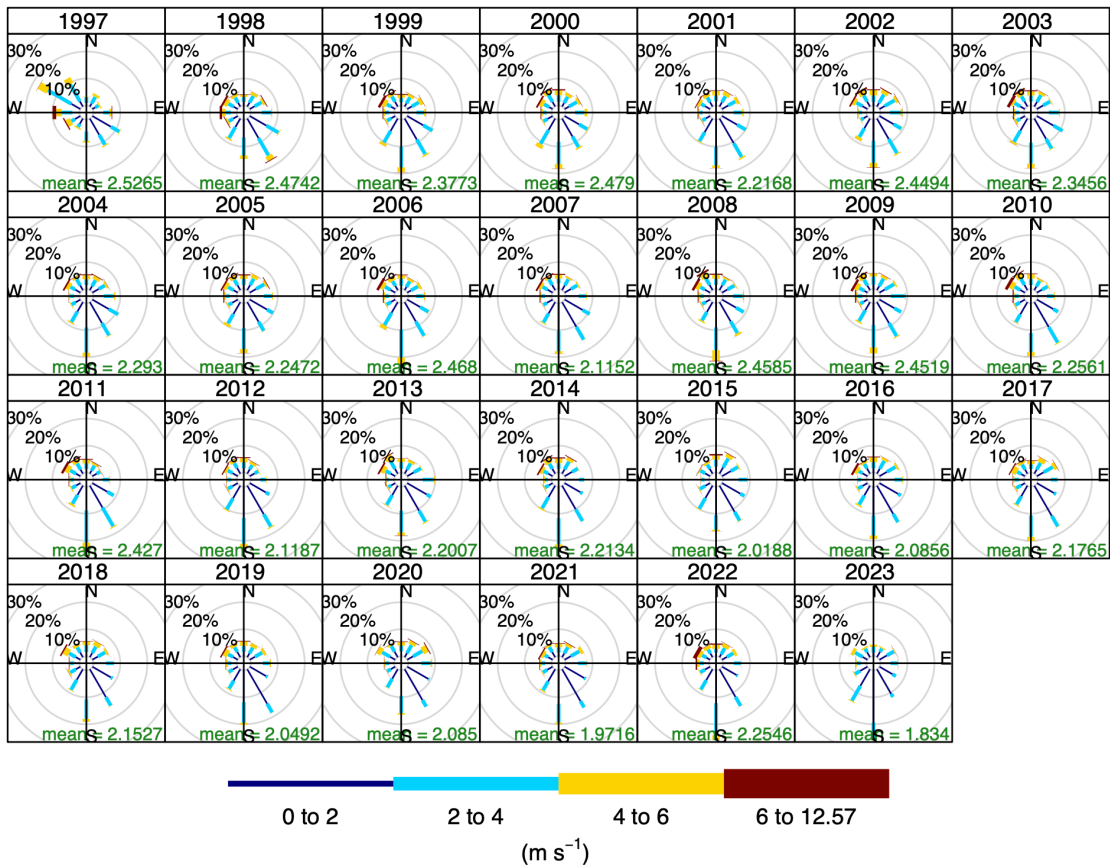
TREND RESULTS FOR TEXAS SITES

Wind Patterns

Hourly wind data from each Texas site were investigated for trends that might affect NMHC measurements, such as changes in the origin of air masses reaching each monitoring site. In general, the Texas sites showed no particular wind patterns from year to year (i.e., reproducible wind conditions with some interannual variability). **Figure 11 (Panel A)** shows wind roses for the LGV site, the site with the longest record, thereby demonstrating these steady conditions with slight interannual variations. An anomaly in wind climatology existed in northern Texas from 2008 to 2014 with slightly stronger winds, which pertained to the Barnett Shale region. Of the five Barnett Shale sites, BWP, MWL, and WFD initiated NMHC data collection in mid- to late-2013, so they are little affected by this wind anomaly. The Decatur Thompson (DCT) and Eagle Mountain Lake (EML) sites began NMHC sampling in 2010, so the first few years of these two sites were affected by a slightly higher frequency of southerly winds and higher mean wind speeds, as seen in the wind roses for EML in **Figure 11 (Panel B)**. Yearly wind roses for the other nine sites, not shown here, can be found in Appendix C.

A

LGV wind roses by year



B

Frequency of counts by wind direction (%)

EML wind roses by year

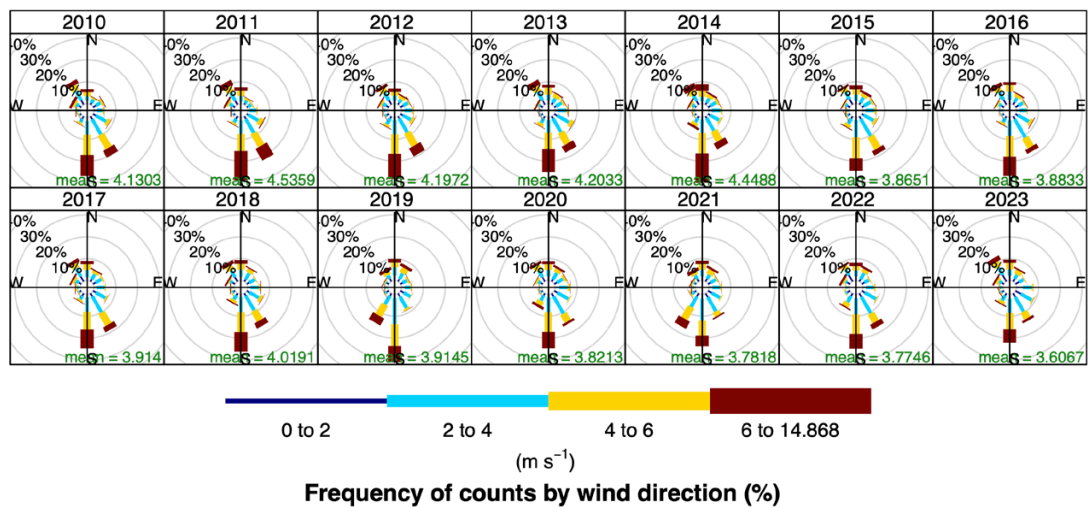


Figure 11. (A) Wind roses for the Texas LGV site, the site with the longest record investigated, located at the edge of the Haynesville Shale; (B) wind roses for the EML site, the Barnett Shale.

Barnett Shale Trends

Long-term ethane abundance trends for all Barnett Shale sites tended to be similar, and we show all five sites together in **Figure 12**. Most of the trends' uncertainty ranges (confidence intervals) overlapped. More detailed Barnett Shale site trend plots, including confidence intervals, are shown in Appendix C. The two sites with the longest records, DCT and EML (blue and orange lines in Figure 12), showed slight, long-term downward trends that were statistically significant. In turn, we observed a slight upward, barely statistically significant, trend at the BWP site (green line in Figure 12). No long-term trend was observed at the other two sites, MWL and WFD. Overall, ambient ethane, propane, and benzene trends in the Barnett Shale did not reflect substantial changes in air quality over time.

Barnett Shale O&G production is dominated by gas production at gas wells, peaking in 2011–2012, followed by a slow, steady decline (~10%/yr) since then (**Figure 13**). Condensate production (liquid hydrocarbons condensed out of natural gas at atmospheric pressures) at gas wells peaked in late 2011, showing a similar decline thereafter. Gas production at oil wells (“casinghead gas”) represents a small fraction of total gas production, which peaked several years later; however, in 2015, 1 to 2 years after oil production peaked (2013–2014). Liquids storage in condensate and oil tank batteries was previously identified through research sponsored by TCEQ as a significant source of hydrocarbon emissions in the Barnett Shale area (Ethridge et al. 2015); <https://www.tceq.texas.gov/airquality/barnettshale/bshale-next>.

The EML Barnett Shale site is of special interest because of its longer record and high data density (hourly measurements). Ambient ethane, propane, and benzene (and NO_x) mixing ratios measured at EML showed similar long-term trends, peaking in 2012, followed by a general decline into the late 2010s, then leveling off (**Figure 14**). Pearson correlations between monthly mean spline trend values and monthly production show these trends are moderately correlated with the Barnett Shale gas production data, with a peak in 2012 followed by a steady decline (propane $r = 0.68$, benzene $r = 0.61$, ethane $r = 0.52$), as well as related condensate production (propane $r = 0.69$, benzene $r = 0.68$, ethane $r = 0.51$). Correlations of ethane, propane, and benzene levels with oil production are stronger (propane $r = 0.84$, benzene $r = 0.75$, ethane $r = 0.70$). Furthermore, as illustrated for ethane and benzene in Appendix Figure C1-2, the compound trends held across different quantiles of the data and log-scale fitting; fitting deseasonalized data also did not alter the basic long-term trend. NO_x data from this site (Figure 14b) broadly followed the NMHC trend, but with less pronounced maxima and minima.

A noticeable uptick in benzene (and long-lived ethane and propane, but not short-lived NO_x) was observed in 2019–2020. While no changes in production volumes were observed during that period, two other developments may have contributed to this temporary NMHC increase at EML: (1) hydrocarbon

production peaked in the Eagle Ford Shale (Figure 18) and in the Permian Basin (Figure 44) in fall/winter 2019, and possible long-range transport of higher hydrocarbon emissions may have contributed to abundances in the Barnett Shale area; and (2) the onset of the COVID-19 pandemic in spring 2020 may have altered company practices because of the widespread shutdowns and economic disruptions at the time, possibly leading to increased local hydrocarbon emissions.

Similar results were obtained for the DCT site (**Figure 15**) in Wise County, also an hourly NMHC measurement site. Long-term downward NMHC trends at DCT (Appendix C) were also correlated with decreasing Barnett Shale gas, condensate, and oil production data. Pearson correlations were generally stronger at DCT than at EML (oil: propane $r = 0.84$, ethane $r = 0.83$, benzene $r = 0.65$; gas: propane $r = 0.93$, ethane $r = 0.85$, benzene $r = 0.91$; condensate: propane $r = 0.90$, ethane $r = 0.77$, benzene $r = 0.84$). Peak ethane and propane levels occurred in 2013–2014, whereas peak benzene levels occurred in 2010–2011. These differences may have been driven locally, as both gas and condensate production peaked in Wise County in 2013, while its oil production peaked before 2010. Linear OLS regression slopes between ethane, propane, or benzene levels and production data (**Table 3**) were significant for all three compounds with oil, gas, and condensate production volumes, but not casinghead gas, at both DCT and EML. Slopes were significantly different between DCT and EML for oil, gas, and condensate with all three compounds (determined by Z-test), and showed a greater response in NMHC levels to production levels at DCT than EML (i.e., larger ppb per production volume slope).

Eagle Ford Shale Trends

Three sites potentially affected by O&G development–related emissions were analyzed: the Floresville (FLV) site directly downwind (southerlies) of the Eagle Ford Shale, the OLN site in southwest San Antonio, also generally downwind of the Eagle Ford Shale, and the Laredo Bridge site (LRB), which is rarely downwind of the Eagle Ford Shale (under northeasterly winds). Only the FLV site provided hourly measurements, and its results are discussed in more detail below.

FLV seasonal and long-term propane trends are shown in **Figure 16**. Ethane and benzene trends, including confidence limits, are shown in Appendix C. Propane both peaked at the beginning of the time series (2013–2014) and during 2019–2020. NMHC abundances were lowest during 2016. The benzene peak abundance in 2020 was not maintained, meaning benzene mixing ratios dropped again since then. Similar to the results at other sites, there were no significant differences observed between trends of different data quantiles or whether seasonality was modeled directly versus using a periodic function (Appendix C).

Comparing the FLV site trends to the Eagle Ford's production data, **Figure 17**, shows that the long-term ethane, propane, and benzene trends correlate broadly with long-term changes

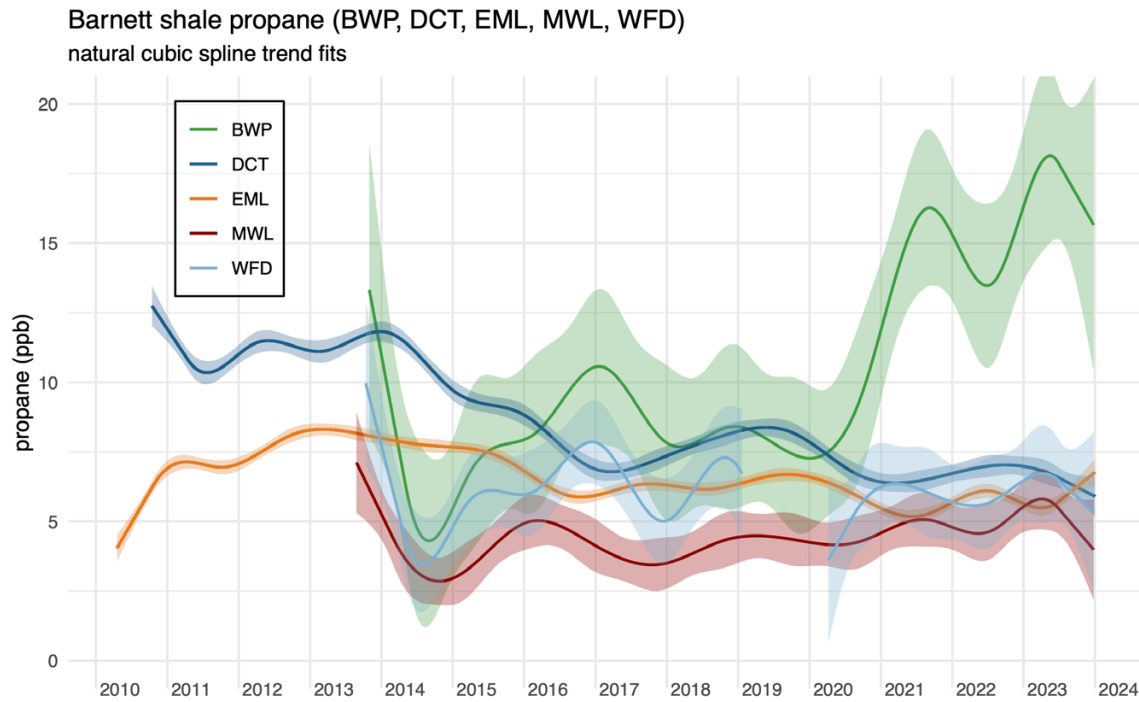


Figure 12. Long-term trend curves for the Barnett Shale sites' propane data with 95% confidence intervals.

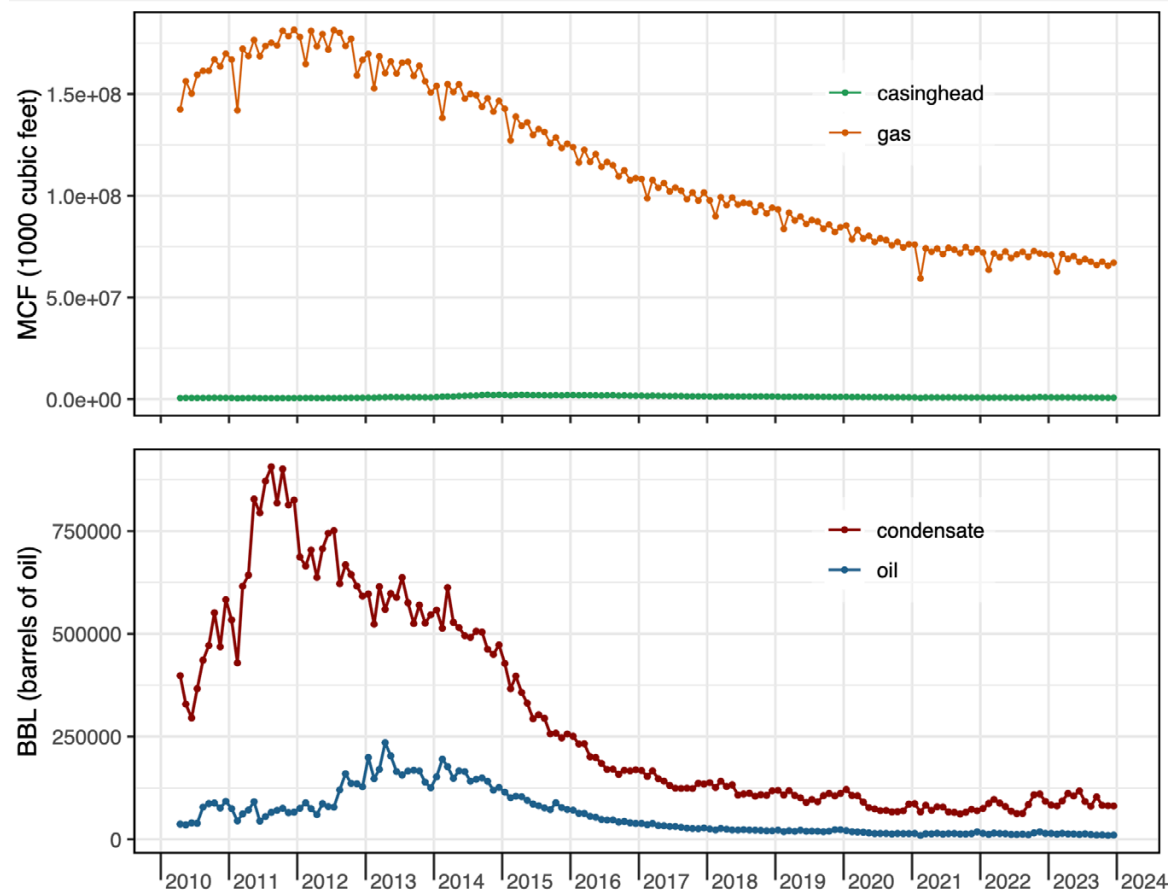
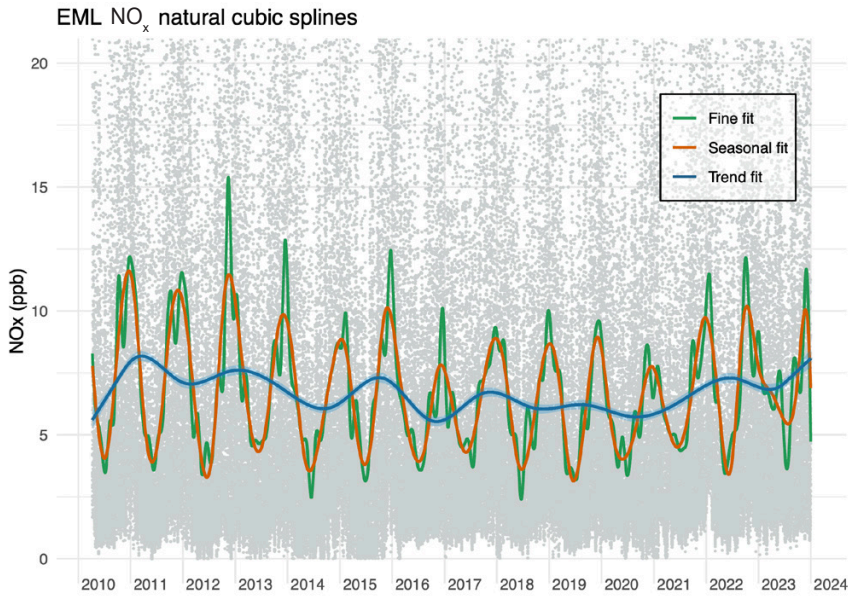
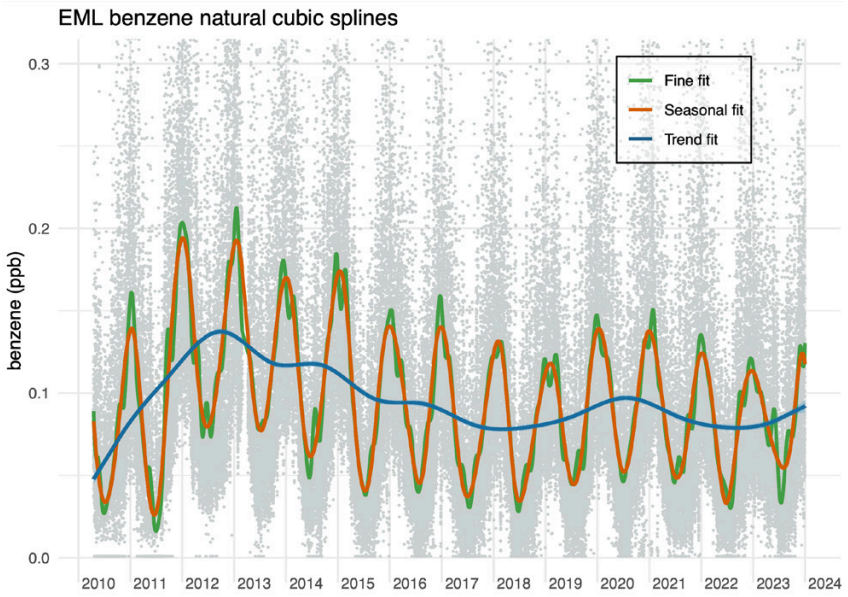


Figure 13. Barnett Shale gas and liquids production volumes. Data source: Railroad Commission of Texas, <https://rrc.texas.gov/oil-and-gas/major-oil-and-gas-formations/barnett-shale/>.



A

Figure 14. (A) EML site benzene data (gray dots) and spline fits (colored lines, long-term trend in blue); (B) shows the NO_x data from this site, which showed a similar long-term trend.



B

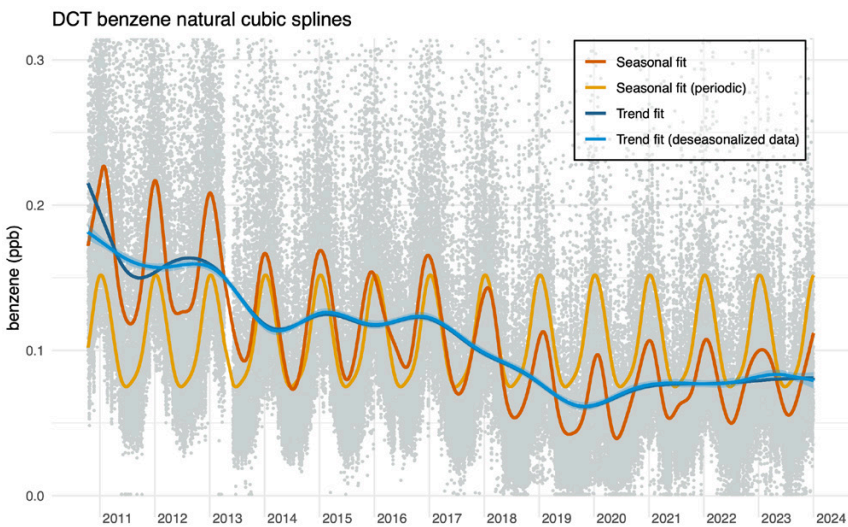


Figure 15. DCT site benzene data (gray dots) and spline fits (colored lines, long-term trend in blue), including the long-term trend using deseasonalized data, which slightly affected the trend prediction for the data start and time preceding 2013.

