Commentary
HEI Energy Review Committee

HEI

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 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

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 Research Report 242.

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 (O_3), 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.

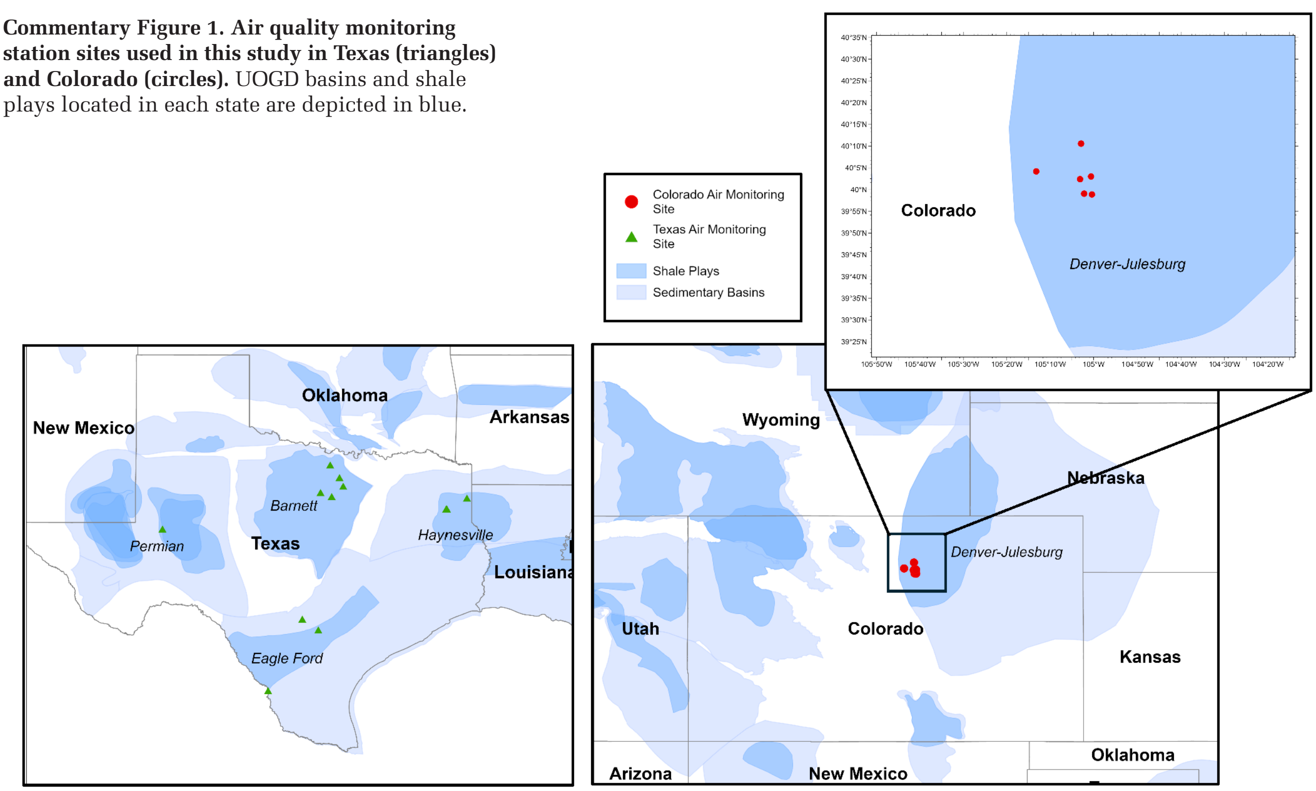
For Aim 2, the investigators focused on satellite-derived formaldehyde observations from 2004 to 2022 across the Permian Basin. Formaldehyde can serve as a proxy for NMHC emissions as it is a secondary oxidation product of NMHCs in the atmosphere. Given the lack of long-term historical data on formaldehyde 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.

