



## **HEI Research Report 242**

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

## **Appendix C. Additional Results**

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# Appendix C. Additional Results

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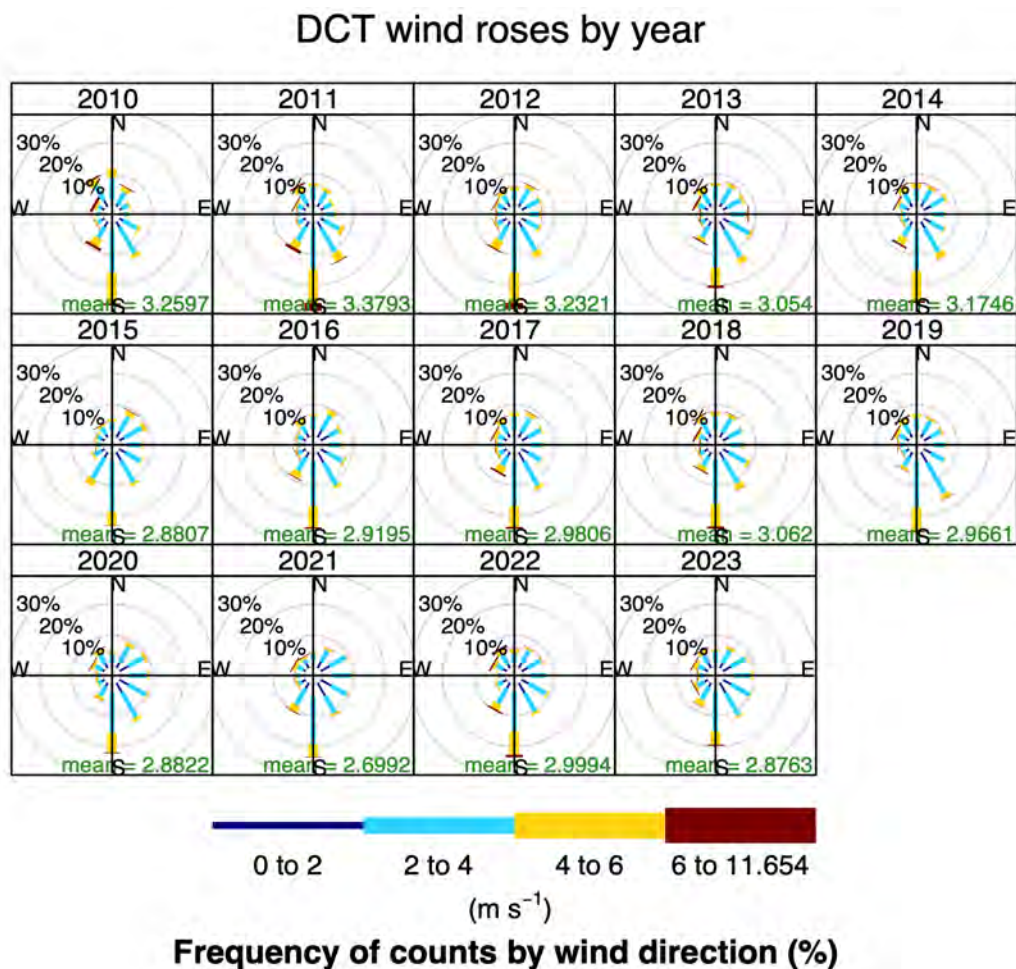
# C1. Additional Results from Analyses of AQM Station Data from Texas

## Texas Wind Patterns

Wind roses for EML and LGV were presented in the main report's Results section. Annual wind roses for the nine other TCEQ sites are shown here, **Figure C1-1**. As noted in the main text, DCT was affected by a small climate anomaly in northern Texas with stronger winds during the 2008 to 2014 period. Otherwise, the sites generally showed highly reproducible wind patterns with some interannual variability.