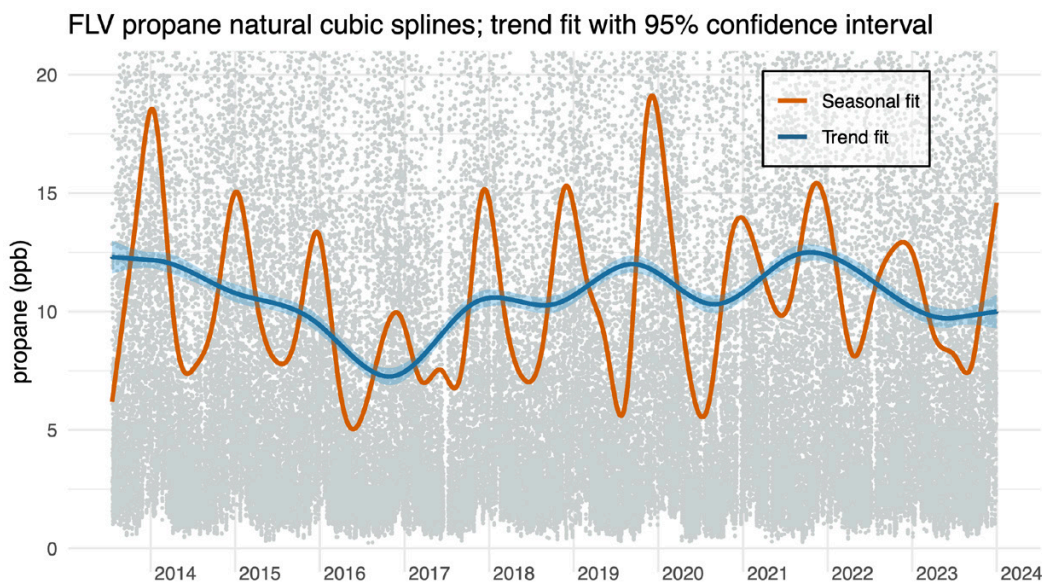
Table 3. Correlations Between the Long-Term Ambient NMHC Data Trends (as Monthly Averages) and Monthly Barnett Shale Production Volume Data

Production Type	NMHC	DCT		EML	
		Pearson <i>r</i>	Slope (ppb per Production Unit) ^{a,b}	Pearson <i>r</i>	Slope (ppb per Production Unit)
Oil	Ethane	0.83	<i>5.18 × 10⁻⁵</i>	0.70	<i>2.40 × 10⁻⁵</i>
	Propane	0.84	<i>3.05 × 10⁻⁵</i>	0.84	<i>1.46 × 10⁻⁵</i>
	Benzene	0.65	<i>4.30 × 10⁻⁷</i>	0.75	<i>2.63 × 10⁻⁷</i>
Gas	Ethane	0.85	<i>7.22 × 10⁻⁸</i>	0.52	<i>2.44 × 10⁻⁸</i>
	Propane	0.93	<i>4.64 × 10⁻⁸</i>	0.68	<i>1.61 × 10⁻⁸</i>
	Benzene	0.91	<i>8.22 × 10⁻¹⁰</i>	0.61	<i>2.90 × 10⁻¹⁰</i>
Condensate	Ethane	0.77	<i>1.03 × 10⁻⁵</i>	0.51	<i>3.85 × 10⁻⁶</i>
	Propane	0.90	<i>7.09 × 10⁻⁶</i>	0.69	<i>2.63 × 10⁻⁶</i>
	Benzene	0.84	<i>1.21 × 10⁻⁷</i>	0.68	<i>5.22 × 10⁻⁸</i>
Casinghead gas	Ethane	0.08	5.45 × 10 ⁻⁷	0.14	5.47 × 10 ⁻⁷
	Propane	-0.12	-4.78 × 10 ⁻⁷	0.15	3.04 × 10 ⁻⁷
	benzene	-0.09	-6.59 × 10 ⁻⁹	0.01	2.09 × 10 ⁻¹⁰

^a“Production unit” is either thousand cubic feet (MCF) for gas and casinghead gas or barrels for oil and condensate.

^bSlopes in bold are significant (95% level). Slopes that are significantly different between DCT and EML are *italicized*.

Figure 16. Hourly propane data and spline fits for the FLV site.



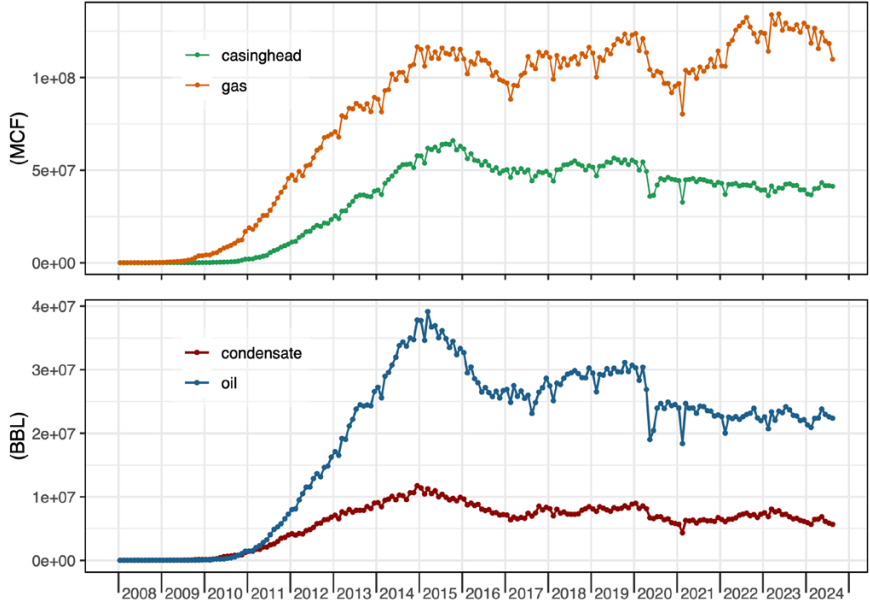
in O&G production: oil production maximized in 2014–2015, gas production shortly afterward (fall 2015). Production volumes declined in 2017, then slightly recovered toward another peak in 2019–2020 before the onset of the COVID-19–related shutdowns. Only gas production recovered since then, peaking again in 2023. However, Pearson correlation analyses using Eagle Ford Shale production data for FLV ethane/propane/benzene suggested poor correlations.

A correlation analysis using upwind county data revealed that the strongest relationship between the ethane data and regional production volumes was for Karnes County *casing-*

head gas production (**Figure 18**). Karnes County has the highest production volumes in the Eagle Ford and is immediately upwind of the FLV AQM station. Both gas and oil are produced in Karnes County, and *casinghead gas* is *associated gas* produced at oil wells, which, in turn, is correlated with gas flaring volumes in these shale areas. The relationship between FLV ethane and Karnes County casinghead gas is most prominent after mid-2015, following a peak in production, with *r* = 0.76.

The second site downwind of the Eagle Ford Shale we investigated was a long-term AQM site in urban San Antonio, called OLN. Data for this site were very consistent over time

Figure 17. Eagle Ford Shale monthly O&G production levels over time. Data source: Railroad Commission of Texas, <https://rrc.texas.gov/oil-and-gas/major-oil-and-gas-formations/eagle-ford-shale/>.



FLV ethane splines trend vs. Karnes County casinghead production
Monthly values

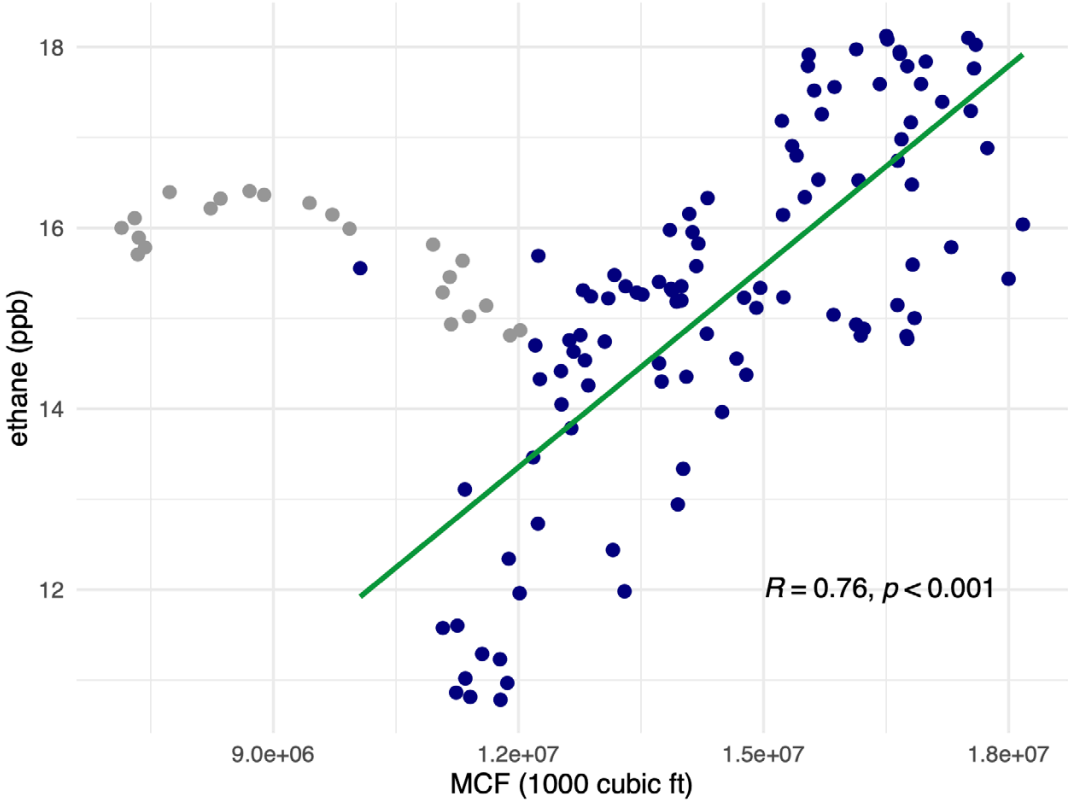


Figure 18. Monthly values of the FLV ethane long-term trend fit are plotted versus monthly Karnes County casinghead gas production volumes. Monthly data before May 2015 exclusive are in gray; monthly data after May 2015 inclusive are in blue. The green line is a linear fit to the blue data, from May 2015 to December 2023.

and displayed distinct long-term trends: Ethane showed steadily increasing abundance between 2007 and 2012, was nearly flat between 2012 and 2015, and dropped to a local minimum during the late 2010s before a temporary increase in 2019–2020 and another drop toward the end of the time series (**Figure 19**). While the initial rise was statistically significant, all three subsequent trends were not.

The initial rise of ethane to its maximum in 2014–2015 parallels the beginning of the shale boom to maximum O&G production (**Figure 17**). Ethane then dropped slightly, parallel to production decreases into the late 2010s. Even the temporary ethane increase in 2019, although not statistically significant, has a parallel in higher production volumes before the COVID-19 shutdowns in spring 2020 affected production (**Figure 17**). OLN site ethane and propane data correlated strongly with Eagle Ford oil and condensate production volumes, and moderately with gas and casinghead production volumes (oil: ethane $r = 0.76$, propane $r = 0.83$; condensate: ethane $r = 0.85$, propane $r = 0.88$; gas: ethane $r = 0.64$, propane $r = 0.75$; casinghead: ethane $r = 0.69$, propane $r = 0.76$). OLN site benzene data had negative correlations with production volumes (oil, $r = -0.71$; gas, $r = -0.79$; casinghead, $r = -0.71$; and condensate, $r = -0.72$), which is likely due to locally dominant traffic-source emissions (**Appendix C**).

To analyze this development further, we carried out an NMF analysis on the OLN site data, which explained approximately 97% of the OLN dataset's variance. We identified a distinct O&G-related factor, which, however, only explained 12% of the dataset's variance (24% considering only nonbackground factors). The time series of this factor and its associated long-term spline trend is shown in **Figure 20**. Similar to the original data, statistically significant peaks were observed in 2011–2012 and 2019–2020. Unlike the original data, the NMF factor suggests a significant effect of O&G production already in earlier years of lower but growing production volumes. Given the uncertainty of the NMF, this result, however, should be viewed with caution. Other results of this NMF, such as the factor scores and other identified source contributions, such as traffic-related emission trends, are shown in **Appendix C**.

The third site investigated for Eagle Ford Shale O&G exploration-related NMHC emissions was the Laredo Bridge (LRB) site at the United States–Mexico border (Puente Internacional Número II) in Laredo. This site has one of the longest records with only one significant data gap in 2017, and **Figure 21** shows our long-term trend analysis for propane and benzene at LRB.

Trends for ethane and propane at the LRB site did not show significant upward or downward trends over time. Propane was occasionally higher before the development of the Eagle Ford Shale and only showed a significant upward trend between 2009 and 2014, the growth phase of O&G development in the Eagle Ford Shale. In contrast, benzene showed a highly significant downward trend between 2000 and the end of the 2010s, before leveling off in the 2020s (**Figure 21**).

The NMF analysis in this case identified several straightforwardly identifiable factors: a road traffic emissions factor, which showed a strongly downward trend mostly responsible for the downward trend in benzene shown in **Figure 21**; a power plant emission factor, identified via its compound fingerprint and its strong seasonal periodicity associated with northerly winds advecting air from the 7 km distant plant in winter; and a diesel emissions factor identified via its compound fingerprint of heavy aromatics. Overall, the nonweighted NMF used here identified 92% of the variance in the dataset, but the remaining factors were difficult to interpret. **Figure 22** shows the factor we most closely associate with potential O&G emissions. While it contributed less than 15% to the dataset's variance, its time development suggests an association with O&G development in the Eagle Ford — peaking in the mid-2000s and in the early 2010s — before slowly dropping till the end of the dataset. However, high values in the early 2000s remain unexplained. For comparison, the identified diesel emissions factor (**Appendix C**) shows a clear maximum in the late 2000s, with secondary maxima in the early 2000s and in 2012. Only the broad maximum in the late 2000s coincided with increasing truck traffic until the global recession in 2008–2009 (personal communication with Juan Villa, TTI Laredo).

Haynesville Shale Trends

Two sites in the northern region of the Haynesville Shale (**Figure 2**) were investigated: the Longview (LGV) and Karnack (KNK) sites. An unusual trend was observed in the Karnack site data with substantially higher NMHC levels from 2004 through 2012 (**Figure 6**). A similar feature was also recorded, although to a lesser extent, in the LGV site data, which has a longer record than the Karnack site. Both sites featured relatively high *i*-*n*-pentane ratios, suggesting low O&G emission influences.

Figure 23 compares our trend and NMF analyses for the KNK site along with Harrison County annual gas and condensate production volumes. Ethane and propane data (**Figure 23**, Panels A and B) both showed the unusual feature of rather rapid reductions of pollutant abundance transitioning from 2011 to 2012. In comparison, NO_x measured on an hourly basis at this site did not show such a feature.

Shale gas production in Harrison County grew steadily from the beginning of the shale boom in the early 2000s until 2011, then dropped into the late 2010s, before rising again beginning in 2019. Condensate production peaked earlier in 2008, then again in 2014, before dropping toward the end of the investigated period. Similar production volume developments over time were observed across the Texas portion of the Haynesville Shale (**Appendix C**).

Our uncertainty-weighted NMF analysis identified five interpretable factors, two of which are included in **Figure 23** (Panels D and E). Overall, the NMF explained only 69% of the dataset's variance, with the O&G and diesel emissions factors contributing 14% and 2%, respectively. However, the NMF was skewed by a finding of 53% of its variance explained

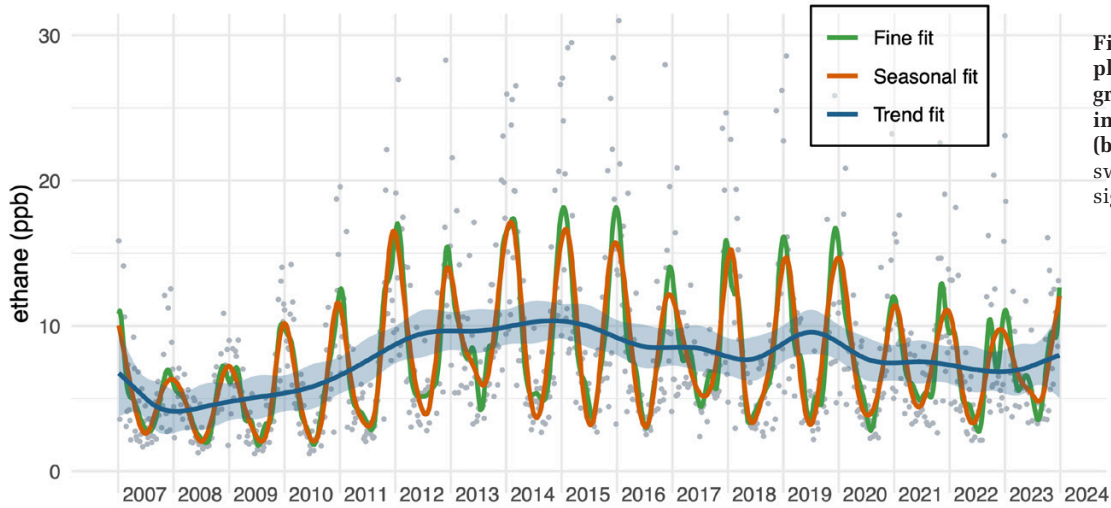


Figure 19. OLN site ethane data plotted with spline curves (solid green, orange, and blue lines), including 95% confidence levels (blue swath). Nonoverlapping swath periods mark statistically significant trends.

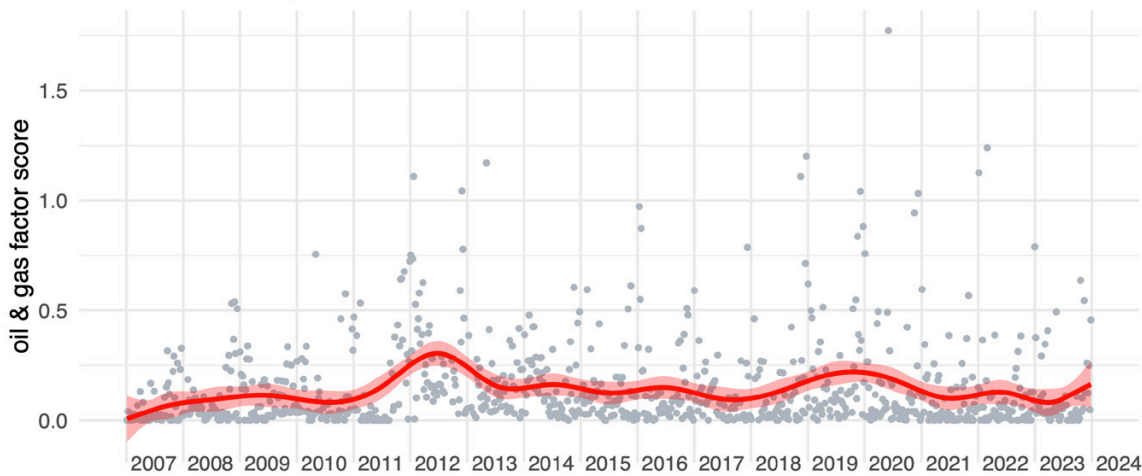


Figure 20. Similar to Figure 19 but showing only the NMF O&G factor score time series for the OLN site's NMHC data (gray dots) and its spline trend (red line and confidence interval swath). According to this factor, the greatest influence of O&G activity occurred in 2012 when exploration was ramping up in the region, and in 2019 during a peak in production before the onset of the COVID-19 pandemic.

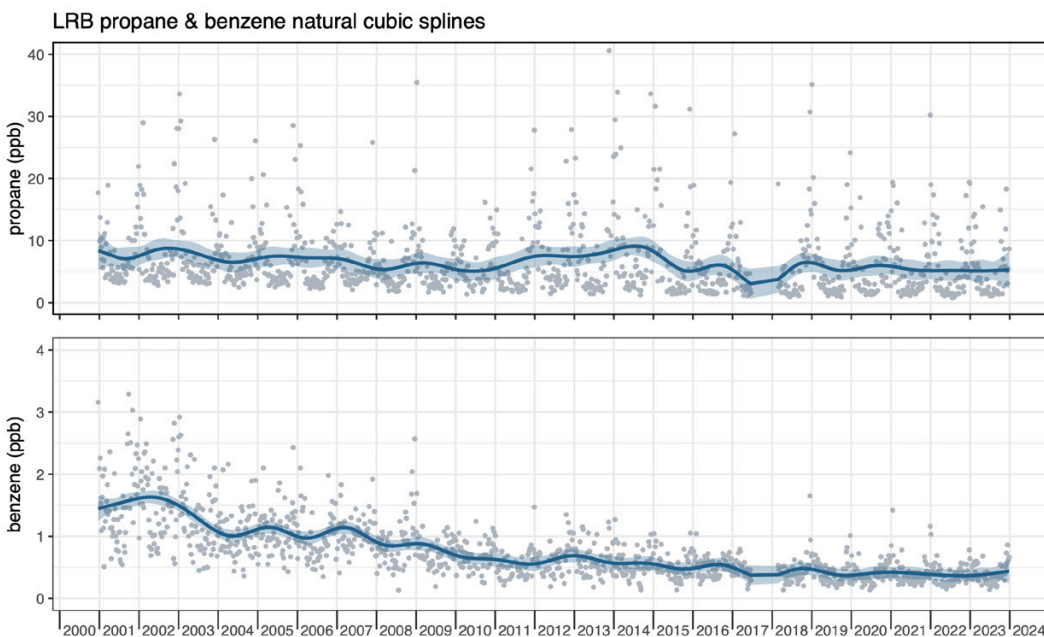


Figure 21. Time series of propane (top) and benzene (bottom) from the LRB site.

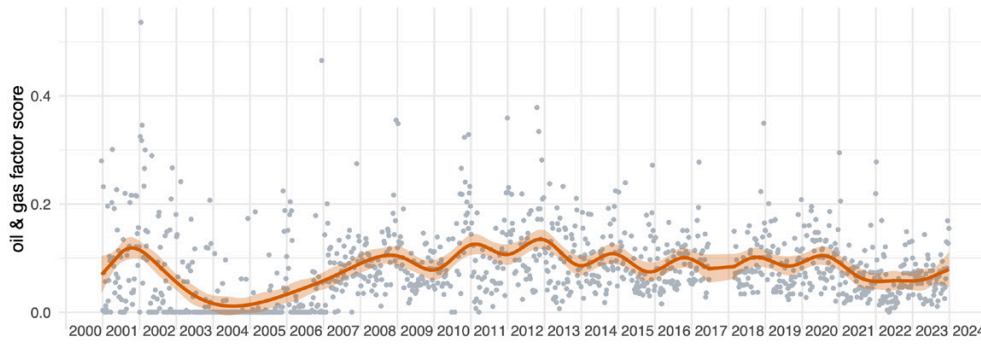


Figure 22. Time series (gray dots) and spline-based trend analysis (orange line and confidence interval swath) of an NMF-based factor tentatively associated with O&G emissions upwind of the LRB site.