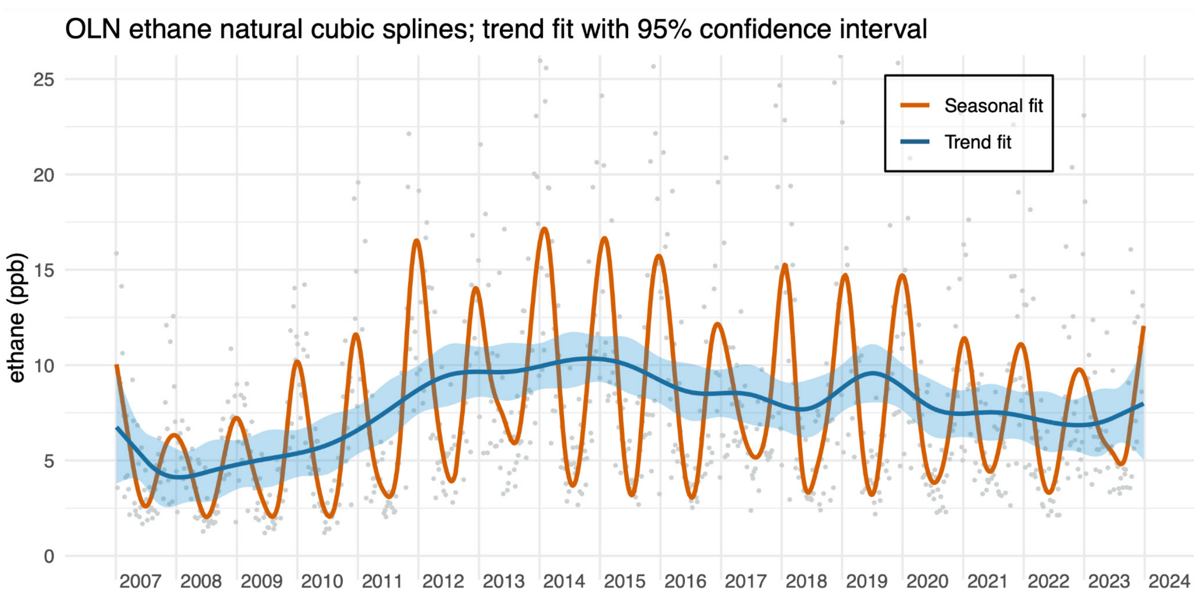
For example, the correlation between the monthly mean spline trend value for benzene mixing ratio and monthly gas production volumes was 0.91 for one site in the Barnett Shale and 0.82 for one site in the Permian-Midland Basin. Some exceptions were for reported casinghead gas in two locations, which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

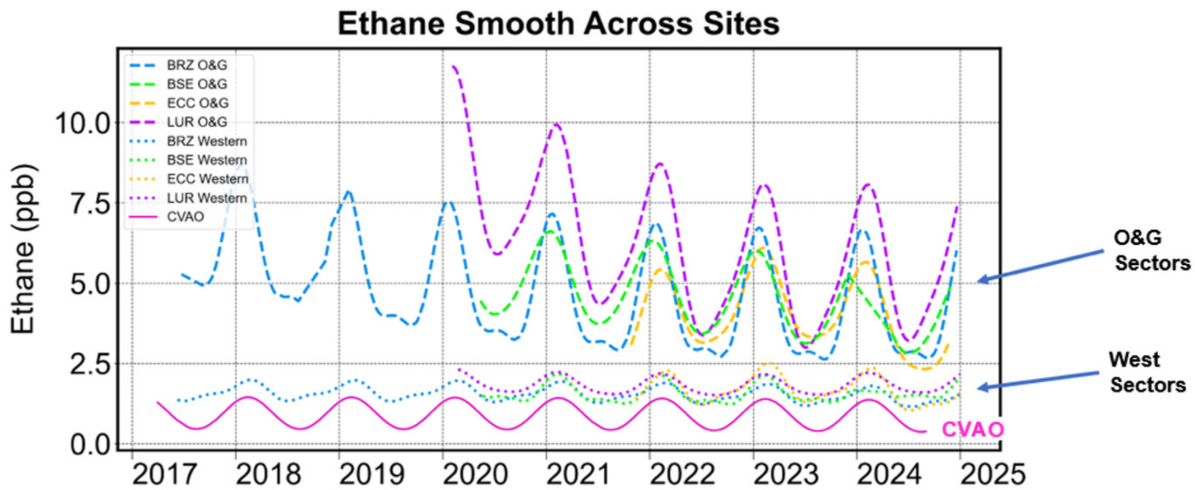
	Nonmethane Hydrocarbon Trend (ppb per Year)				
Air Quality Monitoring Site (years of data)	Benzene	Ethane	Propane	NO_x (ppb per Year)	Methane (ppb per Year)
Boulder Reservoir (2017–2024)	−0.01	−0.2	−0.16	−0.41	7.91
Longmont Union Reservoir (2019–2024)	−0.02	−0.77	−0.75	−1.03	8.33
Erie Community Center (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.

[a]All 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.

[b]Trend calculated starting in 2007 to align with Boulder Atmospheric Observatory methane data.

[c]Trend 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 mixing 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.

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