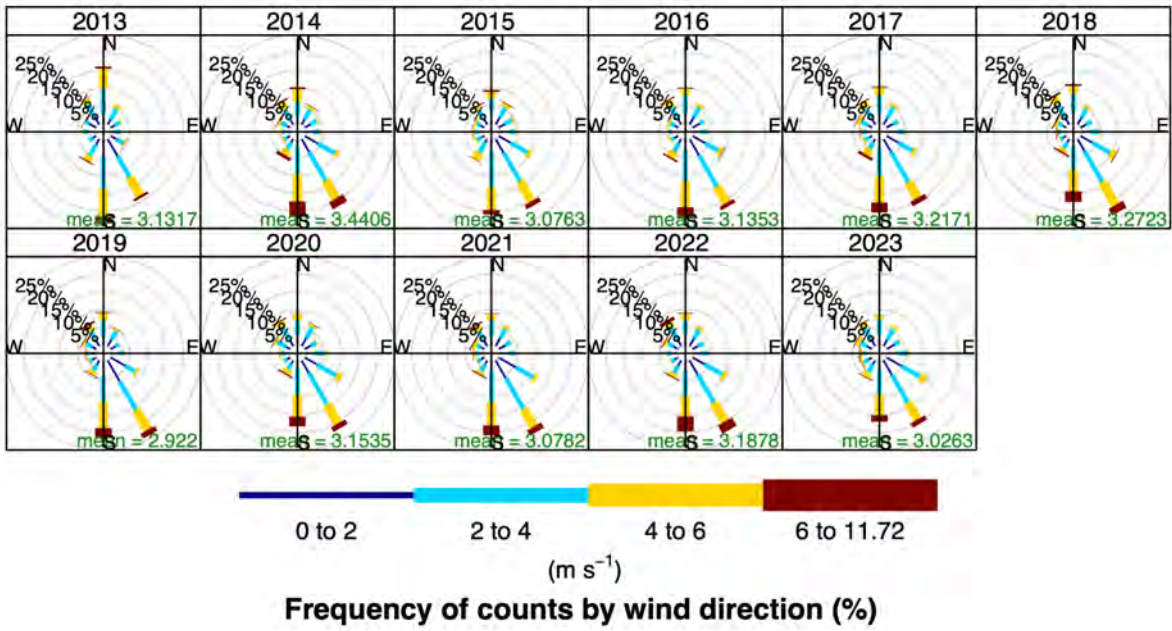
**Figure C1-1.** Yearly wind roses for the nine remaining TCEQ sites not in the Results section. Note that the WFD site (C-1i) had a large data gap in 2019; therefore, the wind rose for that year is not representative and has been removed from the plot.

a.



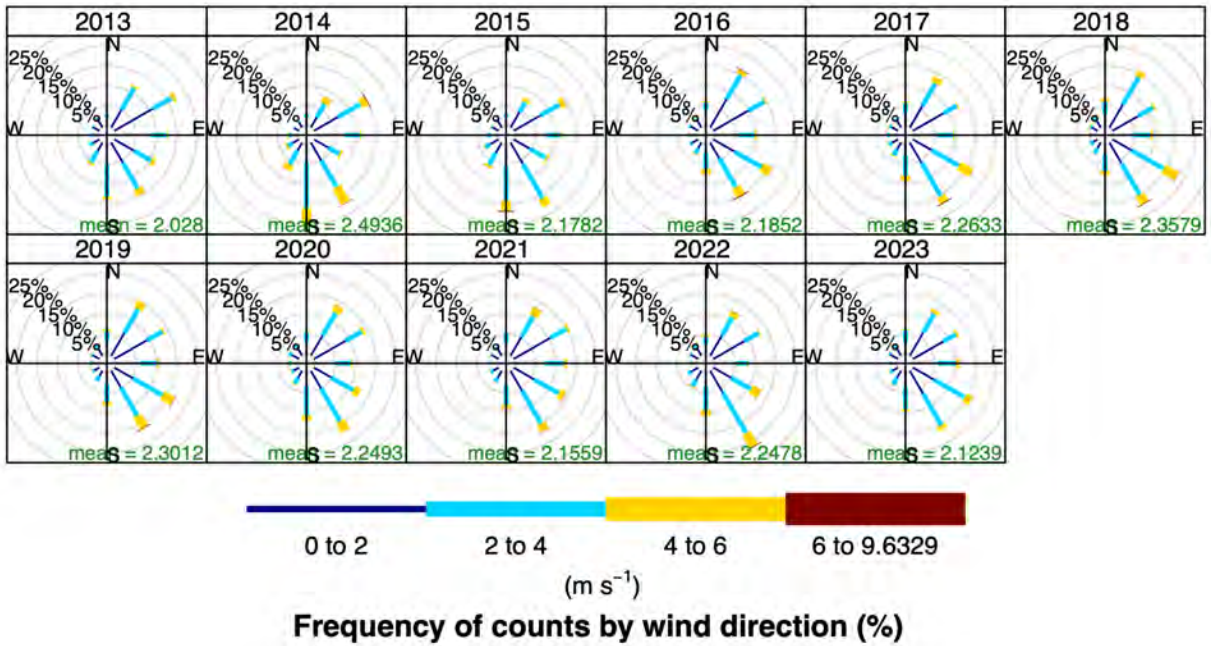
b.