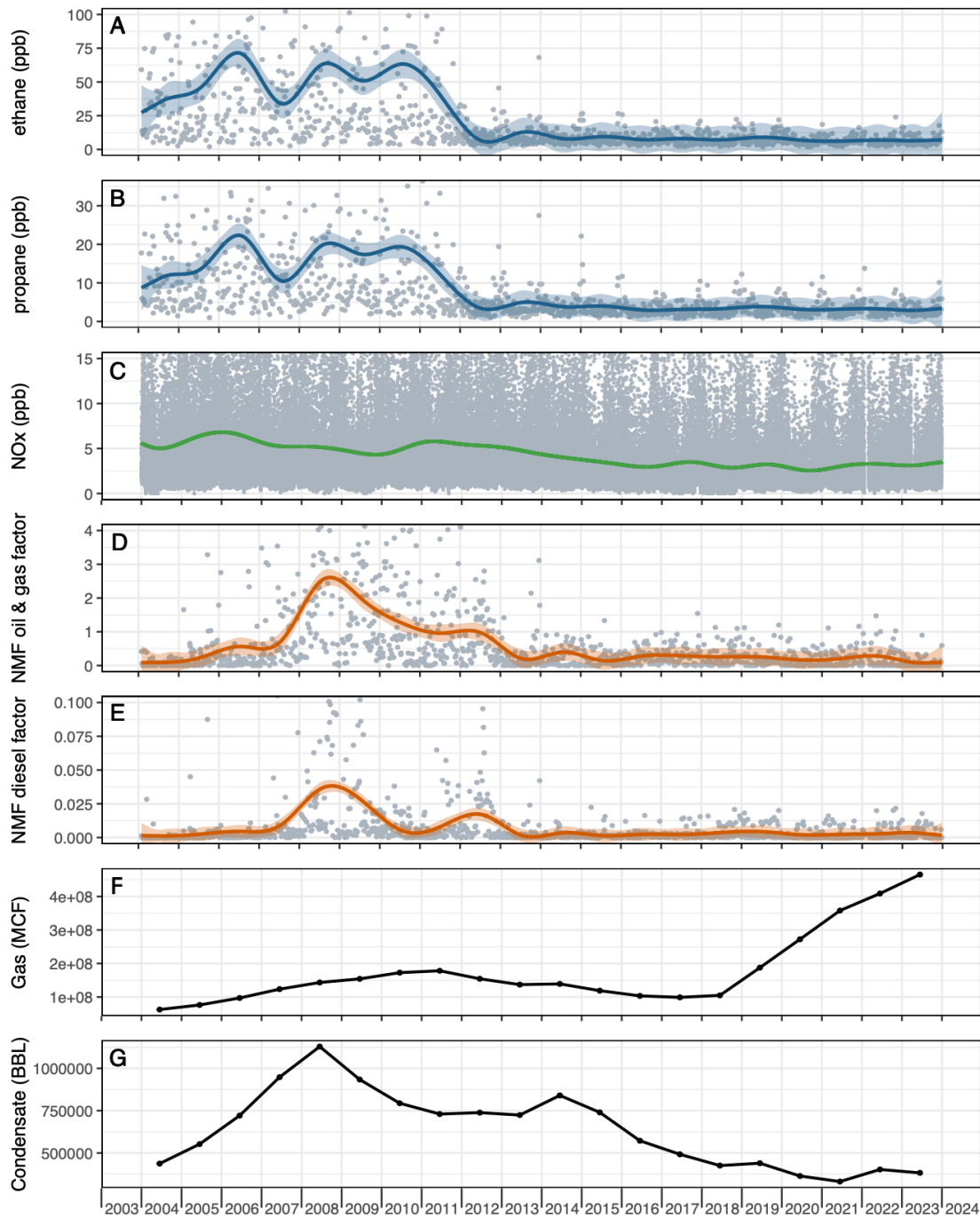


Figure 23. Karnack site comparison between (A) ethane data, (B) propane data, (C) NO_x data, NMF factors for (D) O&G and (E) diesel, as well as Harrison County (F) gas and (G) condensate production volumes. The y-axes for data and NMF factor plots do not include all high data points for increased visibility of trends.

by the background factor, and significant contributions to the background from all other factors (Appendix C). Although the results in Figure 23 (Panels D and E) should thus be viewed cautiously, we note that the 2008 to 2012 peaks of the O&G factor coincide with the early shale boom maximum condensate and gas production volumes; the diesel emissions factor's similar structure and reduction over time might be related to both gas well drilling and O&G development-related truck traffic in this rural area.

Trends investigated at the LGV site were found to be similar to the KNK site (Figure 24). However, a specific feature of high benzene and other aromatics was encountered at this site during the end of the 2006–2010 period that was not present in the ethane and propane data. This feature can probably be explained by the fact that the monitor was and is located at the East Texas Regional Airport, which carried out a major construction project from 2007 onward, including resurfacing one of its runways along with other improvements (https://en.wikipedia.org/wiki/East_Texas_Regional_Airport). After this period, the *i*-*n*-pentane ratio dropped at LGV for several years from prior average values near 2 to consistent averages near 1.6 from 2013 onward, suggesting some O&G impacts in line with the gas production volume trends shown in Figure 23 (Panel F).

Our NMF analysis for this site resulted in five factors, which explain 97% of the variance (50% when unweighted) in the dataset. In this case, few nonbackground factors scored on the background, which explained 22% of the total variance. The O&G and diesel emissions factors, which were identified via their compound compositions, explained 69% and 6%, respectively, of the remaining, nonbackground variance in the dataset. The O&G factor, shown in Figure 25, began rising in 2006, peaked in 2007, and then decreased until 2013 before leveling off for the remaining period. This time, development again coincided partially with Harrison County's condensate production volumes (Figure 23 [Panel G]), and also with the area's drilling permit records. In comparison, the NMF's diesel emissions factor (Figure 25) overlapped mostly with the local airport construction period as well as the drilling permit record for Harrison County, showing drilling maximized between 2005 and 2010 (<https://www.mineralview.com/oil-and-gas-well-data/texas/harrison-county>).

Permian Basin Trends

Our investigations included only one site in the Permian Basin with a long-term AQM record, the Odessa–Hays Elementary (OHE) school site, an urban location. Although TCEQ has deployed three more AQM stations into the eastern, Permian–Midland part of the basin, neither of those is close to the western, Pecos area, and neither has a record longer than 3 years. The OHE record starts at the end of 2015, the year during which the shale boom in the Permian Basin took off (shale O&G production volumes were low before 2015). In Figure 26, we show the site's benzene record and spline-based trend, including confidence limits.

Benzene levels were lowest in 2016 and increased statistically significantly over time to a maximum in 2022. Ethane and propane trends are shown in Appendix C. Pearson correlations showed ethane and propane do not correlate significantly with Permian Basin production data; however, OHE benzene had a strong correlation with Permian gas ($r = 0.82$), condensate ($r = 0.78$), oil ($r = 0.75$), and casinghead gas ($r = 0.77$) production volumes.

Our NMF analysis again revealed five factors, which together explained 90% of the variance in the dataset. Only 11% of the variance was attributable to the predefined background compounds; however, many nonbackground compounds scored on the background factor (Appendix C). As a result, these findings should be interpreted with caution. The strongest contribution in this NMF was 34%, made by the O&G factor, while the diesel emissions and car traffic factors contributed 9% and 23%, respectively. Figure 27 shows the long-term trend of the O&G factor, which resembles the benzene data trend shown in Figure 26, but peaked earlier, in 2020, coinciding with maximum oil production volumes in the Permian Basin. For comparison, we also show the time development of the diesel emissions factor in Figure 28. According to the data, diesel emissions strongly affect the air quality in this region and appear to have reached their peak contribution in 2021.

Discussion of Texas Trend Analysis

An extensive network of AQM stations across Texas enabled inclusion in our analysis of stations from all four shale O&G production regions in the state: the Eagle Ford Shale, the Barnett Shale, the Haynesville Shale, and the Permian Basin. Operated by a single entity, TCEQ, data from all stations can be considered highly comparable within and across the shale regions. AQM stations with a long history were preferentially selected for our analysis, and no prior such analysis had been carried out except for a targeted analysis of the OLN site in San Antonio a few years into the Eagle Ford Shale boom (Schade and Roest 2015). At that time, a clear increase in ethane during the preceding years was found for air masses advecting across the shale from the Gulf of Mexico.

The more extensive analyses shown in this report support the earlier work in that they show, generally, the O&G exploration tracers ethane and propane, but also benzene, increased during the early expansion years of shale O&G production in Texas. For some sites and compounds, this increase was highly significant (e.g., Barnett, EML, DCT; Eagle Ford, OLN; Permian, OHE); in others it was not (e.g., Haynesville). NMF analysis was capable of distinguishing source signatures well in some cases, improving interpretation such as for the Haynesville site data; in other cases it provided only weak evidence for O&G exploration impacts such as for the LRB site. In those latter cases, the NMF analysis still provided insights into other emissions sources and their impacts, such as long-term decreases in road traffic emissions as the most relevant factor for downward benzene level trends in Laredo, Texas.

Figure 26. Time series of benzene data for the OHE site, including spline-based fine, seasonal, and long-term trends. The light blue swath again indicates the 95% confidence level of the long-term trend.

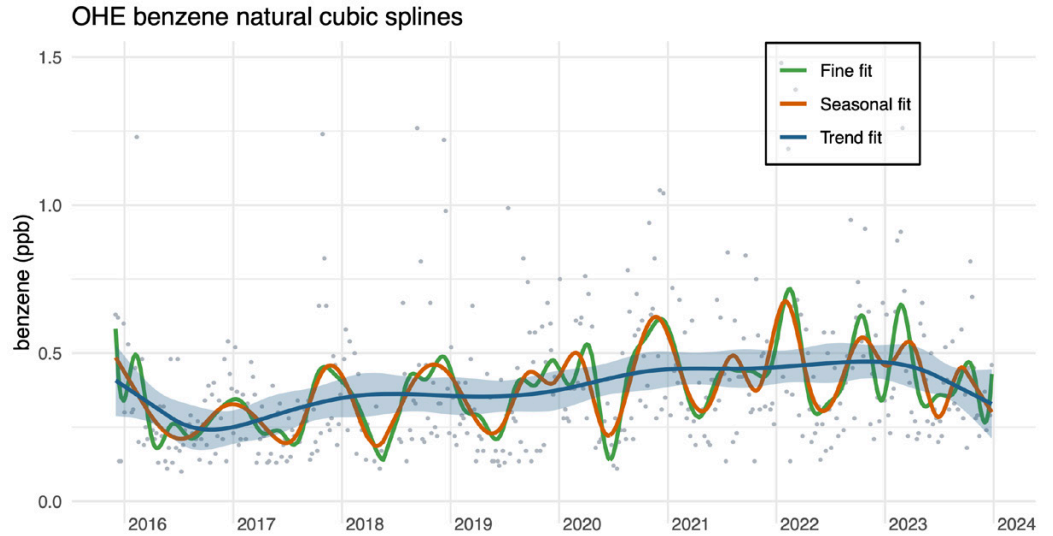


Figure 27. Time series of NMF O&G factor score for the OHE site, including the spline-based long-term trend and its 95% confidence level in orange.

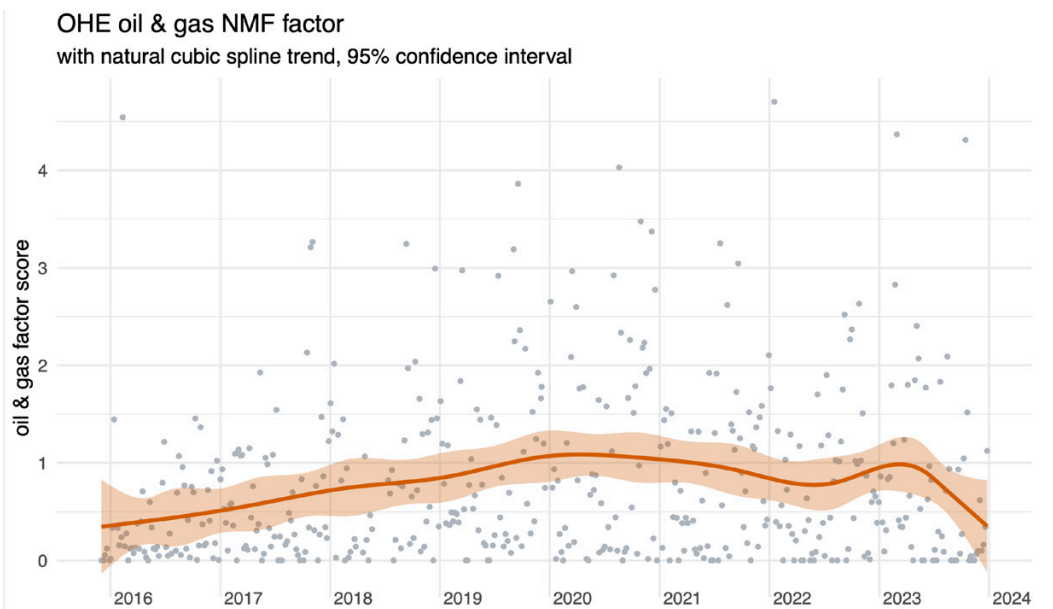
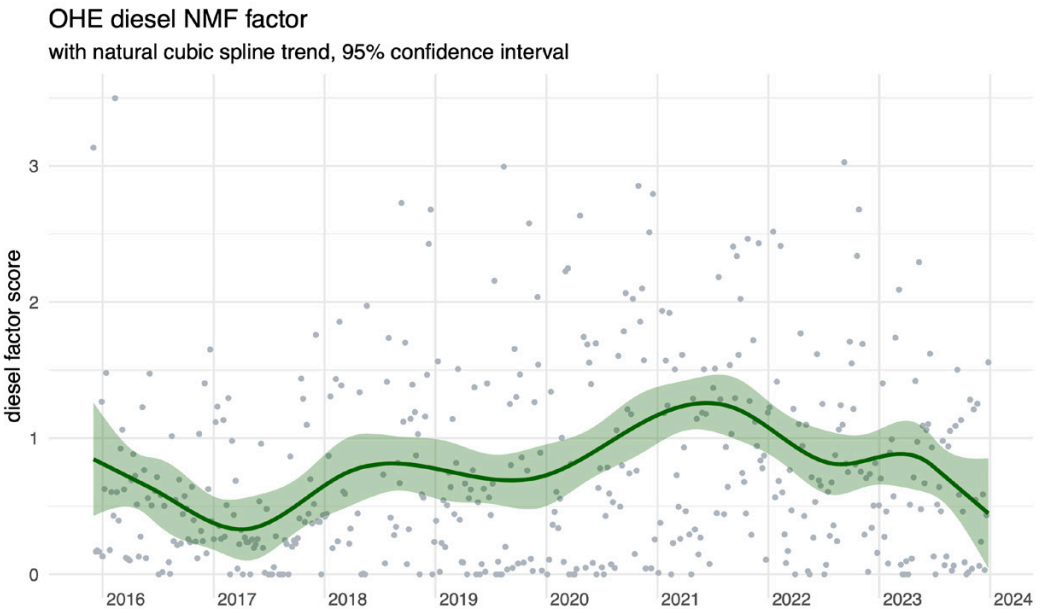


Figure 28. OHE site NMF-based diesel emissions factor time series (gray dots) and long-term trend (green line) with 95% confidence level (green swath) (note, y-axis cutoff at 3.5 for increased trend visibility; maximum factor score was 5.26).



Overall, we found modest correlations between the determined long-term trends and monthly O&G production volumes. Especially at the AQM sites producing long-term, hourly data (FLV in the Eagle Ford and EML and DCT in the Barnett Shale), statistically significant positive correlations were observed for more than one production volume measure and the investigated atmospheric NMHC abundance. These correlations may be driven largely by the initial years of data if and when they overlapped with the beginning years of a shale's exploration, during which rapid production growth occurred. Once a shale area's production volumes had peaked, atmospheric NMHC levels of the compounds investigated did not change substantially thereafter (Eagle Ford), or dropped (Barnett, Haynesville, Permian). This might suggest that emissions at least initially increased with production volumes, but may have stabilized or dropped as gas and oil production leveled or dropped. Even at AQM sites that did not cover the initial boom years, such as the FLV site downwind of the Eagle Ford Shale, fluctuations in production volumes over the years covered were at times correlated with atmospheric NMHC levels, again suggesting that the amount of activity in the O&G industry, as measured by O&G production, is a significant factor in overall emissions, although it may not be the dominant driver at any one particular well pad location.

Lastly, smaller year-to-year fluctuations were generally observed in the gas shales (Barnett, Haynesville) as compared with the oil shales (Eagle Ford, Permian). Except for the BMP site, no Barnett Shale sites with 6-day data collection showed significant trends over time, and no significant long-term changes were observed at the Haynesville sites once the high variability during the initial years had subsided. However, the Barnett Shale sites with hourly data collection (DCT and EML) did trend well with production data. Our investigations found no immediate, reasonable explanations for the changes at the BMP and KNK sites, while a local construction project was hypothesized to have driven some of the LGV site observations. A more in-depth analysis, including local record investigations, may be needed to evaluate some of these local trends. As one of the oldest gas shales explored by the industry (Haynesville), it is interesting that there is a lack of NMHC trends in recent years alongside increasing gas production in the county where the two AQM stations are located, thus suggesting possible improvements to emissions intensity.

TREND RESULTS FOR THE DENVER–JULESBURG BASIN SITES

In the following sections, we present the findings of the trend analyses for methane, selected NMHCs, and NO_x at the NCFR sites.

Methane

Increasing methane mole fractions were observed in all analyzed data records, as would be anticipated given the globally observed increase in background methane on the order of 10 to 15 ppb/yr during the last decade. Potential regional methane

emissions changes require careful analysis against the global background, as ambient methane will always be composed of two contributing components: the $\sim 1,950$ ppb background in air transported into the region, plus any contributions from local sources. A methane time series data record example from the BRZ site is shown in **Figure 29**. Methane never dropped below the $\sim 1,950$ ppb background level. Regional emissions add on the order of 100 to 500 ppb to the background, with occasionally higher peaks. The frequency and magnitude of enhancements increase during the winter months, driven by meteorological conditions that cause stronger and longer-lasting inversions, which trap nearby emissions near the surface. To increase the selectivity of our analysis to regional emissions, the full data series was segregated by air transport sector and wind speed as described in the Methods section. While this approach reduced the total number of considered data points, it provided a clearer representation of background concentrations of methane, selected NMHCs, and NO_x versus those contributed by O&G production region emissions. **Figure 30** presents the results of this analysis for the methane case. Air transported to the BRZ site from the west was less variable and exhibited a more moderate seasonal cycle. The average growth rate over the period represented by these data was 11.3 ppb/yr, which corresponds to $\sim 0.6\%$ /yr. Methane was more variable in air transported from the O&G sector and had a stronger seasonal cycle. Here, the linear growth rate was 7.9 ppb/yr (or $\sim 0.4\%$ /yr). An important finding is that the O&G sector trend resulted in an approximately 40% smaller value than the methane growth rate in background air. This behavior implies that the contribution of methane emissions from the O&G sector has been gradually declining and that both methane series are slowly converging.

Figure 31 includes results from four other NCFR in situ monitoring sites, as well as the BAO and MLO sites. The west sector data parallels the MLO background methane concentrations, reflecting less added continental emissions than for the O&G sector data. For the O&G sector data, results for BNP are the highest, followed by LUR, ECC, and BRZ. This sequence roughly reflects the proximity of the monitoring sites to the DJ Basin O&G operations (**Figure 3**). That is, the sites closest to high emissions in the DJ Basin are subjected to the highest methane, while the lowest methane (even in the O&G sector originating air flow) was observed at the most distant monitoring station, BRZ. Seasonality was strongest in the O&G sector data as compared with the background, indicative of the influence of local emissions that accumulate in the surface inversion layer, with stronger effects during winter (because of stronger and longer-lasting inversions).

Excluding the earlier BAO data, the linear regression fit results for the FFT trends are shown in **Figure 32**. For MLO, this analysis was applied to the 2017–2023 record for consistency with the NCFR data. For all three NCFR cases, the O&G sector OLS slope values were smaller than in the air transported from the west. Furthermore, all NCFR O&G sector slopes were smaller (4.9–8.3 ppb/yr) than the MLO rate of increase (12.4 ppb/yr), which supports the conclusion

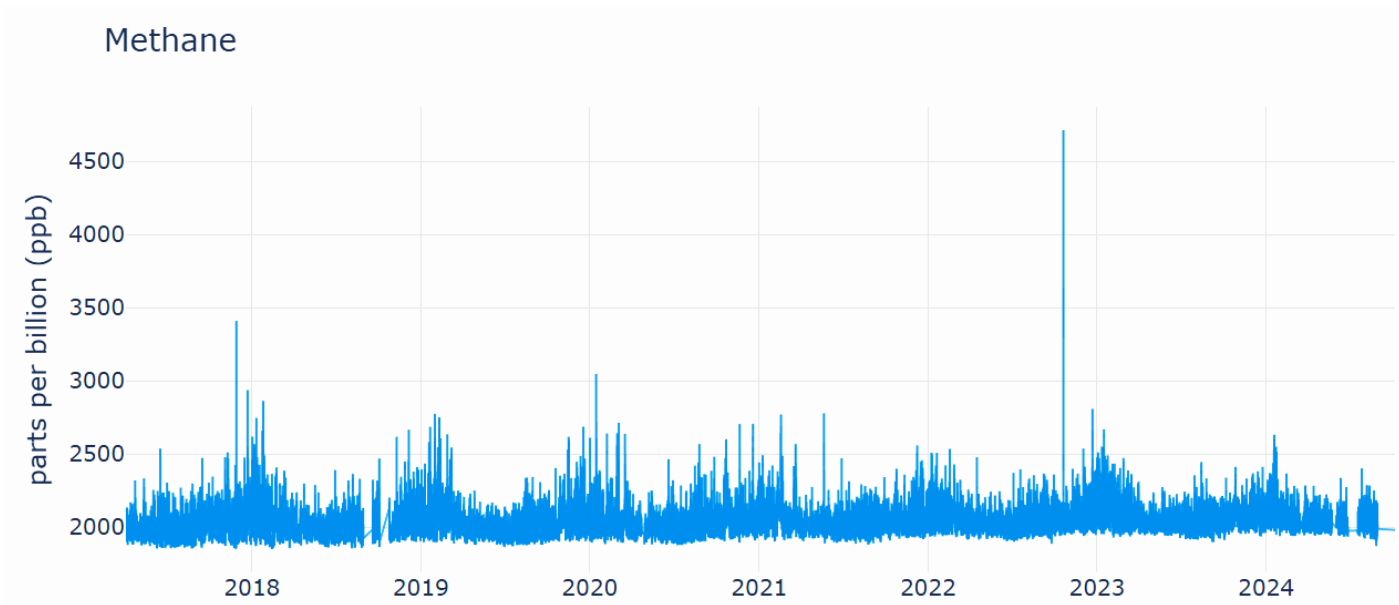


Figure 29. Time series with full methane data record from the Boulder Reservoir.

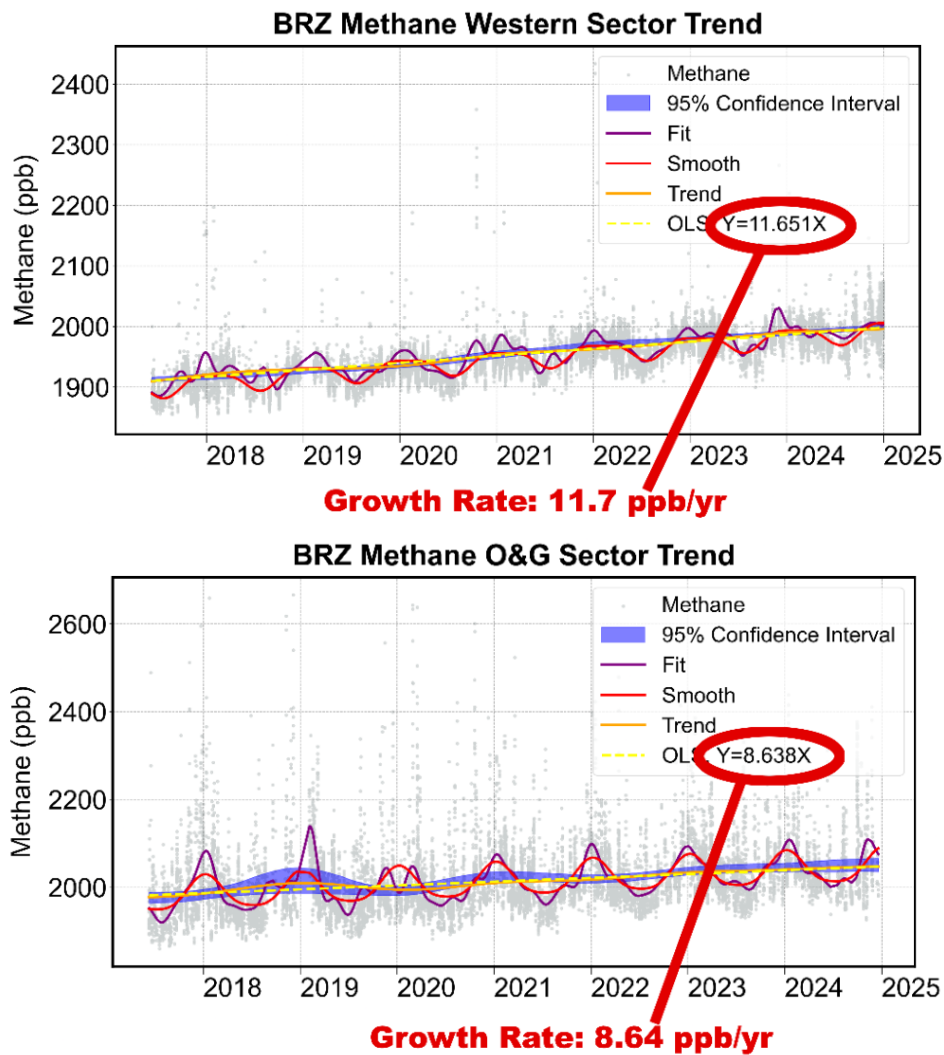


Figure 30. Methane at the Boulder Reservoir site separated by wind sector and filtered for winds >3 m/s. The methane growth rate over the record is given by the regression line slope value shown in the legend.

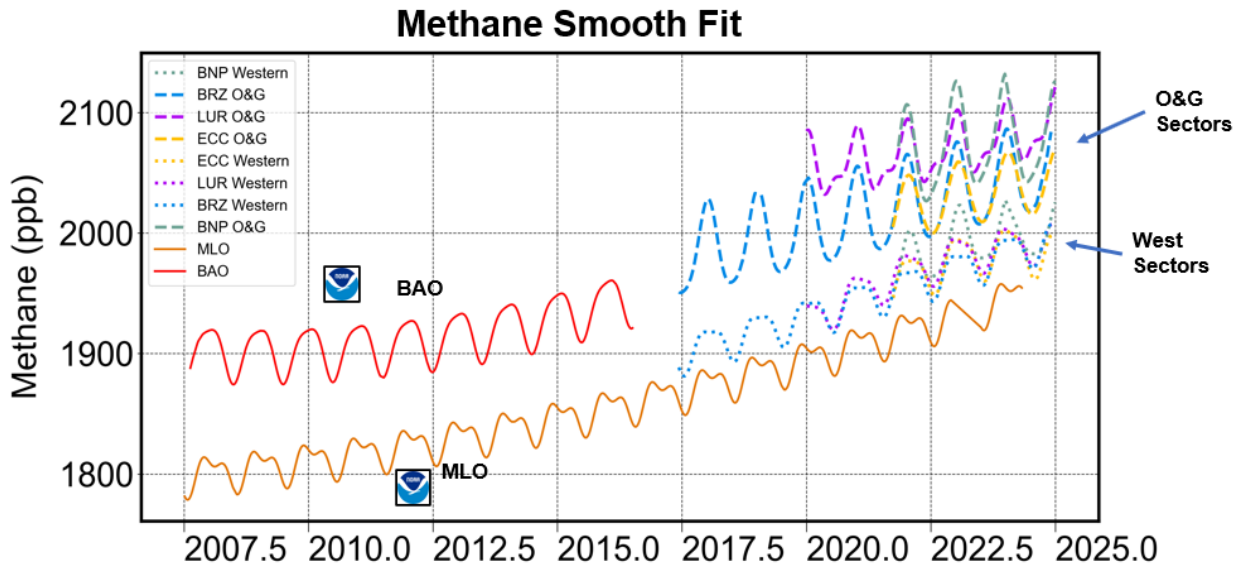


Figure 31. Smooth methane trend results, segregated into western sector versus O&G sector air mass origins for the NCFR surface station data, in comparison with the MLO Northern Hemisphere background data and earlier data from the NOAA-operated BAO.

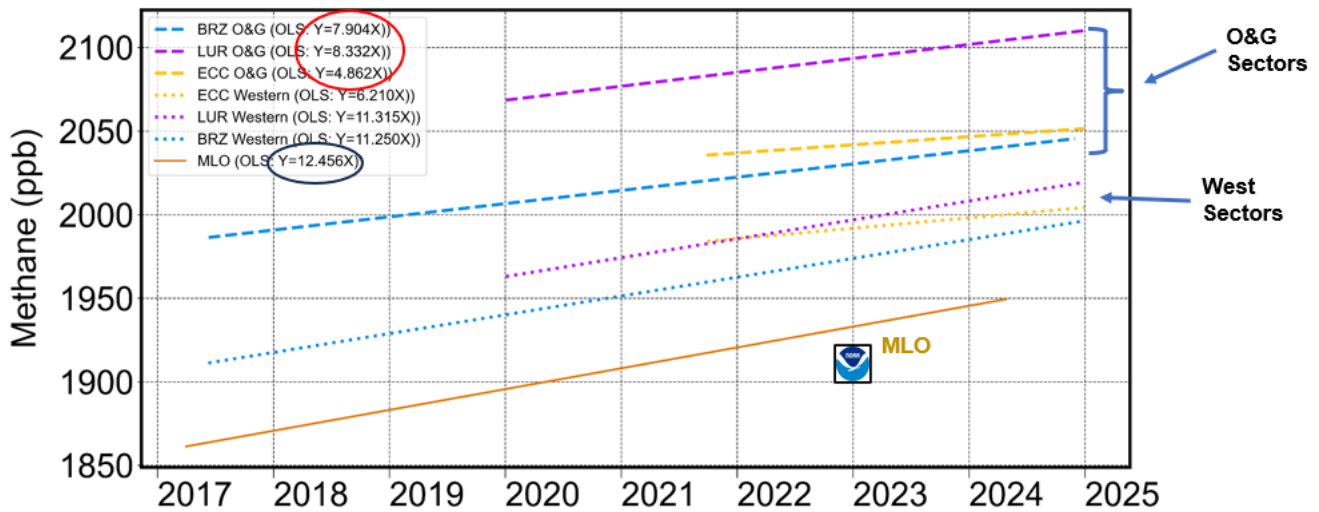


Figure 32. OLS results for three NCFR surface sites in comparison with the MLO methane trend. NCFR data are separated into western versus O&G sector data. Slope values, representing the average rate of change over the entire sample period, are circled in the legend.

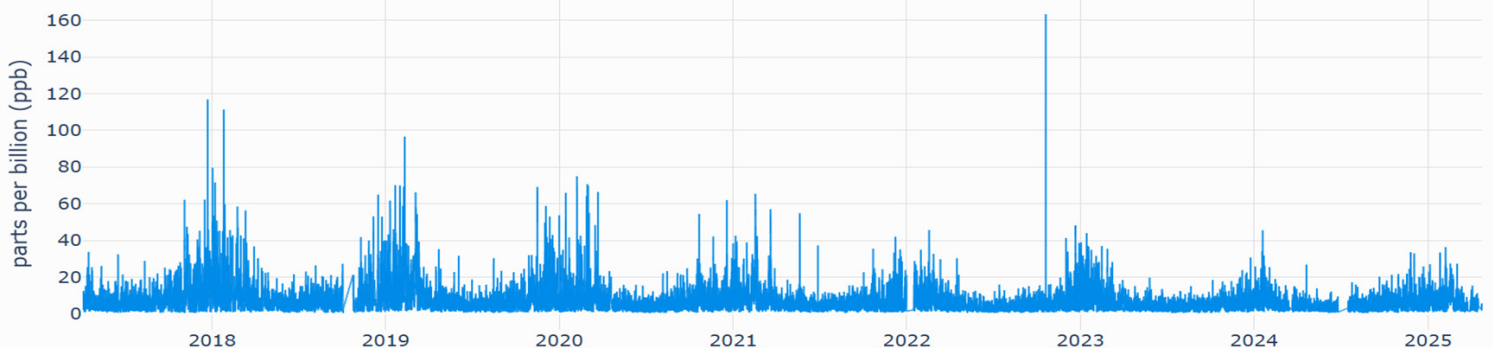


Figure 33. Time series of the full ethane record from the BRZ site.

derived from the BRZ data. In other words, local methane mole fractions (and emissions) appear to be increasing at a slower rate, indicating declining local methane emissions. A summary of OLS regression slopes and their statistics across sites is provided in **Table 4**.

While these findings on declining methane emissions in the O&G sector are intriguing, these conclusions pose some ambiguity and uncertainty. Methane is emitted by a variety of sources: Besides O&G operations, other sources contribute methane to the NCFR, such as landfills, dairies, and beef production feedlots. Previous research attributed ~75% of the DJ Basin methane emissions to O&G sources (Pétron et al. 2014; Peischl et al. 2018). Consequently, our finding of decreasing methane could be caused by emissions reductions from any of those sources, or a combination of them. More definite conclusions are expected from the consideration of ethane, which is a more selective O&G tracer than methane, having only minor emissions (e.g., biomass burning, seepage) from non-O&G sources.

Table 4. Comparison of Methane Analysis Slope and Bounds in Parts per Billion

Site	Sector	Slope (ppb/yr) ^a	Slope Confidence Interval	
			Lower	Upper
BRZ	All	8.82	8.35	9.32
BRZ	O&G	7.91	6.88	8.50
BRZ	Western	11.3	10.8	11.9
LUR	All	8.19	7.67	8.81
LUR	O&G	8.33	7.60	9.02
LUR	Western	11.3	9.73	13.0
ECC	All	-2.77	-5.07	-0.17
ECC	O&G	4.86	3.73	5.63
ECC	Western	6.21	2.71	9.32
BNP	All	5.15	3.68	6.68
BNP	O&G	7.90	6.88	8.50
BNP	Western	14.2	11.2	18.2
MLO ^b		9.12	8.76	9.40
MLO ^c		12.5	12.2	12.8
BAO		4.75	3.20	5.44

^a Slope refers to the OLS regression fit slope. NOAA trend error represents the margin of error at the 95% confidence level, calculated as the half-width of the confidence interval using the NOAA trend standard deviation output.

^b Trends calculated starting with data in July 2007.

^c Trends calculated starting with data in April 2017 (start of monitoring for BRZ).

Ethane, Propane, and Benzene

Ethane and propane were investigated as emissions tracers of O&G emissions. Benzene was included as an O&G production-related emission because of its well-known and well-characterized health effects. The ethane record from the longest-operating NCFR AQM site, BRZ, is illustrated in **Figure 33**. Similar to methane, atmospheric mole fractions were highly variable, with mole fraction swings spanning approximately two orders of magnitude at any time of year. Unlike methane, the visual inspection of the time series graph shows that there has been a gradual decline in the frequency and magnitude of high mole fraction values of ethane over the years, except for one spike in October 2022. Our prior work on the BRZ record has tied concentration spikes of this type to emission events, particularly from accidents at O&G facilities that can result in large bursts of emissions (Helmig et al. 2025). Although fewer such events may suggest an overall downward trend (i.e., declining ethane emissions over time), this interpretation may be overstated if mean or median values behave differently from percentiles and event maxima. **Figure 34** investigates this question by showing a time series plot of selected percentiles of the full data and confirming the impression given by the raw data time series (i.e., the BRZ ethane trended downward at most percentiles).

Figure 35 shows the wind sector (east sector, O&G) and wind speed (>3 m/s) filtered ethane time series from the site with the longest record (BRZ) alongside output from the NOAA trend tool. The long-term trend is shown in orange. **Table 5** and **Figure 36** compare the sector ethane trends across the NCFR surface sites with the CVAO ethane data.

All but one of the Colorado data records available for consideration showed declining ethane mole fractions in air transported from the O&G sector (Table 5). The one exception is the ECC site data, which showed an insignificant upward ethane tendency (yellow dashed line in Figure 36). Given the clear agreement in the remaining four data records (i.e., downward slopes for BRZ, BNP, BSE, and LUR), we do not consider the shorter-record ECC result as contradicting the conclusion that can be drawn from this analysis, especially considering that the ECC site had a less consistent sector definition, as it has a significant number of wells located on its west side.

BRZ, BNP, BSE, and LUR O&G sector trends span a factor of four (i.e., -0.196 to -0.771 ppb/yr). For the longest record from BRZ, the -0.2 ppb/yr decline rate reflects a ~1.4 ppb drop over the record, which accounts for ~25% of its mole fraction at the beginning of the monitoring record. For CVAO, a modest rate of -0.015 ppb/yr was determined, indicating that the results obtained for the Colorado sites are most likely due to local emissions changes and not from changes in background air that is transported from outside the area.

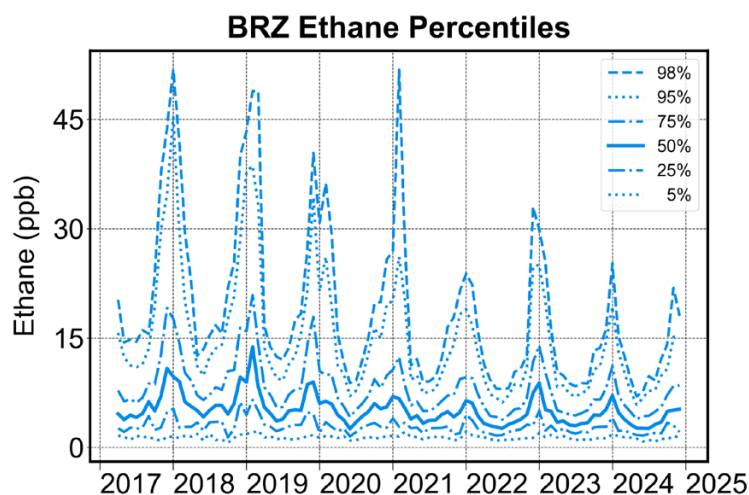


Figure 34. Monthly median and percentile trends over time at the BRZ site.

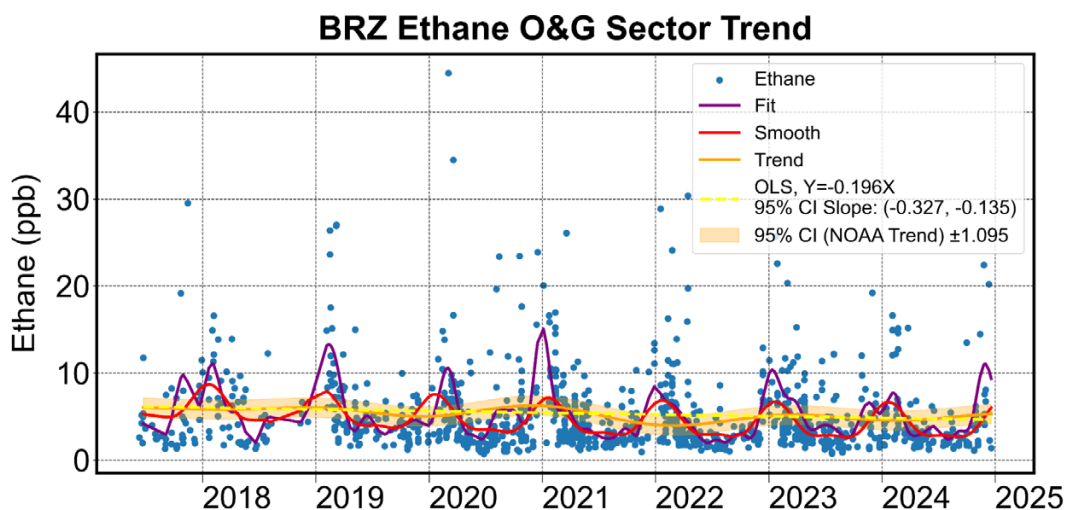


Figure 35. Ethane at the BRZ site transported from the O&G sector with winds >3 m/s, with the results of the trend analyses using the NOAA tool.

Figure 37 adds the NCAR FTIR ethane column observations to the surface data. Because the column observations derive ethane vertical column densities rather than surface mole fractions, all data were converted to an anomaly scale to show relative changes over time in relation to the full record's mean. Overall, the records showed reasonable agreement within the margins of year-to-year variability.

Results for propane, using the same protocols as detailed above for ethane, are depicted in **Figure 38** and Appendix C. Propane displayed tendencies similar to ethane. O&G sector samples were on average ~5 times higher in abundance than the background. OLS results showed declining propane at all sites other than ECC. Rates of decline (except for ECC) span a range of -0.161 to -0.747 ppb/yr, with the highest decline rate seen at LUR, the site that also had the highest overall propane values. For the longest record BRZ site, the propane decline rate of -0.161 ppb/yr added up to a total drop of 1.2 ppb in

average propane, which is approximately 30% of its value at the beginning of the monitoring in 2017. At CVAO, the propane trend was a modest -0.008 ppb/yr, a slower decline rate than the changes seen in the Colorado data.

Trend determination results for benzene are shown in **Figure 39**. A recent source apportionment study on the BRZ data concluded that benzene was associated with O&G, traffic, and other industrial-petrochemical activities contributing to the observed atmospheric benzene (Pollack et al. 2021). Thus, for the benzene analyses, the sector and wind speed segregation was omitted. Nevertheless, all records considered here were consistent in showing declining benzene abundances at average rates spanning -0.006 to -0.016 ppb/yr over the available period data, reflecting an approximately 30% drop in atmospheric benzene since the onset of monitoring at BRZ. Although we did not evaluate in this project which sources may have contributed most to the observed decline, the

Figure 36. Smooth fit trend results for ethane from the NCFR surface sites segregated by wind sector (top panel) and OLS regression results to the trend output to illustrate average changes over the full data record (bottom panel). CVAO data trends are included for comparison with the ethane behavior in Northern Hemisphere background air.

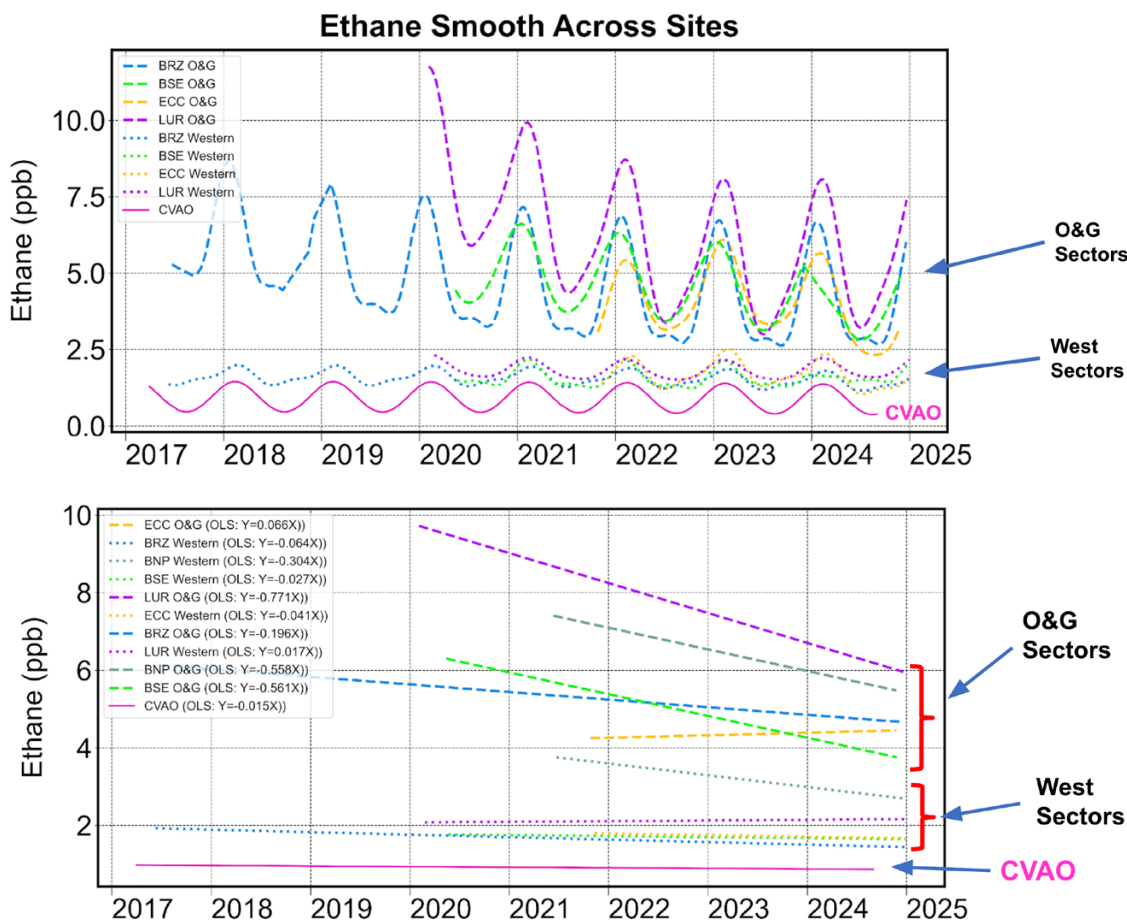


Table 5. Comparison of Ethane Analysis Slope and Confidence Interval in Parts per Billion

Site	Sector	Slope (ppb/yr) ^a	Slope Confidence Interval	
			Lower	Upper
BRZ	O&G	-0.2	-0.33	-0.14
LUR	O&G	-0.77	-1.16	-0.31
BSE	O&G	-0.56	-0.67	-0.44
BNP	O&G	-0.56	-1.01	0.41
ECC	O&G	0.07	-0.18	0.47
BRZ	Western	-0.06	-0.12	-0.04
LUR	Western	0.02	-0.03	0.05
ECC	Western	-0.04	-0.17	0.07
BNP	Western	-0.30	-0.52	-0.09
BSE	Western	-0.03	-0.05	0.07
CVAO	None	-0.015	-0.02	-0.01

^aSlope refers to the linear OLS regression fit slope. NOAA trend error represents the margin of error at the 95% confidence level, calculated as the half-width of the confidence interval using the NOAA trend standard deviation output.

association of benzene with O&G emissions suggests that the decline identified in the methane, ethane, and propane likely also contributed to the reduction in benzene. For instance, Helmig and colleagues (2025) determined a 0.0112 relative ratio of benzene/ethane in O&G pollution plumes. Applying that ratio value to the BRZ ethane trend of -0.196 ppb/yr results in an inferred O&G benzene emissions trend of -0.002 ppb/yr, which accounts for $\sim 38\%$ of the overall benzene trend of -0.006 ppb/yr, which was derived from the regression analyses.

NO_x

NO_x data were available from BRZ, BSE, and LUR. Similar to benzene, NO_x data were not separated by wind sector and wind speed but treated as one body of data. Results of their trend analyses are shown in Figure 40. Results were consistent in showing declining NO_x across these sites, spanning a range of -0.26 to -1.03 ppb/yr. These are significant rates of NO_x reduction, adding up to a ~ 3 ppb decline at BRZ over the record. Like benzene, NO_x has a variety of contributing sources, including mobile sources, electrical power generation, domestic heating, and O&G. According to the Regional Air Quality Council inventory (RAQC 2024), the O&G contribution to regional NO_x emissions is estimated as the largest at 45%.

Figure 37. NCFR ethane long-term trends converted to anomalies of the overall mean for each site.

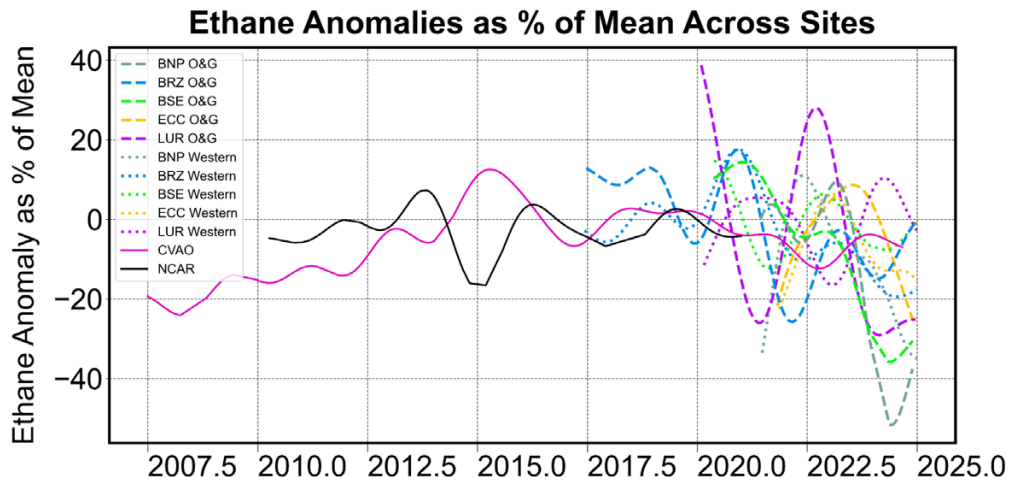


Figure 38. Smooth fit trend results for propane from the NCFR surface sites segregated by wind sector (top panel) and OLS regression results to the trend output to illustrate average changes over the full data record (bottom panel).