BWP wind roses by year



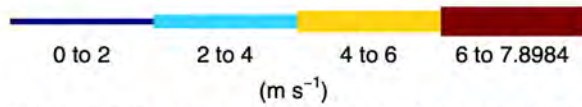
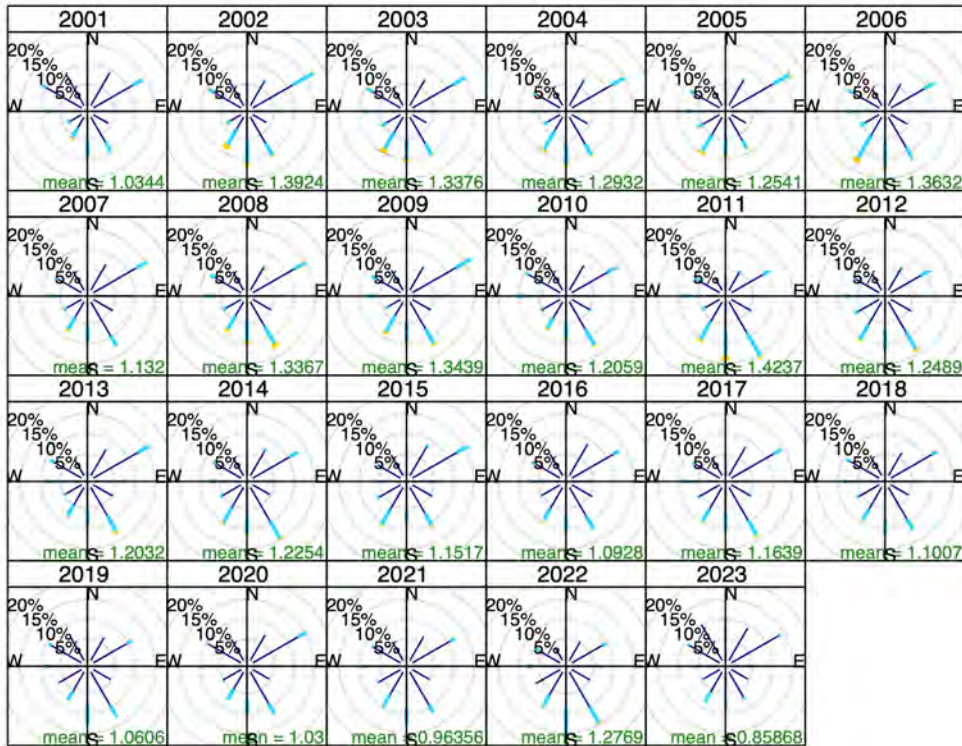
c.

FLV wind roses by year



d.

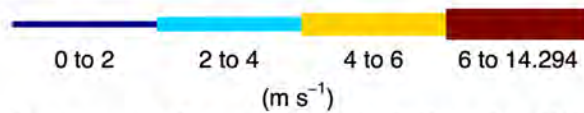
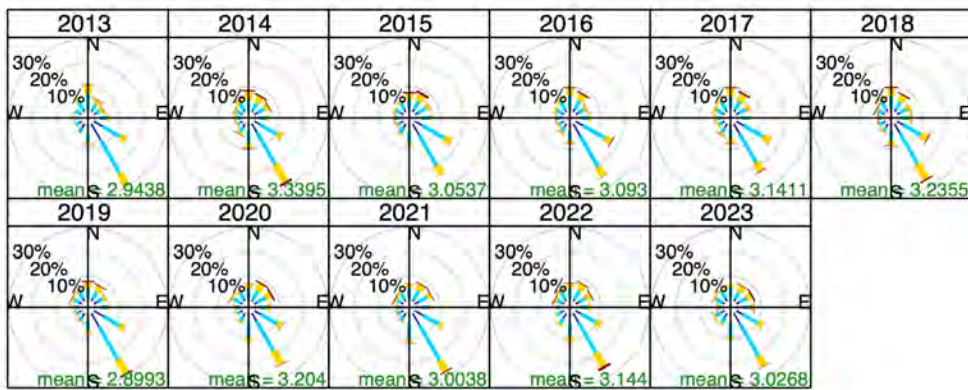
### KNK wind roses by year



Frequency of counts by wind direction (%)

e.