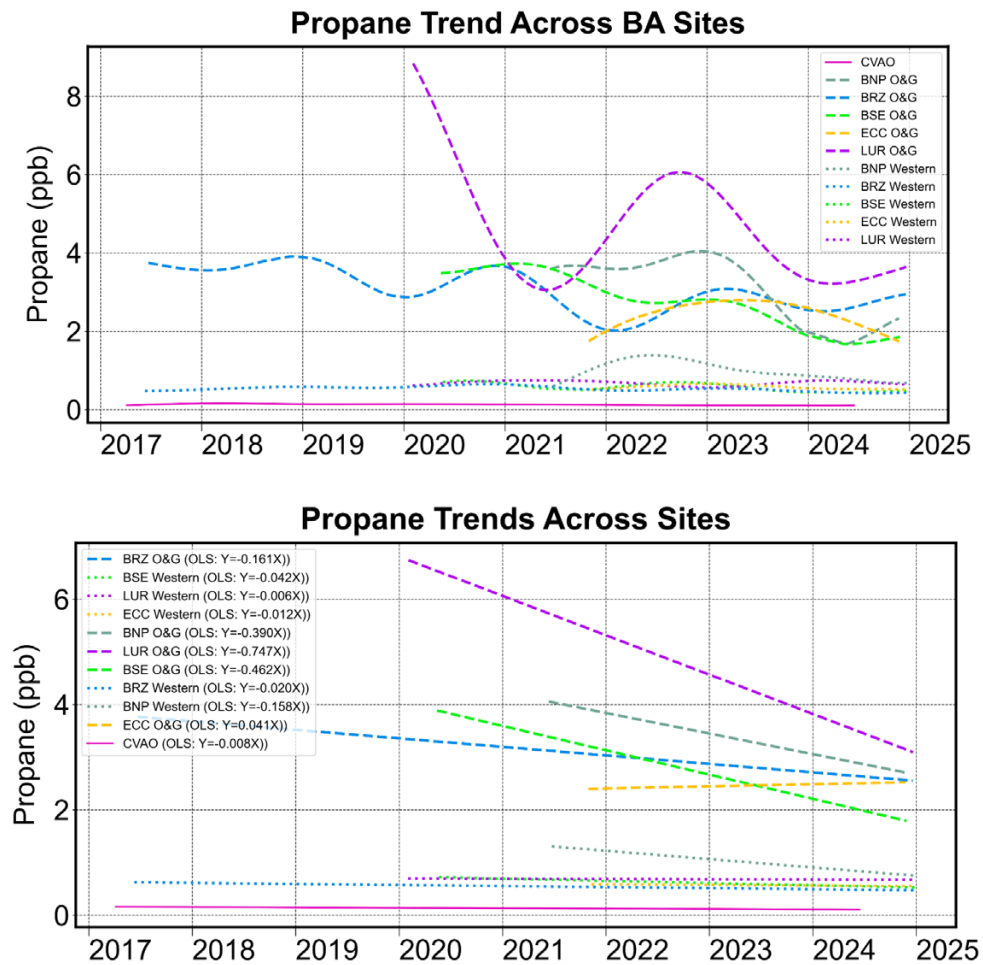


Figure 39. Smooth fit trend results for benzene from the NCFR surface sites segregated by wind sector (top panel) and OLS regression results to the trend output to illustrate average changes over the full data record (bottom panel). In this case, all data were pooled as benzene is not as strongly associated with O&G emissions as are ethane and propane.

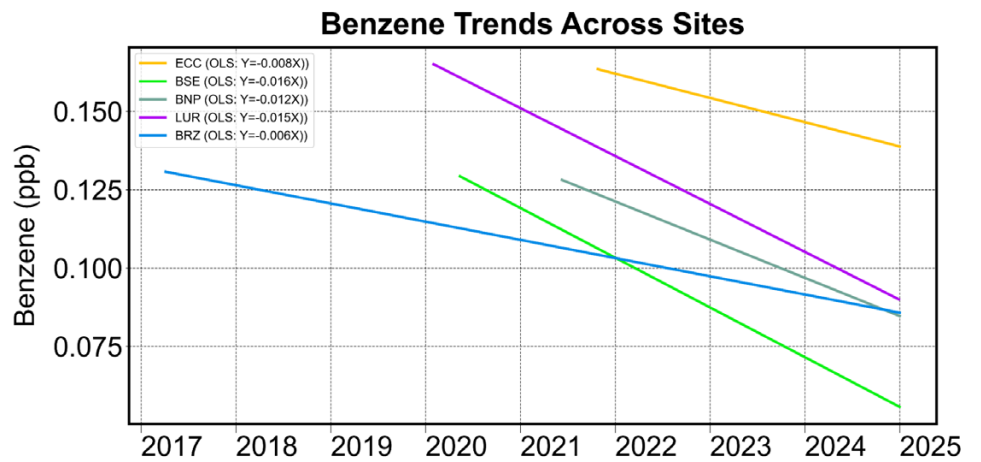
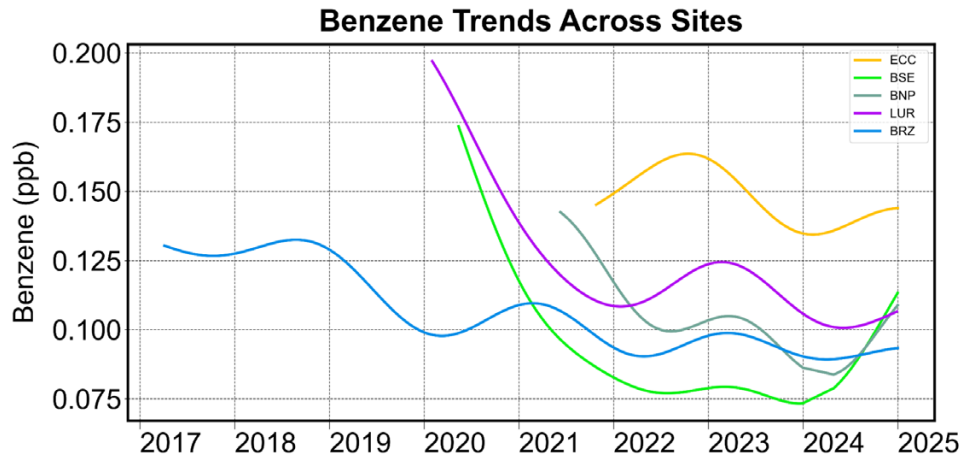


Figure 40. NOAA trend tool-derived NO_x trends across the NCFR sites operated by Boulder AIR.

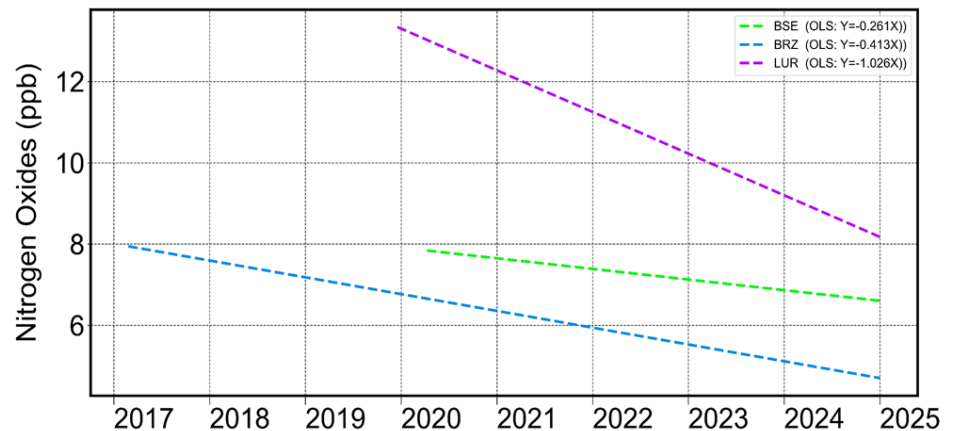
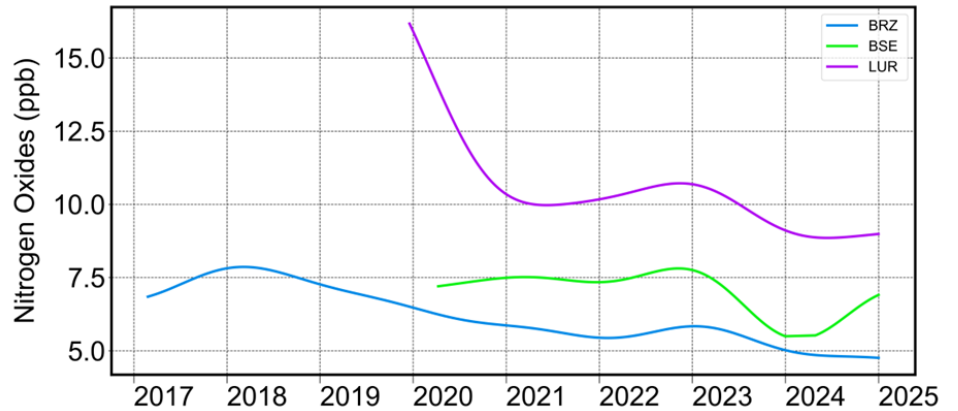
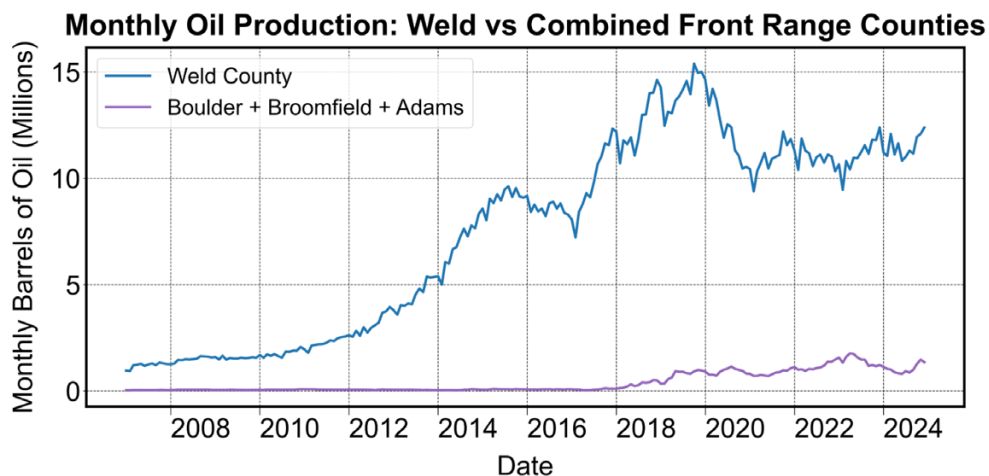
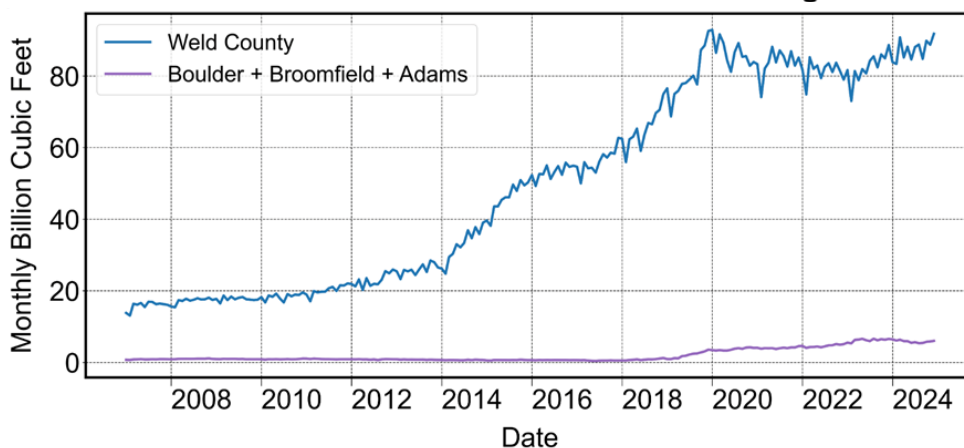


Figure 41. Development of oil (top panel) and gas production (bottom panel) in the NCFR, split between Weld County and Broomfield, Boulder, and Adams County, where the AQMs are located.



Monthly Natural Gas and Coalbed Production: Weld vs Combined Front Range Counties



Declining atmospheric NO_x has been reported for the NCFR previously (Abeleira and Farmer 2017; Bien and Helmig 2018); <https://airquality.gsfc.nasa.gov/no2/usa/colorado/denver>, as well as for the United States at large, with very few regional exceptions (Duncan et al. 2016). The NASA satellite data linked here indicate a 43% decline in surface NO_x during the 2005 to 2016 period. The findings from our NO_x trend analyses add to this steadily increasing body of literature.

Discussion of Colorado Trend Analysis

O&G drilling and production activities in Colorado have seen a dramatic increase, with most of this growth evident during the years spanning 2010 to 2020. Most of this growth has occurred in the NCFR, with more than 80% of the increase concentrated in Weld County (Figure 41). Natural gas and oil production show similar trend curves, with both peaking before the COVID-19 pandemic and leveling since then. Our study was able to collect monitoring data from within Weld County (BAO, LUR) and in proximity to the west of the DJ Basin (Figure 3). We were able to increase the selectivity of the data for characterization of O&G production region emissions by careful data filtering using wind data (confirmed via HYSPLIT air transport analyses).

The findings from our data analyses depict a consistent picture of gradually declining emissions effects in the NCFR. These signals were evident in time series trends of methane and the more selective O&G tracers ethane and propane. From these observations, we estimate NMHC emissions reductions on the order of 20% to 30% from the industry during the 2017 to 2024 period. Declining ambient air concentrations were also found for benzene and NO_x . This study determined that reductions in O&G emissions contributed ~38% of the observed decline in atmospheric benzene at the Boulder Reservoir monitoring station.

These findings, which build on high-accuracy data from longer records and incorporate observations from multiple sites, go well beyond the tools and data available for previous studies. Oltmans and colleagues (2021), using BAO observations, found a relatively small ($-1.6\%/yr$) decline in propane in the 2008–2016 data, which was only approximately a quarter of the estimated inventory emission changes. Lyu and colleagues (2021) reported larger reductions, identified through their analysis of 2013–2016 PVCO data; however, as noted by Oltmans and colleagues (2021), uncertainties in trend determinations are large when considering such short data records, and we found the quality of these data to be insufficient for regional trend determination (Appendix C). Two recent studies used satel-

lite-based remote sensing to assess methane and VOC trends in the DJ Basin. Reddy and Taylor (2022) reported a 55% decrease in methane emissions and a 73% decrease in ethane emissions from oil and natural gas sources between 2013 and 2020, with most of the reduction occurring after the period analyzed by Oltmans and colleagues (2021). Lu and colleagues (2023) found an annual 11% decrease in methane fluxes in the DJ Basin from 2010 to 2019. In our previous investigation of O&G emissions, building on earlier and shorter-record 2017–2020 data, we had not yet identified a clear trend signal in methane. O&G tracers, however, were found at declining rates of 5%–9%/yr, toluene at -0.012 ± 0.004 ppb/yr, and benzene at -0.007 ± 0.003 ppb/yr. Substantial uncertainty remains, however, about whether previously identified trend results were truly representative of long-term emissions changes, as the final year of the considered record was influenced by potential changes in drilling and production during the COVID-19 pandemic. Our findings presented here are a timely extension of this earlier work, with post-COVID data now being available for consideration. Observations of declining atmospheric concentrations of O&G emissions are generally in line with this previous literature, providing more certainty on these earlier evaluations because of the increased body of data, both in terms of the records' lengths and the available data products/sites.

The declining atmospheric concentrations (and inferred O&G emissions) during a period when the industry expanded (until ~2020) and then remained at a level close to its peak production are an indication that the emissions intensity (emissions per quantity of produced oil or gas) has and probably continues to decline. The resulting improvements to air quality are positive news, and they might reflect the benefit of the series of regulations that have been implemented in Colorado over the past 15 years (Table 1). A motivation for these progressively enacted Colorado State laws was the mandated federal requirement to reduce ozone precursor emissions, given that the NCFR has been designated an ozone NAAQS nonattainment area since 2008. Because the NCFR was further downgraded to severe nonattainment of the 2008 75 ppb ozone NAAQS in 2022, additional legislation targeting further emissions reductions may be required to bring the region closer to attainment.

CHAPTER 4: PERMIAN BASIN AIR QUALITY TRENDS FROM SATELLITE FORMALDEHYDE COLUMNS AS A PROXY FOR HYDROCARBON EMISSIONS

INTRODUCTION

Satellite-based observations of the troposphere use highly spectrally resolved measurements of reflected UV-vis radiation absorbed by target molecules in the atmosphere at various altitudes above the surface. Given its sources and sinks in the atmosphere, HCHO can be highly abundant in the tropospheric boundary layer. HCHO is a largely secondary product of atmospheric methane and NMHC oxidation. It thus represents an excellent tracer of the regional photochemistry of VOCs (Hong et al. 2021; Huang et al. 2023a, 2023b; Itahashi et al. 2022; Li et al. 2021) and has been extensively used to estimate biogenic isoprene emissions because of isoprene's high reactivity (short atmospheric lifetime) and large oxidative HCHO yield (e.g., Kaiser et al. 2018). HCHO VCDs derived from satellite measurements have been used to identify regions where atmospheric chemistry is dominated by isoprene emissions (Kaiser et al. 2018; Millet et al. 2008) or to estimate anthropogenic NMHC impacts on atmospheric chemistry. Recently, Li and colleagues (2021, 2022) have analyzed HCHO columns to constrain VOC emissions over Shanghai and the Pearl River Delta regions in China. Furthermore, Dix and colleagues (2023) have presented Permian Basin HCHO VCDs (using newer TROPospheric Monitoring Instrument [TROPOMI] instrument data) in the context of NMHC and NO_x emission inventory validation, demonstrating that HCHO in that environment is overwhelmingly formed from O&G-related NMHC emissions. However, because of the lower atmospheric reactivities of the overwhelmingly saturated hydrocarbon emissions from the O&G industry, HCHO becomes a poor tracer for NMHC emissions during winter.

In this section, we discuss our results of OMI instrument HCHO VCD data analysis with the goal of evaluating long-term trends across rapid shale O&G development in the Permian Basin in the 2010s up to 2022. All satellite datasets were stored on a personal computer (OneDrive cloud space) and backed up on an external hard drive. All satellite data analyses and plots were conducted using R software (Version 4.2.2). Gaussian smoothing was performed using the R function *ksmooth* with a "normal" Gaussian kernel.

DATA ACQUISITION AND ANALYSIS

SATELLITE DATA ACQUISITION

HCHO satellite data (and accompanying metadata parameters) are from the OMI instrument on the Aura satellite using

the OMI/Aura Formaldehyde (HCHO) Total Column Daily L3 Weighted Mean Global 0.1 deg Lat/Lon Grid V003 (Chance 2019) product, obtained from the NASA GES-DISC (Goddard Earth Sciences Data and Information Services Center, <https://disc.gsfc.nasa.gov/>). NASA Level 3 daily data gridded at 0.1° × 0.1° resolution are derived by NASA from Level 2 observations excluding retrievals with solar zenith angle (SZA) >70° and cloud fraction >0.3, and it includes only retrievals with "good" data quality flags screened to avoid OMI row anomalies. HCHO data were additionally restricted by the research team to <20 × 10¹⁶ molecules/cm² to avoid outliers. Metadata were downloaded with the HCHO data, including a NASA estimate of uncertainty for each daily gridded HCHO value.

Data were acquired for the entire OMI measurement period of ~17.5 years, from October 2004 to June 2022, specifically for a region over the Permian Basin in western Texas and southeastern New Mexico. TROPOMI HCHO data (available from May 2018 to December 2023) were not included in the study as originally proposed (see Appendix B for rationale). Aura OMI HCHO data were obtained for three regions: (1) the Permian Basin study area (104.5 to 100.5° W, 30.5 to 33.5° N); (2) a region over the Pacific Ocean (170 to 167° W, 30 to 33° N) for comparison at similar latitudes to assess global background and OMI satellite data drift; and (3) a (upwind) sparsely populated southern Arizona and northwestern Mexico region (113.5 to 111.5° W, 31 to 33° N) to represent immediate background air entering the Permian Basin from the west. More details on data acquisition are in Appendix B.

HCHO DATA LIMITATIONS AND VALIDATION

Several HCHO data products exist from the OMI satellite, each utilizing different algorithms. For this study, the downloaded OMI HCHO Level 3 data were produced using the Smithsonian Astrophysical Observatory (OMI-SAO) retrieval algorithm (Gonzales Abad et al. 2015). Validation of this HCHO product has shown a strong spatial correlation with aircraft observations in multiple separate studies (Liao et al. 2025; Zhu et al. 2016, 2020). Liao and colleagues (2025) reviewed several HCHO satellite retrieval products (including the OMI HCHO product from the Royal Belgian Institute for Space Aeronomy) to validate them against in situ observations from the NASA Atmospheric Tomography Mission (ATom) mission and found the OMI-SAO to have the best agreement. Zhu and colleagues (2016) validated and intercompared six retrievals of HCHO columns from four different satellite instruments (OMI, GOME2A, GOME2B, and OMPS) with HCHO aircraft observations from the NASA SEAC4RS campaign, and pointed specifically to a systematic error in the Royal Belgian Institute for Space Aeronomy product's assumed vertical HCHO shape profiles for the AMF calculation, but not for OMI-SAO. They found all the retrievals were consistent in spatial and day-to-day variability, and all are biased uniformly low. The low bias seen by Zhu and colleagues (2016) would not affect the trend analysis focus of this study; therefore, no correction factor was applied to the data.

However, a negative bias under high-HCHO conditions and a positive bias under low-HCHO conditions for OMI-SAO were reported later by Zhu and colleagues (2020). The authors compared HCHO OMI-SAO retrievals to 12 aircraft campaigns. They found negative biases under high-HCHO conditions and high biases under low-HCHO conditions, and specifically stated that the a priori vertical shape profiles are not a major driver of these biases. This bias pattern was similarly seen comparing the Royal Belgian Institute for Space Aeronomy product to the MAX-DOAS ground network, with HCHO columns biased high at low concentrations and biased low at high concentrations (De Smedt et al. 2021), and again when comparing to FTIR and aircraft measurements (Müller et al. 2024). This common bias pattern would indeed affect the current trend analyses by dampening trends.

Overall, HCHO satellite data validation and comparison studies do not universally support any HCHO product as a better match with independent (aircraft, surface) observations, nor do they invalidate the OMI-SAO product used here; rather, a negative bias under high-HCHO conditions and a positive bias under low-HCHO conditions have been reported.

The determination of total column HCHO from satellite data has limitations, with the algorithms relying on inputs and assumptions including cloud cover, surface albedo, vertical profile, and air mass factors. The highest uncertainty contribution is from the slant column density retrieval for both the OMI-SAO product (Gonzales Abad et al. 2015) and the Belgian OMI product (De Smedt et al. 2021), which is directly related to the signal-to-noise ratio of the instrument that has remained relatively stable over the years (De Smedt et al. 2021). The OMI satellite, in particular, has experienced significant aging since its start, with anomalies affecting the detector, causing progressively more track rows to be discarded as invalid. As of 2018, the degradation in coverage was up to 50% (Torres et al. 2018).