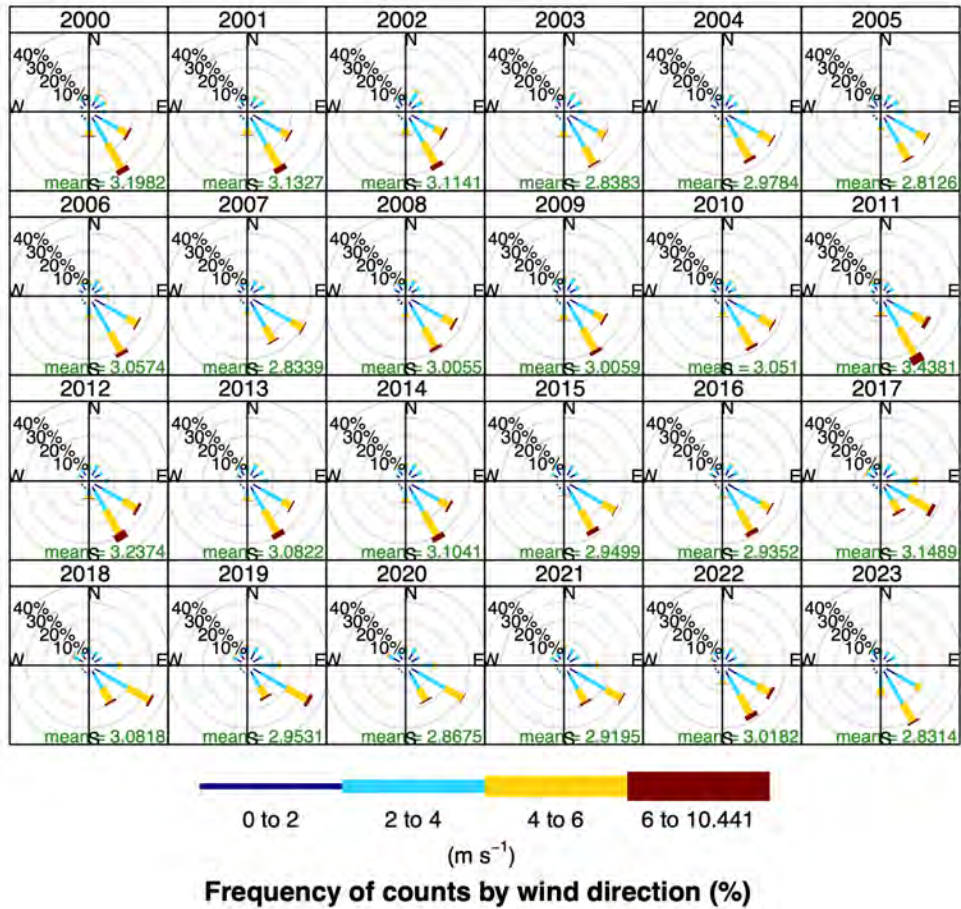
### MWL wind roses by year



Frequency of counts by wind direction (%)

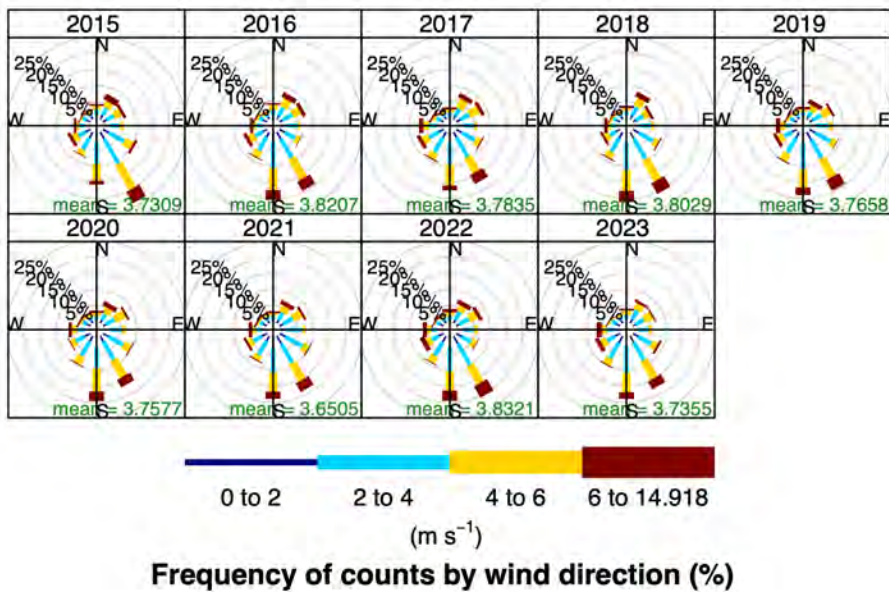
f.

LRB wind roses by year



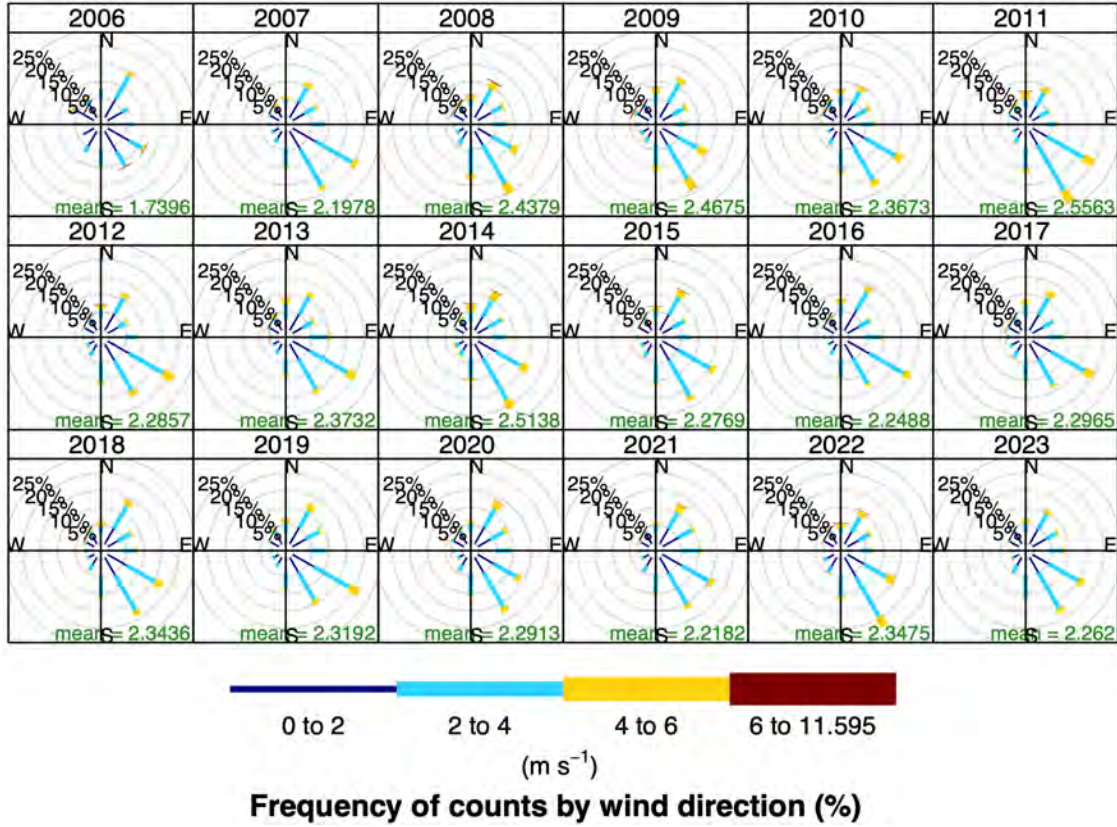
g.