In the current study, Appendix B includes details on the number of monthly averaged grid cells going into the Permian spatial average calculation (each month providing a maximum of 1,200 grid cells), with the number of months with fewer averaged grid cells becoming more common in later years. This observation coincides with the increased annual average uncertainty seen in the Results section of this chapter. The increasing error band on trend estimates, combined with the above-noted high bias on low-HCHO concentrations and low bias on high-HCHO concentrations, constrains the ability of OMI HCHO satellite data to detect long-term trends. However, the record of the OMI dataset from 2004 is of a similar time frame to the Texas ground measurements studied here, and thus, the attempt to gather further trend information was pursued.

Detailed methods on the treatment of the OMI-SAO HCHO satellite data regarding time and spatial averaging, background drift correction, and temperature correction are included in Appendix B.

RESULTS

The monthly and spatially averaged HCHO time series shows strong seasonality as expected from precursor emissions and atmospheric chemistry, with higher chemical production from NMHCs in the warmer and sunnier summer months. **Figure 42** shows the monthly time series and Gaussian smooth curves for the defined Permian, Arizona, and Pacific regions after the OMI data drift correction. The regions outside the Permian served as upwind and background references, respectively.

Both the Permian Basin and Arizona regions have elevated HCHO concentrations above the Pacific background and show increasing trends compared with the Pacific background, as expected given the influence of land masses and human populations providing biogenic and anthropogenic sources of NMHCs. Within this context, the Permian Basin data display distinctly more elevated HCHO concentrations and a steeper trend compared with the Arizona region. Because the sparse vegetation of the Chihuahuan Desert, in which the Permian Basin is located, is not a significant source of isoprene, anthropogenic NMHC emissions, along with direct HCHO emissions (such as from gas flaring) are most likely dominating the increased Permian HCHO levels (Dix et al. 2023).

Within the Permian Basin are the two major subregions of the Delaware and Midland basins, each with their own makeup of O&G exploration activities (e.g., conventional vs. unconventional production, amount of oil vs. gas development, gas flaring). We found negligible differences between the west and east regions after spatial averaging (Appendix B); thus, we decided to study the Permian Basin region as a whole with respect to the potential impacts of O&G production activities on HCHO levels.

We observed that the satellite HCHO data for the defined Permian study region, in general, lack strong spatial gradients, especially in the monthly averaged data. Occasional hotspots were evident, however, even in the monthly averaged data. Investigating these hotspots was beyond the scope of this study, but they would be interesting to pursue as they may be linked to emissions events, recurring high emissions from specific operators, or long-term trends in the appearance of hotspots (i.e., biases).

Annual average uncertainty increased with time, mainly because of the reduction in the number of valid OMI measurements, not because OMI measurement uncertainty increased (Appendix B). The predominant source of uncertainty in the OMI HCHO column is error in the fitted slant column densities, which has remained stable. However, between 2005 and 2019, the number of valid OMI measurements decreased by ~30% (De Smedt et al. 2021). As a result, the uncertainty-reducing effect of averaging is lessened in later years, which is manifested in our data analysis as an increasing uncertainty over time, plotted in **Figure 43** together with the long-term trend.

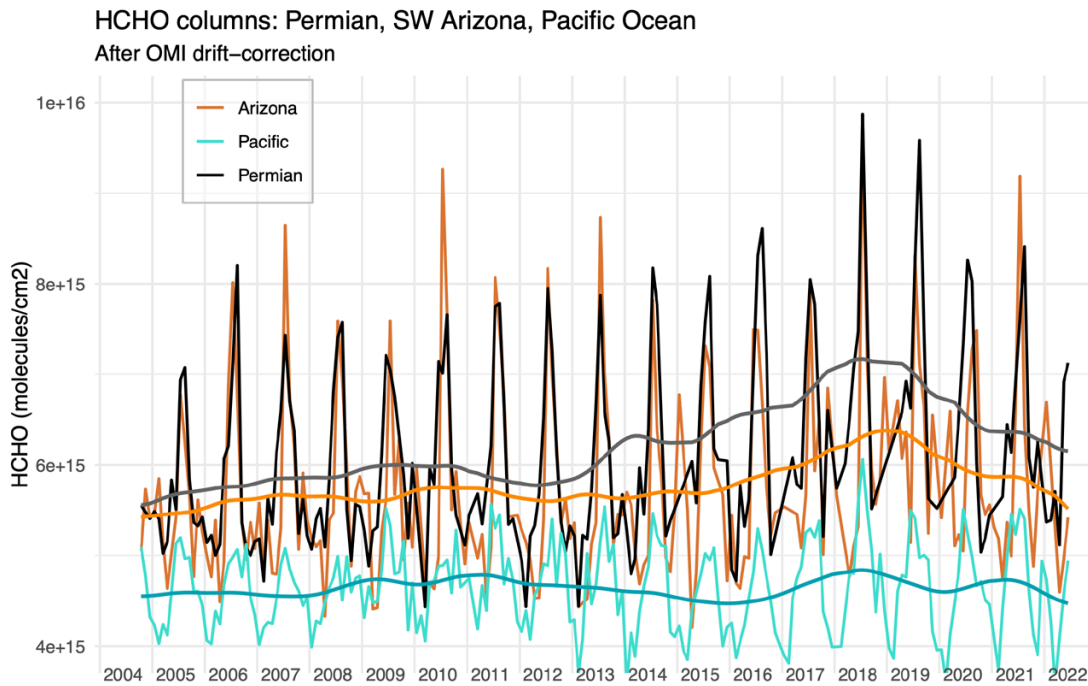


Figure 42. Permian Basin, southwest Arizona, and Pacific Ocean regions monthly time series plotted together after the application of the OMI data drift correction, as defined by the original Pacific Ocean time series. Data have not been normalized to temperature. Detection limit is estimated at approximately 4×10^{15} molecules/cm². Source: Millet et al. 2008.

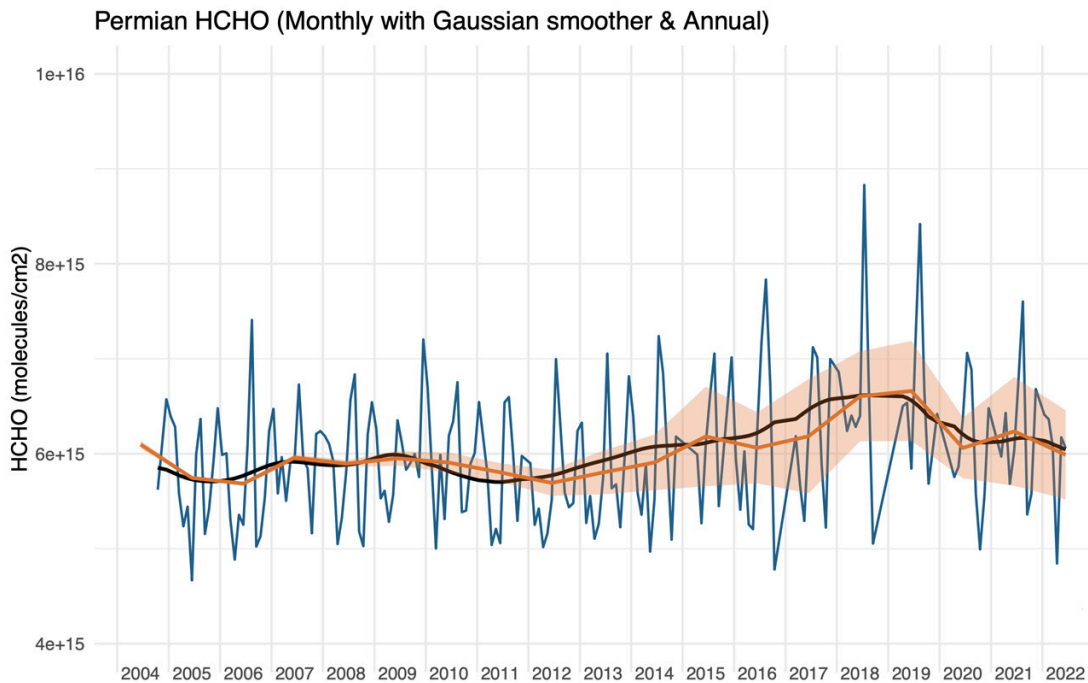


Figure 43. Time series for the Permian study region showing monthly average values (blue) with a Gaussian smooth line, and annual values (orange) with an uncertainty band as propagated from the NASA-provided daily VCD measurement uncertainties

The regionally averaged monthly and annual HCHO time series appear to increase around 2013–2014 up to a maximum in 2019. This increase correlates with the rapid increase in O&G production volumes over the same period (Figure 44). Following 2019, atmospheric HCHO VCD levels over the Permian region declined slightly again, departing from the O&G production trend. This decline might represent improved efficiencies and changed O&G or flaring practices, which led to fewer NMHC emissions. The Arizona data, however, also show this decline (Figure 42), suggesting influences of the larger-scale background affecting the post-2019 HCHO decline seen in the Permian region.

DISCUSSION AND CONCLUSIONS

Analyses of OMI HCHO columns have been extensively used, especially in the last ~10 years, to determine VOC emission trends (Barkley et al. 2017; Bauwens et al. 2016; Bauwens et al. 2022; Millet et al. 2008; Pavel et al. 2021; Shen et al. 2019; Stavrakou et al. 2018; Strada et al. 2023; Vohra et al. 2021; Wang et al. 2021; Xia et al. 2024). Both trends in anthropogenic VOC emissions in metropolitan areas (e.g., Vohra et al. 2021) and trends in biogenic isoprene emissions (e.g., Strada et al. 2023) have been investigated. However, instrument drift has not always been corrected for, and the high uncertainty of individual measurements (Xia et al. 2024), together with recently evaluated biases (Müller et al. 2024), renders the detection of small trends uncertain.

Similar anthropogenic emission trends have been evaluated from satellite data using the strong UV-A absorption of NO_2 , considering that NO_x emissions from the surface into the troposphere are typically dominated by fossil fuel combustion sources (Duncan et al. 2016; Ojeda-Castillo et al. 2025). Satellite NO_2 data were not analyzed here as they have already been documented for the Permian Basin in several prior works (Dix et al. 2020, 2022; Gyawali et al. 2023), whereas potential changes in HCHO have not. Furthermore, the observed regional increase in NO_2 column densities is not directly related to hydrocarbon emissions, but rather to a set of different O&G production activities, such as drilling, which are

often not directly related to NMHC emissions. NO_x emissions are temporary with respect to drilling and gas flaring, and more permanent considering stationary engines and mobile sources in the industry, such as the truck traffic the industry generates, which leads to a general correlation between methane and NO_x (Gorchov Negron et al. 2018; Hungund et al. 2023). In summary, NO_x emission dynamics may not vary in close parallel with NMHC emission dynamics because of different emission processes, and our focus in this work was on NMHCs.

The small trend we discovered (2%/yr) for the Permian Basin in the second half of the 2010s appears significant, and may increase with the recently developed, improved retrieval algorithm (Ayazpour et al. 2025; Müller et al. 2024). It does correlate well with the rapid growth phase of O&G exploration in the Permian Basin between 2014 and 2020, during which gas flaring in the area also increased dramatically. A somewhat similar trend was observed for a desert region of southern Arizona, for which we did not expect to find a long-term trend. As shown in Figure 42, however, the difference between these regions increased sharply in 2014 and remained higher than before that time for the remainder of the data, albeit somewhat lower in the last 2 years of the OMI dataset period.

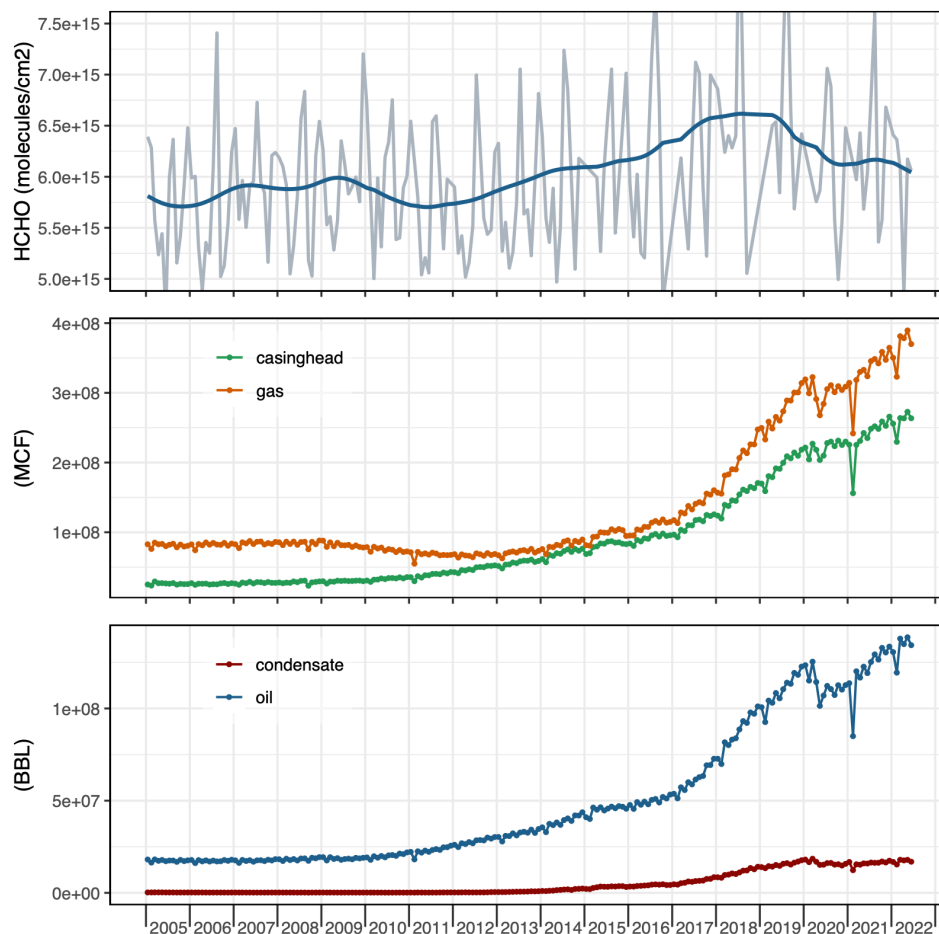


Figure 44. HCHO VCD time series for the Permian study region with a Gaussian smooth line in comparison with the reported O&G production volumes for the Texas Permian Basin. Data source: Railroad Commission of Texas, <https://rrc.texas.gov/oil-and-gas/major-oil-and-gas-formations/permian-basin/>.

We conclude that the increasing trend in the OMI HCHO VCD data between 2014 and 2020 is likely real, but a renewed effort should be made with improved OMI retrievals to better quantify these changes. As the relative changes we derived are small (+10% over 5 years), they may not accurately reflect the anthropogenic VOC emissions changes in the Permian Basin because of preexisting biases in the retrievals we employed. It is unlikely that a doubling to tripling of O&G production over these 5 years (Figure 44) would have resulted in only a 10% increase of HCHO VCDs over this period, given the sharp increase of hydrocarbon emissions associated with new O&G exploration (Allen 2016; Helmig et al. 2016). Furthermore, Dix and colleagues (2023) pointed out that HCHO formation from hydrocarbons is sensitive to NO_x . Because NO_x abundances in the Permian Basin increased over the period in question (Dix et al. 2020, 2022) — most likely also due to the region's O&G development (Gyawali et al. 2023) — it makes sense that HCHO abundances in the Permian Basin should have increased much more than 10% over the O&G exploration growth period.

Presuming the derived OMI trends for the region underestimate actual trends but are reproducible from year to year, an apparent decoupling between HCHO VCDs and production data was observed after the onset of the COVID-19 pandemic in 2020. Although hydrocarbon production volumes remained high or increased further (Figure 44), and thus, NO_x emissions may have been stable, HCHO VCDs did not increase further. While this deviation cannot be evaluated through this project's data, the industry has repeatedly asserted that it improved its methane emissions intensity, as it improved its flaring intensity. If such improvements did occur and went along with similar improvements in NMHC emissions, the decoupling observed around 2020 between the production volume data and HCHO VCDs (Figure 44) could be explained.

CHAPTER 5: SYNTHESIS, INTERPRETATION, AND IMPLICATIONS OF FINDINGS

Hydrocarbon trends were remarkably different between the Texas and Colorado sites investigated during this project. Broadly, all sites in Texas, regardless of which shale production area they were in or near, appeared to show trends that followed hydrocarbon production volumes. In many cases, there was a significant correlation; in some cases, there was only an effect on air quality observed during the beginning of the boom; in others, coarse periodic tendencies were reflected in the air quality data. These results were somewhat surprising considering the continued federal rulemaking (New Source Performance Standards Subpart OOOO rules) to reduce NMHC emissions. In principle, emissions reduction at the sources should improve emissions intensity and thus reduce the correlation between production volumes and ambient air pollutant levels over time for the investigated, industry-dominant compounds. The effect may be present in the Haynesville data, but it is not obvious at other Texas AQM sites.

The surface AQM station data were not contradicted by the satellite-based OMI HCHO VCD data we analyzed for the Permian Basin. While HCHO VCDs were comparatively low throughout the nearly 18-year OMI record, a significant upward trend was observed between approximately 2015 and 2020, which coincided with the rapid development of the shale resource in the Permian Basin up to the pandemic crash in 2020. The 5-year HCHO increase of 10% was highly uncertain because of the degradation of the OMI satellite coverage during this period. Moreover, a 10% increase appeared to be small relative to the increase in O&G production volumes. After the pandemic crash, HCHO VCDs leveled or decreased, but it is unclear whether this effect was driven by reductions in NMHC emissions, NO_x emissions, or both.

Unlike those in Texas, results for the Colorado sites showed generally decreasing atmospheric mixing ratios for the NMHCs investigated and consistency between the researched sites. Downward trends were more pronounced the closer a site was to the shale O&G production region. The Colorado findings depict a consistent picture of gradually declining emissions impacts in the NCFR. These signals were evident in time series trends of methane and the O&G tracers ethane and propane. From these observations, we estimate NMHC emission reductions on the order of 20% to 30% from the industry during the 2017–2024 period. Declining ambient air concentrations were also found for benzene and NO_x. We determined that reductions in O&G emissions contributed approximately 38% of the observed decline in atmospheric benzene at the Boulder Reservoir monitoring station. In comparison, something was clearly different between the developments in Texas and Colorado.

In Texas, the state regulator, TCEQ, has overseen implementation of EPA's Quad-O rules, which began in 2012, but TCEQ has passed no additional air quality regulations for the O&G industry. Operational activities such as gas flaring are regulated instead by the TxRRC. Few Texas AQM records were available for the early period of the boom before 2012, and we therefore cannot determine the effects of the federal Quad-O rulemaking on NMHC emissions in Texas with confidence. However, there were two small indications of possible effects in the data:

- The two AQM sites at the northern end of the Haynesville Shale showed significant air quality effects in the late 2000s up until 2012, when ambient NMHC levels dropped somewhat quickly (Figure 24). This improvement of air quality was larger than expected from the more gradual decrease in shale area production volumes; thus, possibly, federal rules, which first addressed shale gas (not oil) production, may have had an effect in this gas-producing shale region.
- O&G production was still increasing rapidly in the Eagle Ford when the first Quad-O rules were passed and peaked in 2015. Although air quality generally worsened from 2008 to 2015 at the OLN site downwind in southwestern San Antonio (Schade and Roest 2015), we observed a small drop from 2012 to 2013 (Figures 19 and 20), suggesting a possible consequence of the first set of federal regulations addressing shale gas production.

No obvious consequences of federal rulemaking could be detected in the atmospheric data in the two other shale production areas in Texas, the Barnett Shale and the Permian-Midland Basin. Similarly, no immediate effects of the minor flaring-related rule changes implemented in Texas in the early 2020s were evident in the observed atmospheric NMHCs.

Overall, these findings indicate that federal Quad-O rulemaking had little direct effect on air quality in Texas, and that any resulting emissions reductions were not strongly reflected in the atmospheric molar mixing ratios examined for this study.

The development in Colorado may have been different. As all site records began after 2016, any effects of the initial and second set of federal Quad-O rules could not be investigated. Hence, we have insufficient information on the possible effects of the Quad-O rulemaking in Colorado. However, state rulemaking did significantly precede and sufficiently overlap with the measurement periods in Colorado. The consistent improvements in NCFR air quality as affected by emissions in the DJ Basin could have resulted from associated changes to O&G (field) operations in Colorado, which in turn may have caused significant emission reductions over time, not correlating with O&G production volumes, meaning operations have improved their emissions intensity. However, if O&G operations in the field were uniformly changing across the industry, similar air quality improvements would be expected at least in parts of Texas as well. It seems unlikely that general, industry-wide

emissions intensity improvements would be achieved in Colorado and not in Texas, given that numerous operators are active in both states. Comparable improvements in emissions intensity in both states, combined with larger growth in O&G exploration activities and production in Texas, could counteract the efficiency gains achieved in Texas. Although plausible for the Permian Basin, where production continues to increase, stagnant or decreasing production rates in the Eagle Ford and Barnett Shale regions, together with more limited air quality improvement, suggest that factors other than emissions intensity also play a role. For example, regional differences between Colorado and Texas could play a role. Coloradans have been pushing for more responsible, lower emissions operations, and these advocacy efforts may have contributed to lower emissions over time in Colorado; however, the associated operational changes may not have translated to similarly sized improvements in Texas.

Our analyses included benzene, a toxic NMHC. Benzene levels in Texas were below 0.5 ppb on average at most AQM stations. Where benzene levels had been higher in the past at AQM stations with long-term records, such as at the LRB site, they have come down over time, similar to observations at many other, mostly urban AQM stations (Fortin et al. 2005; Holland et al. 2022). Benzene levels remain elevated (approximately ≥ 0.5 ppb) or have not declined consistently over the past decade in the Longview area downwind of the Haynesville Shale and at the United States–Mexico border in Laredo. In both locations, emissions sources other than O&G, such as truck traffic, are likely to contribute more to ambient benzene levels. In the Permian Basin, where O&G production has continued to increase, the rise in benzene levels observed throughout the 2010s and early 2020s appears to have subsided; however, a closer look at TCEQ's recently deployed AQM monitors in the area is needed to assess recent trends more accurately, particularly outside the western Permian-Delaware Basin.

Benzene levels in the NCFR were, on average, lower than in Texas, rarely exceeding 0.5 ppb, and with averages generally below 0.2 ppb. However, benzene levels were regularly above 1 ppb at the PVCO station at the beginning of its record, partly because the canister samples at that site were collected during the early morning hours, when shallow nighttime boundary layers typically lead to higher ambient air pollutant concentrations. Benzene at that station has since come down to levels generally below 0.5 ppb as well, but ongoing concerns about the site's sampling protocol and data quality provide little confidence in the reliability of these data and their trends.

Overall, we conclude that toxic benzene emissions have been decreasing in most shale O&G production areas. However, some air quality concerns remain in areas where multiple sources of benzene, both O&G-related and other, emissions persist, such as in populated areas of the Permian Basin, where emissions have correlated with increasing O&G production volumes in the recent past.

DATA AVAILABILITY STATEMENT

NMHC data from both Colorado and Texas, as well as the analyzed OMI data, are accessible through the Texas Data Repository at the following links: <https://doi.org/10.18738/T8/178PP5> for the Texas NMHC and winds datasets, <https://doi.org/10.18738/T8/RXFVFO> for the Colorado NMHC and winds datasets, and <https://doi.org/10.18738/T8/6I1JIT> for the OMI satellite formaldehyde vertical column datasets.

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HEI QUALITY ASSURANCE STATEMENT

The conduct of the study “*Air Quality Trends in Texas and Colorado Associated with Unconventional Oil and Gas Development*” was subjected to an independent audit by Scott Adamson, CCM, and Nic Hofmann of Trinity Consultants, Inc. Mr. Adamson and Mr. Hofmann are experts in quality assurance for air quality monitoring studies and data management.