OHE wind roses by year



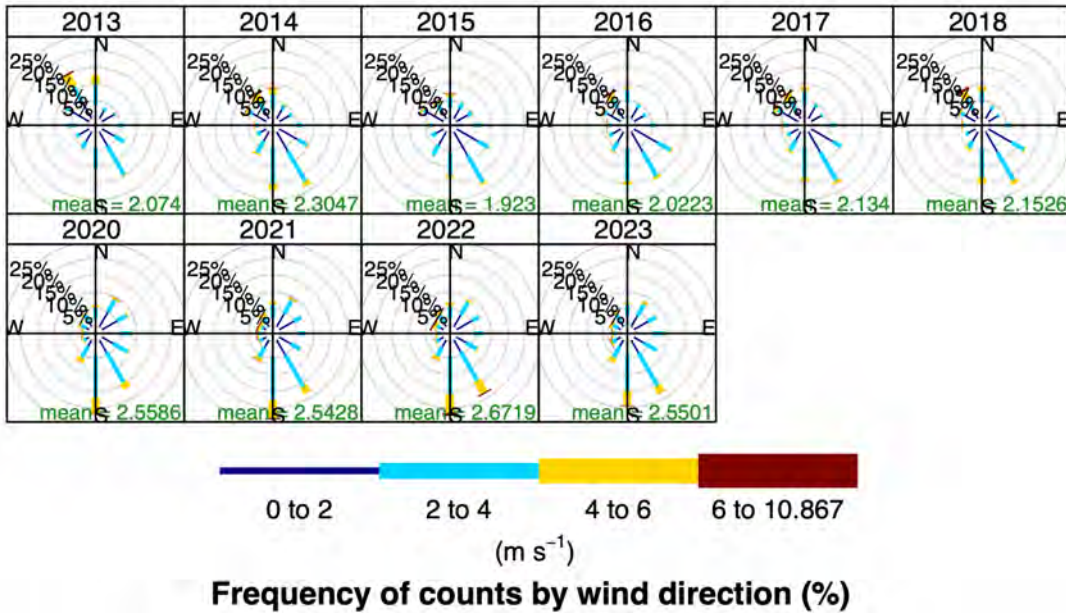
h.

### OLN wind roses by year



i.