The audit included a review of data quality for conformance to the study protocol as detailed in the final report and the study’s quality assurance plan, reviewing data quality for each of the study components. In January 2026, an off-site audit was conducted via a teleconference with primary study personnel. The audit concentrated on the study’s quality assurance and data management activities and included a review of the overall process used to acquire and screen existing ambient air quality monitoring data and to analyze and evaluate long-term air quality trends through statistical methods. Also evaluated were the procedures and measures undertaken to ensure quality and consistency across the processed databases and modeling results. Study personnel displayed representative examples of different types of data and modeling files, which were reviewed for consistency, clarity, and completeness.

A written report of the audit was provided to the HEI project manager, who transmitted the findings to the principal investigators. The quality assurance audit demonstrated that the study was conducted by an experienced team with great concern for data quality. Study personnel were responsive to audit questions and recommendations, providing formal responses that adequately addressed all issues. The report appears to be an accurate representation of the study.



Scott Adamson
Principal Consultant, CCM

SUPPLEMENTARY APPENDICES ON THE HEI WEBSITE

Appendices A–C contain additional material not included in the main report. They are available on the [HEI website](#).

Appendix A. Detailed Method Descriptions

Appendix B. Additional Methodological Details Concerning the Satellite Data Analysis

Appendix C. Additional Results

ABOUT THE AUTHORS

Gunnar W. Schade holds a PhD from the University of Mainz in Germany. As a postdoctoral researcher with Allen Goldstein at the University of California at Berkeley, he was in charge of an Ameriflux network site’s volatile organic compound flux measurements in the Sierra Nevada of California from 1998 to 2002 before returning to Germany for a prestigious Emmy-Noether grant in 2003. After a brief 2-year stay at the University of Bremen from 2003 to 2005, he moved into a tenure-track position in the Atmospheric Sciences department at Texas A&M University in College Station. Schade worked on urban flux measurements of energy and trace gases, including hydrocarbons, at a unique tower site in Houston before switching to research on the effects of the shale O&G boom in the United States on air quality in 2014. He was among the first to point out the potential impacts of oil and gas exploration-related emissions on ozone air quality in 2015 and has since completed a series of air quality measurements and analysis projects related to O&G-related emissions in Texas.

Detlev Helmig holds a PhD in environmental chemistry from the University of Duisburg, Germany. He conducted his postdoctoral research at the University of California Statewide Air Pollution Research Center in Riverside and the National Center for Atmospheric Research in Boulder, Colorado. He subsequently received an EPA Young Investigator Award and became a research professor at the University of Colorado. The core of his research is the study of air composition, air quality, atmospheric chemistry, composition changes, and atmospheric transport, with an emphasis on local to regional air quality. Most recently, he became the founder and owner of Boulder Atmosphere Innovation Research (AIR). Boulder AIR has been contracted by local governments to implement the monitoring of air quality indicators at several locations across the Colorado Front Range. Helmig led the development, deployment, and operation of the Loving stationary air monitoring station. His research has resulted in some 250 peer-reviewed publications. He is the editor-in-chief of the Atmospheric Science Domain of the online, nonprofit journal

Elementa-Science of the Anthropocene, published by the University of California Press. In that role, he is overseeing the manuscript peer review of several special features, such as “Oil and Natural Gas Development: Air Quality, Climate Science, and Policy,” “Quantification of Urban Greenhouse Gas Emissions: The Indianapolis Flux Experiment,” and “Reactive Gases in the Global Atmosphere” (<https://online.ucpress.edu/elementa/pages/specialfeatures>).

Katherine Potter holds a PhD in climate physics and chemistry from the Massachusetts Institute of Technology. Her doctoral and subsequent work included laboratory-based analytical instrument development and air/environmental measurements. After obtaining her PhD, she collaborated with the Advanced Global Atmospheric Gases Experiment global air monitoring network to lead the establishment of the Rwanda Climate Observatory, working in the field in Rwanda and making continuous in situ air quality measurements. Most recently, she worked with Boulder AIR, running a set of eight air monitoring stations in the NCFR, making continuous high-frequency air quality measurements.

Michel Stahl holds bachelor’s degrees in mathematics and economics from the University of Colorado Boulder, graduating cum laude. During his time at the University of Colorado Boulder, he was inducted into the Pi Mu Epsilon National Mathematics Honor Society, awarded a competitive economics merit scholarship, and contributed to a psycholinguistic research project that received multiple grants. Trained in econometrics, mathematical statistics, and data science, he further strengthened his technical background through additional data science coursework completed through an online bootcamp. Stahl is currently a contracted data analyst at Boulder AIR, where he focuses on data quality assurance and statistical modeling.

Gabriel Greenberg holds a bachelor’s degree with a focus in chemistry from Quest University Canada and a master’s degree in data science from the University of Wisconsin. During his academic career, he contributed to the development of experiential forensic geochemistry curricula and interned at the University of Colorado’s Institute of Arctic and Alpine Research, analyzing gas chromatography data for global monitoring of volatile organic compounds. Trained in statistical methods, machine learning, and high-performance computing, he possesses a robust technical background utilizing Python, R, SQL, and big data tools. Gabriel is currently a data scientist at Boulder AIR, where he focuses on data quality control, pipeline automation, statistical modeling, machine learning applications, and the visualization and analysis of greenhouse gases and atmospheric pollutants.

OTHER PUBLICATIONS RESULTING FROM THIS RESEARCH

PRESENTATIONS AND POSTERS

- Air Quality Trends in Texas and Colorado Associated with Unconventional Oil and Gas Development (UOGD)
Gunnar W. Schade and Detlev Helmig
Poster at the HEI Annual Conference 2024, Philadelphia, PA, May 2024
- Trends of Oil and Natural Gas Emissions and Their Impact on Air Quality in the Northern Colorado Front Range
Detlev Helmig, Gabriel Greenberg, Katherine Potter, Gunnar Schade, and Michel Stahl
Poster at the HEI Annual Conference 2025, Austin, TX, May 2025
- Air Quality Trends in Texas Associated with Unconventional Oil and Gas Development (UOGD)
Katherine E. Potter and Gunnar W. Schade
Poster at the HEI Annual Conference 2025, Austin, TX, May 2025
- Sources and Trends of Atmospheric Volatile Organic Compounds in the Northern Colorado Front Range
Detlev Helmig, Dani Caputi, Ryan W. Daly, Lisa Darby, Jacques Hueber, Gabriel Greenberg, Kat Potter, Gunnar Schade, Susan Simoncic, and Michel Stahl
Oral presentation at the AWMA Conference on Air Quality Measurement Methods and Technology 2025, Aurora, CO, April 23–25, 2025

Research Report 242, *Air Quality Trends in Texas and Colorado Associated with Unconventional Oil and Gas Development*, by G.W. Schade and D. Helmig et al.

INTRODUCTION

The scale and rate of onshore oil and natural gas development in the United States since the early 2000s differ markedly from earlier periods because of technological changes, including increased use of hydraulic fracturing (i.e., “fracking”) and horizontal drilling. Although hydraulic fracturing has captured much public attention, the process itself is not new; neither are horizontal drilling and oil and gas extraction from unconventional formations, such as tight (i.e., low-permeability) sandstone and shale. What is new is the use of high-volume (millions of gallons of water per well) multistage hydraulic fracturing combined with horizontal drilling extending thousands of feet.

Unconventional oil and natural gas development (UOGD)* has been associated with a wide range of potential exposures to chemical and nonchemical agents. The rapid expansion of this development has given rise to concerns about possible effects on human health. Moreover, knowledge gaps remain about these exposures that must be addressed to better understand these potential health effects.

In 2023, Health Effects Institute Energy (HEI Energy) issued a *Request for Qualifications (RFQ) E23-1: Trends in Air Quality and Community Exposures Associated with Oil and Gas Development*. The goal of the RFQ was to comprehensively analyze air quality and other data for one or more US regions to assess trends in air quality and air pollutant emissions (including, but not limited to, UOGD) since the early 2000s alongside the corresponding effects on population exposures. To the extent feasible, investigators were asked to assess the contribution of UOGD-related emissions to the observed trends in air quality and exposure and the effectiveness of evolving policy and industry practice intended to reduce exposures to emissions associated with UOGD. This research complements previously funded HEI Energy studies that examine how population-level exposures to UOGD-related

Drs. Gunnar W. Schade’s and Detlev Helmig’s 1-year study, “Air Quality Trends in Texas and Colorado Associated with Unconventional Oil and Gas Development,” began in May 2024. Total expenditures were \$273,316. The draft Investigators’ Report from Schade, Helmig, and colleagues was received for review in April 2025. A revised report, received in October 2025, was accepted by the HEI Energy Review Committee in November 2025.

During the review process, the HEI Energy Review Committee and the investigators had the opportunity to exchange comments and clarify issues in both the Investigators’ Report and the Review Committee’s Commentary. This Commentary has not been reviewed by public or private party institutions, including those that support HEI Energy, and may not reflect the views of these parties; thus, no endorsements by them should be inferred.

* A list of abbreviations and other terms appears at the end of this report.

emissions have changed since the early 2000s, together with changes in UOGD operations and governance.

In November 2023, co-principal investigators Drs. Gunnar W. Schade and Detlev Helmig submitted a full application, “Air Quality Trends in Texas and Colorado as Associated with Unconventional Oil and Gas Development.” The Energy Research Committee thought that the proposed study addressed key aspects of the RFQ and had notable strengths, including the use of high-resolution, high-quality historical data for the proposed analyses. The Committee also thought that the focus on nonmethane hydrocarbons (NMHCs), air pollutants associated with UOGD, was appropriate given their relevance to health. This study is one of three studies funded under *RFQ E23-1* (see Preface).

This Commentary provides the HEI Energy Review Committee’s independent evaluation of the study. It is intended to aid the sponsors of HEI and the public by highlighting the study’s strengths and limitations and placing the results presented in the Investigators’ Report in a broader scientific and regulatory context.

SCIENTIFIC AND REGULATORY BACKGROUND

UOGD OVERVIEW

UOGD refers to the development and production of oil and natural gas through multistage hydraulic fracturing in horizontal wells (HEI Special Scientific Committee on Unconventional Oil and Gas Development in the Appalachian Basin 2015). UOGD processes occur on and off the well pad and include the following:

- **Field development:** exploration, pad preparation, vertical and horizontal drilling, well completion (casing and cementing, perforating, acidizing, hydraulic fracturing, mill out, flowback, and well testing) in preparation for production, and management of wastes
- **Production operations:** extraction, gathering, processing, and field compression of gas extraction and processing of oil and natural gas condensates; management of produced water and wastes; and construction and operation of field production facilities
- **Postproduction:** well closure and land reclamation

Although some UOGD operations are regulated at the federal level under the Clean Air Act, the Clean Water Act, and the Safe Drinking Water Act, state-level regulations play

a larger role in governing UOGD more generally. Such regulations vary among states, with some states defining minimum setback distances between UOGD and specific land uses, such as residential homes and schools, to protect local populations. For example, in Colorado, the setback distance is at least 500 feet, but any oil and gas site within 2,000 feet of a residential building requires additional approvals (ECMC 2025), whereas Texas does not have a uniform statewide setback distance.

UOGD AND AIR QUALITY

UOGD can affect local air quality in nearby communities and regional air quality, as well as the broader climate, through the emission of greenhouse gases. UOGD processes emit a mixture of methane and NMHCs, such as ethane, propane, and benzene, which may affect air quality directly (benzene is considered a hazardous air pollutant) or indirectly by reacting with other air pollutants to form criteria air pollutants, such as particulate matter (PM) and ozone (O₃), as methane, ethane, and propane can act as such precursor gases (HEI Special Scientific Committee on Unconventional Oil and Gas Development in the Appalachian Basin 2015). UOGD operations may also directly emit other precursor gases such as nitrogen oxides (NO_x) (Nsanzineza et al. 2019).

Both criteria and hazardous air pollutants are of concern to human health. For example, criteria air pollutants, such as ozone, have been associated with adverse respiratory outcomes (US EPA 2020). Hazardous air pollutants, such as benzene, have been associated with both cancer and noncancer outcomes (US EPA 1998, 2002).

The atmospheric concentrations of these pollutants depend on emission rates, dispersion patterns, and chemical transformations, all of which vary depending on conditions at specific sites. This variability makes exposure assessments difficult, especially exposures that result from intermittent sources or specific meteorological conditions. Concentrations that persist for a relatively brief period of hours to weeks (i.e., short-term) or for months to years (i.e., long-term) can both be problematic, depending on the toxicity and concentration of the pollutant and the extent of human exposure. In general, the highest air pollutant concentrations occur at or immediately downwind of UOGD sites. However, the spatial extent of their effect on air quality and how exposures vary among various populations is not well understood (HEI Energy Research Committee 2020).

Federal, state, and local regulations and policies have evolved alongside UOGD industry practice since the early 2000s. Many of these changes have been designed to address concerns about potential population exposure to air emissions. Concurrently, many studies have been conducted to understand potential human exposures and health effects associated with UOGD (Rosofsky and Adelsheim 2022). In addition, routine monitoring has continued, and remote sensing has emerged as an increasingly important tool for understanding atmospheric pollutant concentrations and human exposure.

Recent research has begun the process of reviewing air quality data in specific regions where UOGD is present (e.g., Lim et al. 2019, Long et al. 2019, Lyu et al. 2020) and assessing trends in air quality in those regions (Lange et al. 2023). With adequate data, studies may now be able to evaluate trends in air quality and population exposures associated with UOGD in the United States. They may also be able to link observed concentrations to source emissions (where feasible, depending on the extent and quality of emissions information and available air quality models). It is important to note that efforts to link UOGD emissions with air pollutant concentrations need to consider how air quality in UOGD locations may be affected by emissions from conventional oil and gas development and other local and regional sources (e.g., industrial activities, non-UOGD traffic, and naturally occurring chemicals). This study expands upon such preliminary research assessing trends in air quality in regions with UOGD using a longer record of historical data from multiple air quality monitoring locations across different regions of the United States.

STUDY OBJECTIVES

The overarching objective of the investigators' study was to evaluate existing air quality records from monitoring stations in two important UOGD regions in the United States, Texas and Colorado, to determine any identifiable trends in NMHCs (specifically, ethane, propane, and benzene) and NO_x emissions associated with UOGD. The investigators additionally evaluated trends in formaldehyde emissions in the Permian Basin, which spans Texas and New Mexico, which, in 2025, produced the crudest oil in the country (US EIA 2026). The study had two specific aims:

Aim 1. Evaluate trends in air quality in Texas and Colorado using air quality monitoring data collected in and around UOGD basins with a focus on changes in the concentrations of certain NMHCs (ethane, propane, benzene) and NO_x.

Aim 2. Evaluate trends in air quality in the Permian Basin in Texas and New Mexico using satellite-based measurements with a focus on vertical column densities (VCDs) of formaldehyde.

For Aim 1, the investigators first compiled publicly available data on measurements of ethane, propane, benzene, and NO_x from air quality monitoring stations across Texas in proximity to the Barnett Shale, Eagle Ford Shale, Haynesville Shale, and eastern Permian Basin. They also collected ethane, propane, benzene, and NO_x data from air quality monitoring stations in Colorado in proximity to the Denver–Julesburg Basin. In Colorado, they were also able to obtain methane concentration data, whereas no air quality monitoring stations in Texas measure methane. Air quality data roughly spanned 1997–2023 for Texas and 2008–2024 for Colorado, depending on data availability by monitor.

The investigators next analyzed the data to identify any trends in air pollutant concentrations that may be related to

increases in UOGD production volume. They used two statistical techniques for analyzing trends in time series data (i.e., trend analysis): natural cubic splines, which were applied to the Texas data, and NOAA’s Fast Fourier Transform (FFT) curve-fitting routine, which was applied to the Colorado data.

To help differentiate the effects of local versus regional or other sources of air pollution, the investigators used information on wind direction and speed to identify air mass origin sectors in the data. To help distinguish between local sources of air pollution and background levels of air pollution, they compared the data with air pollutant concentrations at two reference locations in the Northern Hemisphere (Hawaii and Cape Verde), when feasible.

For Aim 2, the investigators focused on satellite-derived formaldehyde observations from 2004 to 2022 across the Permian Basin. Formaldehyde can serve as a proxy for NMHC emissions as it is a secondary oxidation product of NMHCs in the atmosphere. Given the lack of long-term historical data on formaldehyde from air quality monitoring stations in the region, they obtained satellite measurement data from the Ozone Monitoring Instrument (OMI) on the US National Aeronautics and Space Administration (NASA) Aura satellite. They then averaged measurements over space and time to obtain regional monthly averages for the entire Permian Basin. Finally, they evaluated trends in formaldehyde VCDs over time by applying Gaussian smoothing, another technique that can be used to analyze trends in time series data. As in Aim 1, they additionally compared these data with formaldehyde

column measurements at two reference locations (a remote part of the Pacific Ocean and southern Arizona/northwestern Mexico) to discern local pollution sources and trends from background levels.

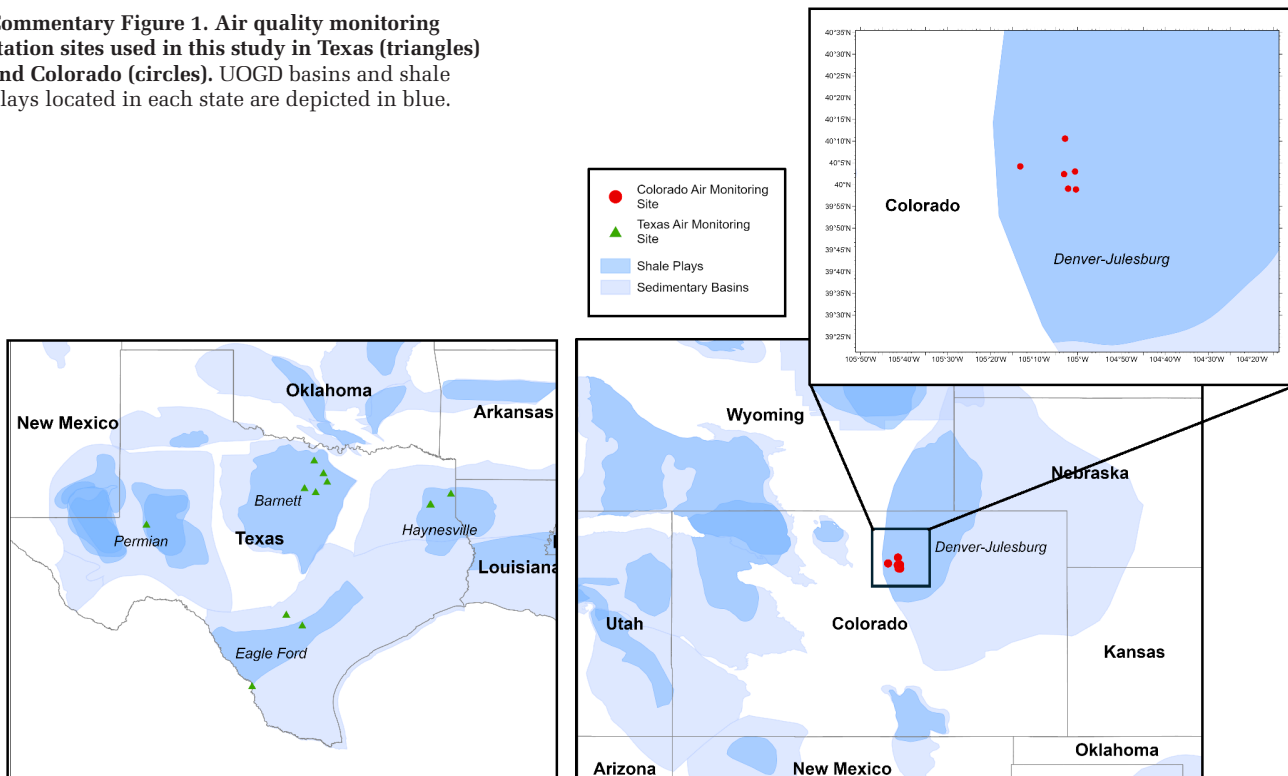
SUMMARY OF METHODS AND STUDY DESIGN

EVALUATION OF LONG-TERM TRENDS IN AIR QUALITY NEAR UOGD BASINS IN TEXAS

To evaluate long-term trends in concentrations of NMHCs and NO_x near UOGD in Texas, the investigators gathered data on benzene, ethane, propane, and NO_x, as well as meteorological data, from 11 air quality monitoring sites. The sites are in or near four UOGD basins: Eagle Ford Shale, Barnett Shale, Haynesville Shale, and the eastern Permian Basin (Commentary Figure 1). Data were collected from the earliest date available for each site (between 1997 and 2015) through December 31, 2023, broadly encompassing the 1997–2023 period (i.e., before and throughout the “shale boom” in Texas). The temporal resolution of the data varied depending on the monitoring frequency (e.g., hourly, weekly).

To help distinguish background sources of air pollution from other sources and long-range transport of air pollution, the investigators used meteorological data on wind speed and direction to categorize the air quality monitoring data into UOGD and non-UOGD air mass origin sectors. However, given the high density of oil and gas activity around the

Commentary Figure 1. Air quality monitoring station sites used in this study in Texas (triangles) and Colorado (circles). UOGD basins and shale plays located in each state are depicted in blue.



Permian and Barnett Shales, the investigators were unable to delineate non-UOGD wind sectors in these two regions. For sites where data categorization using information on wind was not successful, they applied a mathematical tool known as non-negative matrix factorization (NMF) to decompose the air quality data into its contributing factors that help identify potential air pollutant sources and source contributions.

Next, the investigators performed a trend analysis by fitting natural cubic spline curves (Wang and Yan 2021) to the time series data for each air quality monitoring site and pollutant. Different curve “fits” were applied to capture various timescales in the data. For example, the “seasonal fit” accounts for seasonality and its variations between different years in the time series data, the “fine fit” accounts for short-term variations within years, and the “trend fit” accounts for the overall long-term trends in the data.

Finally, to further assess the relationship between long-term trends and UOGD, the investigators calculated Pearson correlations between the fitted curve coefficients and various types of UOGD production volumes over time (i.e., oil, gas, casinghead gas [natural gas that is produced alongside crude oil], or condensate [a type of natural gas liquid produced at the wellhead]) using publicly available data on UOGD production from the Railroad Commission of Texas.

EVALUATION OF LONG-TERM TRENDS IN AIR QUALITY NEAR UOGD BASINS IN COLORADO

To evaluate long-term trends in concentrations of NMHCs, NO_x , and methane near UOGD in Colorado, Helmig and colleagues gathered data on ethane, propane, benzene, NO_x , methane, and wind speed and direction from six air quality monitoring sites located in the northern Colorado Front Range region adjacent to the Denver–Julesburg Basin (Commentary Figure 1). The data broadly spanned the years from 2008 to 2024, depending on each specific site, and the temporal scale again varied depending on each site’s monitoring frequency. The investigators categorized the air quality monitoring data into UOGD and non-UOGD air mass origin sectors using data on wind speed and direction.

In addition, to distinguish observed pollutant concentration trends from background levels of air pollutants, they collected methane monitoring data from Mauna Loa Observatory, Hawaii, and ethane and propane monitoring data from the Cape Verde Atmospheric Observatory in the North Atlantic. Those locations were chosen because they are two of the few remote regions in the Northern Hemisphere where NMHC data are available. Helmig and colleagues fit trend curves using NOAA’s FFT curve-fitting tool (Thoning et al. 1989) to each site and air pollutant. Again, different curve “fits” were applied to account for varying timescales in the data. In addition, to identify and compare long-term trends across air quality monitoring sites, the investigators fit linear regressions (in other words, lines of best fit) to the trend curves to calculate a rate of concentration change over the full period of available data for each air pollutant. They

also qualitatively compared long-term trends in air pollutant concentrations with overall trends in various types of UOGD production volumes in the Denver–Julesburg Basin.

EVALUATION OF LONG-TERM TRENDS IN FORMALDEHYDE ACROSS THE PERMIAN BASIN

To evaluate long-term trends in concentrations of NMHCs across the Permian Basin, which spans Texas and New Mexico, the investigators focused on formaldehyde as a proxy of NMHC emissions. They obtained publicly available satellite-derived data on daily atmospheric VCD measurements of formaldehyde for 2004–2022 from NASA’s OMI (Chance 2019). They collected formaldehyde data from OMI for a region over the Pacific Ocean and a region over southern Arizona and northwestern Mexico to differentiate trends in the Permian from background levels of formaldehyde. These regions were chosen because they represent locations with minimal influence from vegetation and human pollution (as both can produce formaldehyde).

The investigators then averaged the satellite-observed formaldehyde observations over space and time to compute regional monthly averages for the entire Permian Basin, as well as both reference locations. They also applied corrections to the data to address possible biases that may be introduced from instrument aging (termed “background drift”) and surface temperatures (as a proxy of seasonality). The latter may occur because formaldehyde production from hydrocarbon emissions is dependent on emission rates and atmospheric chemistry, which are both dependent on surface temperature. Thus, formaldehyde concentrations in the air are generally higher on warm days.

Finally, the investigators applied Gaussian smoothing to the time series data to assess long-term trends in formaldehyde VCDs before and during the Texas “shale boom.” This statistical technique was chosen because there were comparatively fewer data points in the formaldehyde dataset compared with the surface monitor analyses in Texas and Colorado.

ADDITIONAL ANALYSES

To assess whether the use of different techniques for trend analysis affected their results for the Aim 1 analyses, the investigators qualitatively compared the two independently derived long-term trends in ethane concentrations for data from the Floresville air quality monitoring site in Texas and from the Longmont Union Reservoir air quality monitoring site in Colorado.

SUMMARY OF KEY RESULTS

LONG-TERM TRENDS IN AIR QUALITY NEAR UOGD BASINS IN TEXAS

The investigators reported that trends in concentrations of the NMHCs ethane, propane, and benzene generally increased

in the early years of the study period across the Barnett Shale, Eagle Ford Shale, Haynesville Shale, and the eastern Permian Basin in Texas, alongside rapid UOGD expansion in the state. Trends in concentrations of these NMHCs subsequently leveled off or decreased over time, along with UOGD production volumes in the respective shale plays. For some basins and pollutants, the initial upward trend for NMHC concentrations was statistically significant, for example, for ethane at the Old Highway 90 site near the Eagle Ford Shale (**Commentary Figure 2**). Although NO_x data were only available for four monitoring sites in Texas, trends in NO_x displayed a similar pattern.

Across several UOGD basins in Texas, ethane, propane, and benzene mixing ratios, calculated as monthly mean spline values, tracked closely with production volume trends over time (Pearson correlation coefficient = 0.51–0.93; **Commentary Table 1**). Production volumes were reported in barrels (BBL) for oil and condensate and thousand cubic feet (MCF) for gas and casinghead gas.

For example, the correlation between the monthly mean spline trend value for benzene mixing ratio and monthly gas production volumes was 0.91 for one site in the Barnett Shale and 0.82 for one site in the Permian-Midland Basin. Some exceptions were for reported casinghead gas in two locations, which showed correlations of –0.12 to 0.15.

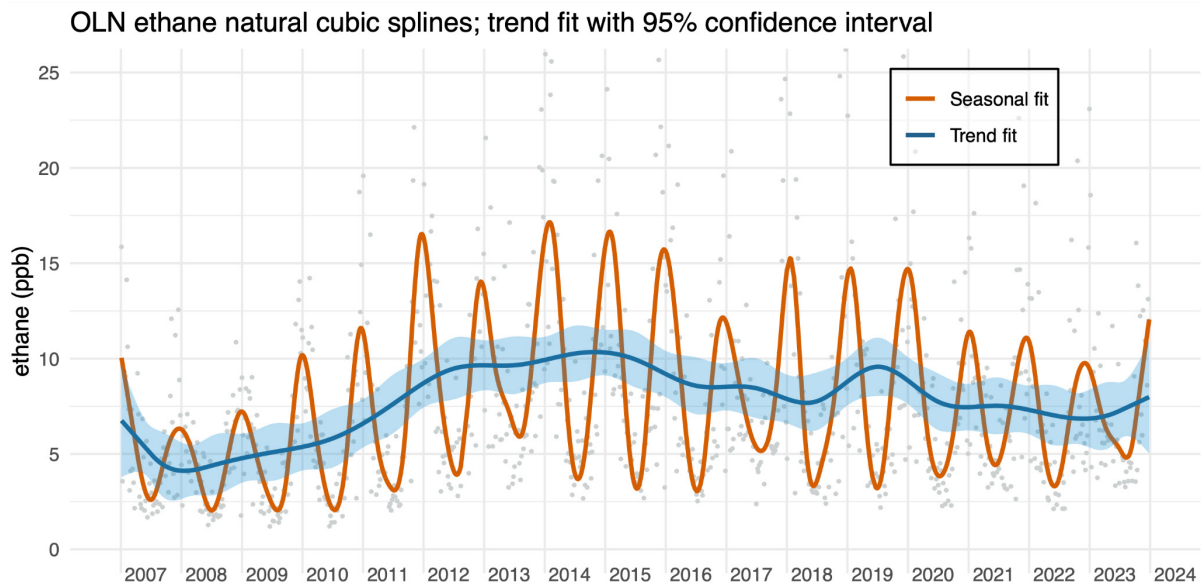
The investigators observed multiple statistically significant positive correlations between trends in NMHC mixing ratios and several types of UOGD production volumes. Many of those correlations were found for trends at air quality monitoring sites with the longest monitoring records of hourly data, such as the Eagle Mountain Lake and Decatur Thompson sites in the Barnett Shale. In other cases, however, such

as the Floresville site near the Eagle Ford Shale, long-term trends in ethane, propane, and benzene mixing ratios were found to be poorly correlated with different types of UOGD production volumes (not shown). The Old Highway 90 site north of the Eagle Ford Shale had negative correlations with UOGD production volumes for benzene, between –0.79 to –0.71, likely due to locally dominant traffic-source emissions (IR Appendix C), but were positively correlated for both ethane and propane (**Commentary Table 1**).

The investigators posited that overall, their findings for long-term trends in air quality (interpreted as an indicator of changes in emissions levels) do not clearly demonstrate a reduction in the emissions per quantity of oil or gas produced (i.e., emissions intensity) over time in Texas. They also suggested that their findings do not indicate an obvious effect of the state regulatory activity (including implementation of federal rules or the state flaring reporting rules) on air quality.

LONG-TERM TRENDS IN AIR QUALITY NEAR UOGD BASINS IN COLORADO

Across air quality monitoring sites in the northern Colorado Front Range region of the Denver–Julesburg Basin in Colorado, the investigators reported that long-term trends in NMHCs — ethane, propane, benzene, and NO_x — generally demonstrated a gradual decline over time (as shown by a negative slope, see **Commentary Table 2**). At the same time, UOGD experienced initial growth in production up to the onset of the COVID-19 pandemic in early 2020. Regression slopes from long-term trends in ethane demonstrated decreases ranging from –0.2 to –0.8 ppb per year across sites, in contrast to a more modest, nonstatistically significant decline in ethane of –0.02 ppb per year at a background monitoring site (Cape



Commentary Figure 2. Ethane mixing ratios at the Old Highway 90 air quality monitoring site near the Eagle Ford Shale, Texas. Dots depict monthly average ethane mixing ratios. Data are summarized as spline curves in orange (seasonal fit) and blue (trend fit, i.e., overall trend). Blue shading indicates 95% confidence intervals for the trend fit. Periods for which the vertical range of the confidence interval does not overlap between time points indicate statistically significant changes in ethane concentrations. Source: Investigators’ Report Appendix C1–3c and Investigators’ Report Figure 19.

Commentary Table 1. Pearson Correlations Between Long-Term Trends in NMHC Mixing Ratios and Monthly UOGD Production Volume Data

UOGD Basin/Air Quality Monitoring Site	UOGD Production Type	Benzene	Ethane	Propane
Eagle Ford Shale – Old Highway 90	Oil	-0.71	0.76	0.83
	Gas	-0.79	0.64	0.75
	Casinghead gas	-0.71	0.69	0.76
	Condensate	-0.72	0.85	0.88
Barnett Shale – Eagle Mountain Lake	Oil	0.75	0.70	0.84
	Gas	0.61	0.52	0.68
	Casinghead gas	0.01	0.14	0.15
	Condensate	0.68	0.51	0.69
Barnett Shale – Decatur Thompson	Oil	0.65	0.83	0.84
	Gas	0.91	0.85	0.93
	Casinghead gas	-0.09	0.08	-0.12
	Condensate	0.84	0.77	0.90
Permian Basin – Odessa-Hays Elementary School	Oil	0.75	NR	NR
	Gas	0.82	NR	NR
	Casinghead gas	0.77	NR	NR
	Condensate	0.78	NR	NR

NR = not reported; UOGD = unconventional oil and gas development.

Commentary Table 2. Linear Regression Slopes from Trend Curves Applied to Air Quality Monitoring Sites Near the Denver-Julesburg Basin in Colorado^a

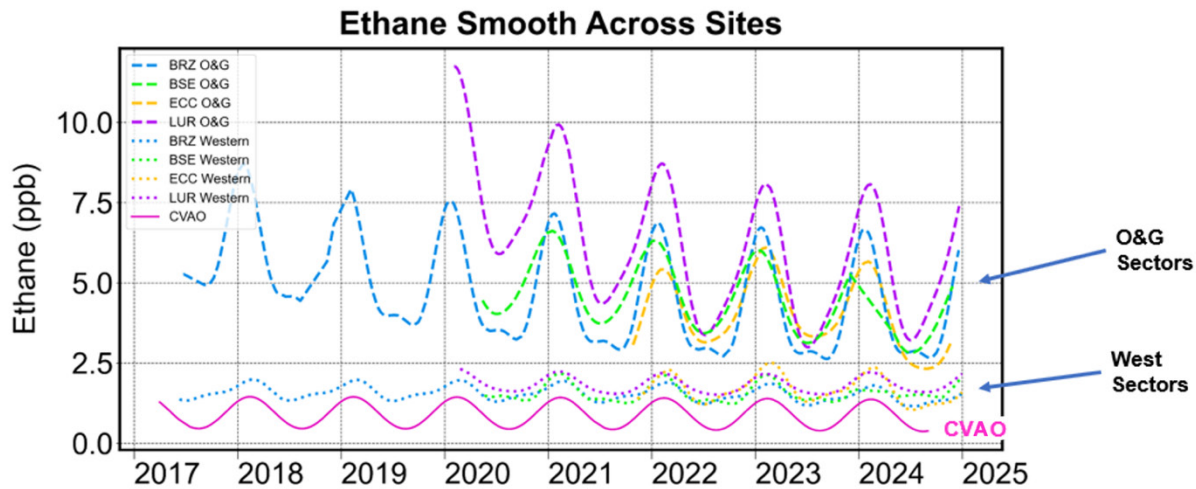
Air Quality Monitoring Site (years of data)	Nonmethane Hydrocarbon Trend (ppb per Year)			NO _x (ppb per Year)	Methane (ppb per Year)
	Benzene	Ethane	Propane		
Boulder Reservoir (2017–2024)	-0.01	-0.2	-0.16	-0.41	7.91
Longmont Union Reservoir (2019–2024)	-0.02	-0.77	-0.75	-1.03	8.33
Erie Community Center (2021–2024)	-0.01	0.07	0.04	N/A	4.86
Broomfield North Pecos (2021–2024)	-0.01	-0.56	-0.39	N/A	7.90
Broomfield Soaring Eagle Park (2020–2024)	-0.02	-0.56	-0.46	-0.26	N/A
Boulder Atmospheric Observatory (2007–2017)	N/A	N/A	N/A	N/A	4.75
Mauna Loa Observatory (1987–2024)	N/A	N/A	N/A	N/A	9.12 ^b 12.5 ^c
Cape Verde Atmospheric Observatory (2006–2024)	N/A	-0.02	-0.01	N/A	N/A

N/A = not applicable; NO_x = nitrogen oxides.

^aAll slopes presented are from trends for the UOGD air mass origin sector for each site, except for Boulder Atmospheric Observatory, where available wind data did not correspond to NMHC data collection periods, and the two reference locations: Mauna Loa Observatory and Cape Verde Atmospheric Observatory.

^bTrend calculated starting in 2007 to align with Boulder Atmospheric Observatory methane data.

^cTrend calculated starting in 2017 to align with other air quality monitoring site data.



Commentary Figure 3. Long-term trends in ethane mixing ratios across air quality monitoring sites near the Denver–Julesburg Basin in Colorado. Dashed lines (those above 2.5 ppb) depict smoothed best-fit curves for ethane mixing ratio measured in air that was transported from the sector with upstream oil and gas development (“O&G Sectors”). Dotted lines (below 2.5 ppb) indicate ethane concentration trends from the western air mass origin sector with little or no UOGD influence (“Western Sectors”). The solid pink time series depicts long-term trends in ethane from the reference location Cape Verde Atmospheric Observatory (CVAO) for the northern hemisphere. Source: Investigators’ Report Figure 36.

Verde Atmospheric Observatory) (Commentary Figure 3). Decreasing trends in propane were of similar magnitude as for ethane. Decreasing trends in benzene concentrations were more modest, ranging from -0.01 to -0.02 ppb per year.

In contrast, the investigators observed a general increase in concentrations of the greenhouse gas methane at air quality monitoring sites in the northern Colorado Front Range throughout the study period. This observation is consistent with the documented increase in background methane that has been observed globally. Ambient methane levels in Colorado are generally much higher than global background levels. Regression slopes from long-term trends in methane across monitoring sites ranged from 4.9 to 8.3 ppb per year. However, the upward trends in methane in the northern Colorado Front Range were found to be smaller than the upward trend observed at the Mauna Loa Observatory reference location, which demonstrated an increase of 12.4 ppb per year.

Overall, the investigators noted that the slower rate of increase in long-term trends in ambient air pollutants and methane compared with background levels suggests that overall emissions intensity near UOGD in Colorado might be declining, which they posited might be partially driven by the regulatory framework in the state.

Moreover, they suggested that the differences in long-term trends found in Texas and Colorado likely reflect variation in factors affecting emissions intensity (including regulation and UOGD operational changes), as well as other regional factors such as local meteorological conditions.

LONG-TERM TRENDS IN FORMALDEHYDE ACROSS THE PERMIAN BASIN

The investigators reported that long-term trends in VCDs of formaldehyde across the Permian Basin illustrated modest increases, alongside UOGD production volumes in the region, up to 2020. The upward trend in formaldehyde VCD in the Permian Basin was statistically significant, corresponding to a 2% increase per year between 2014 and 2020. After 2020, however, they reported a declining trend toward the end of the study period, which did not align with reported UOGD production volumes (Investigators’ Report Figure 44). This pattern of increase and subsequent decrease in the VCDs of formaldehyde was also observed in the background region in Arizona (Investigators’ Report Figure 42). Notably, the investigators found that uncertainty in formaldehyde measurements increased throughout the study period, resulting from reductions in the number of valid measurements from the OMI monitoring instrument.

ADDITIONAL ANALYSES

The team used two trend-fitting methods: the NOAA FFT curve-fitting tool for Colorado data and natural cubic splines for Texas data. To assess whether these two trend-fitting methods would lead to differences in trend outputs, the investigators compared trend results from each tool on the hourly ethane datasets from the Texas Floresville site (Investigators’ Report Figures 10a–10c) and the Colorado Longmont Union Reservoir site (Appendix A). While some differences exist between the NOAA tool’s seasonal estimates of ethane mix-

ing ratios and the year-to-year variation captured by splines (splines showing interannual variation), both methods produce similar amplitudes and yield consistent long-term trend results.

HEI ENERGY REVIEW COMMITTEE'S EVALUATION

This study assessed long-term trends in air pollutants from air quality monitoring sites around UOGD basins in Texas and Colorado, with a focus on NMHCs and NO_x . It also evaluated long-term trends in formaldehyde as a proxy for NMHCs in the Permian Basin. Schade, Helmig, and colleagues found decreasing long-term trends in NMHCs and NO_x concentrations in Colorado, despite steady growth in UOGD production in the state. In contrast, they found that long-term trends in NMHCs and NO_x concentrations in Texas increased and then stabilized over time, and those trends generally correlated with UOGD production volumes. The investigators additionally found a small increasing trend in formaldehyde column densities in the Permian Basin in Texas and New Mexico until 2020.

In its independent evaluation, the HEI Energy Review Committee determined that, overall, this study demonstrated differences in long-term trends in air quality across UOGD production regions in Texas and Colorado. Such differences likely suggest the effects of a combination of local and regional factors, including differences in state-level regulatory frameworks. The Committee appreciated that the investigators thoughtfully outlined the aims of their study in the context of relevant federal and state regulations. More broadly, it generally agreed with the results presented. However, the Committee noted that the interpretation of the study's findings seemed to overstate the influence of regulation on air quality trends. Further details on the strengths and limitations of the study are discussed below.

STUDY DESIGN, DATASETS, AND ANALYTICAL APPROACHES

The Committee thought that the comparison of long-term trends in air pollutant concentrations associated with UOGD in Colorado and Texas with varying local and regional contexts and different regulatory frameworks was a key strength of the study. It is also appreciated that the investigators were able to evaluate trends in ambient air pollutant concentrations using a long historical record of air quality data.

The Committee generally found the overall study design and analytical approaches used to analyze the Texas and Colorado data to be appropriate. However, the Committee thought that the analysis of trends in formaldehyde density columns across the Permian Basin had many limitations stemming from the satellite-derived data from OMI. First, the formaldehyde data product used in the study was known to produce biased data. Specifically, its retrieval algorithm is biased high at low formaldehyde column densities, with

negative biases under high formaldehyde conditions. This pattern of bias may therefore have weakened the reported long-term formaldehyde VCD trends, which is acknowledged by the investigators in their report.

In addition, aging of the OMI satellite has led to degradation in coverage over time, resulting in fewer valid measurements and increasing uncertainty, as demonstrated in the study's long-term trend findings. Although acknowledged by the investigators, the Committee nonetheless thought that these issues limited the contribution of this analysis to the overall study. It is thought that the study may have benefited from additional sensitivity analyses using formaldehyde data products that were based on a different retrieval algorithm. Even so, uncertainty in the results associated with the aging of the instrument would remain a limiting factor.

The Committee also noted that the investigators used two fundamentally different statistical techniques (i.e., natural cubic splines versus FFT curves) to analyze the Texas and Colorado data. This approach was not clearly justified. Nonetheless, the Committee appreciated that the investigators compared the results of their statistical trend-fitting methods, albeit qualitatively, for ethane at one site in each state. It was reassuring that they found only minor overall differences between the long-term trends obtained with the two approaches, although such a comparison was only conducted for two sites and one air pollutant.

FINDINGS AND INTERPRETATION

The investigators observed distinct long-term trends in concentrations of NMHCs and NO_x in Texas and Colorado in their evaluation of long-term trends in air quality near UOGD basins in each state. Long-term trends in NMHCs and NO_x concentrations increased and then stabilized over time, showing moderate correlations with UOGD production volumes in Texas. In contrast, long-term trends in concentrations of NMHCs and NO_x , as well as methane, steadily declined over time in Colorado. Other studies have also found a decreasing trend in NMHC and/or methane concentrations in the Denver–Julesburg Basin (Lu et al. 2023; Oltmans et al. 2021; Reddy and Taylor 2022), and some studies have shown that NMHC concentrations increased in the early years of UOGD expansion in Texas (Lange et al. 2023). However, the present study generally encompasses a longer historical record of data from a larger number of air quality monitoring sites than these earlier analyses.

The Committee broadly agreed with the results presented for these analyses. However, it found that the investigators' interpretation of their findings appeared to overemphasize the role of differences in regulatory frameworks in Texas and Colorado, given that no formal analysis of regulatory effects was conducted in this study. For example, the investigators noted that the long-term trends observed in Texas suggested little direct effect of the relevant regulatory framework on air quality. Although they acknowledged that differences in long-term air quality trends between the states might be driven by

other factors, such as improvements in UOGD operations, the Committee concluded that differences stemming from a combination of local and regional factors warranted a more comprehensive discussion in the text.

For the analysis of long-term trends in satellite-derived formaldehyde columns across the Permian Basin in Texas and New Mexico, the investigators reported a small upward trend through 2020. Nonetheless, they ultimately concluded that the findings from this analysis were uncertain given the limitations of the data, a conclusion with which the Committee agreed. Other studies have used satellite-derived formaldehyde data to investigate trends in emissions of NMHCs across cities and countries (Bauwens et al. 2016; Vohra et al. 2021; Xia et al. 2024). However, none have done so in the context of evaluating long-term trends in formaldehyde and UOGD. As described earlier, the Committee found that the limitations associated with this analysis reduced the utility of these reported findings.

CONCLUSIONS

In summary, this study contributed to our knowledge about long-term trends in air quality near UOGD in Texas and Colorado. The study showed that long-term trends in benzene, ethane, propane, and NO_x in proximity to UOGD basins differed between the two states. Air pollutant concentrations decreased over time in Colorado despite increased UOGD, whereas air pollutant concentrations in Texas generally correlated with UOGD activity.

This study enhances previous research on long-term air quality trends near UOGD by analyzing a long historical record of air quality monitoring data from multiple sites across different states.

Overall, the Committee thought the results reflected differences arising from a combination of local and regional factors in each state, including regulatory frameworks. However, it emphasized that the unique role of regulation remains difficult to disentangle from other contributing factors.

ACKNOWLEDGMENTS

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ABBREVIATIONS AND OTHER TERMS

AIR	Atmosphere Innovation Research	NAAQS	National Ambient Air Quality Standard
AQM	air quality monitoring	NASA	National Aeronautics and Space Administration
BAO	Boulder Atmospheric Observatory	NCAR	National Center for Atmospheric Research
BNP	Broomfield North Pecos	NCFR	Northern Colorado Front Range
BSE	Broomfield Soaring Eagle Park	NMF	Non-negative Matrix Factorization
BVOC	biogenic volatile organic compound	NOAA	National Oceanic and Atmospheric Administration
BWP	Bowie Patterson	NSPS	New Source Performance Standards
BRZ	Boulder Reservoir	O&G	oil and gas
CVAO	Cape Verde Atmospheric Observatory	OHE	Odessa–Hays Elementary (school)
CDPHE	Colorado Department of Public Health and Environment	OLN	Old Highway 90
COGCC	Colorado Oil and Gas Conservation Commission	OLS	ordinary least-squares
DCT	Decatur Thompson	OMI	ozone monitoring instrument
DJ Basin	Denver–Julesburg Basin	OPEC	Organization of the Petroleum Exporting Countries
ECC	Erie Community Center	PR	production report
EML	Eagle Mountain Lake	PVCO	Platteville Middle School
FEM	federal equivalent method	SOP	standard operating procedures
FFT	Fast Fourier Transform	svd	singular value decomposition
FLV	Floresville	TCEQ	Texas Commission on Environmental Quality
HYSPLIT	HYbrid Single-Particle Lagrangian Integrated Trajectory	TxRRC	Texas Railroad Commission
KL	Kullback-Leibler	UOGD	unconventional oil and gas development
KNK	Karnack	US EPA	United States Environmental Protection Agency
LGV	Longview	VCD	vertical column density
LRB	Laredo Bridge	VOC	volatile organic compound
LUR	Longmont Union Reservoir	WFD	Weatherford
MDL	minimum detection limit	Wdr	wind direction
MLO	Mauna Loa Observatory		
MWL	Mineral Wells		

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