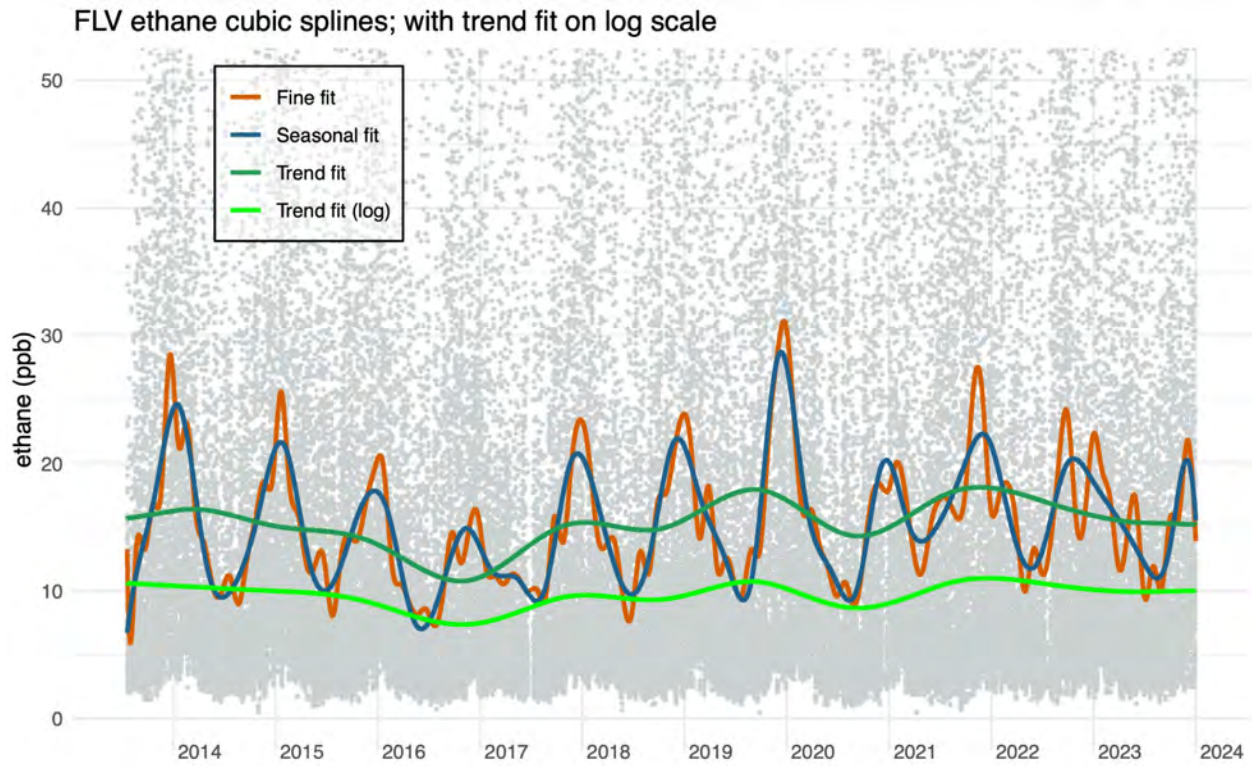
### WFD wind roses by year



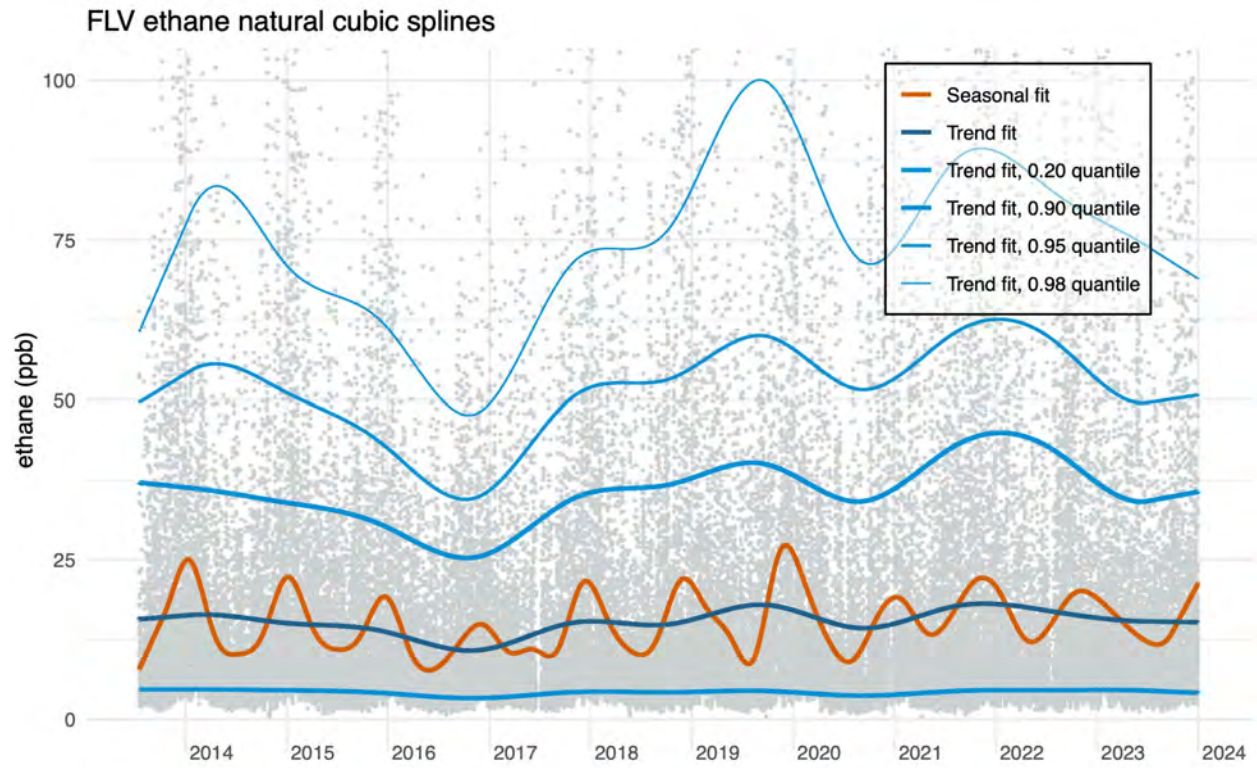
## Spline Fit Variations: Log-Scale Fit, Quantiles Fit, Deseasonalized Data Fit

**Figure CI-2.** Spline fit variations (log-scale, quantile fits, and deseasonalized data) for FLV (a, b, c) ethane and (d, e, f) benzene, MWL (g, h, i) ethane and (j, k, l) benzene, and BWP (m, n, o) ethane and (p, q, r) benzene, DCT (s, t, u) ethane and (v, w) benzene, and EML (x, y, z) ethane (DCT benzene deseasonalized and EML benzene all variations in main Results).

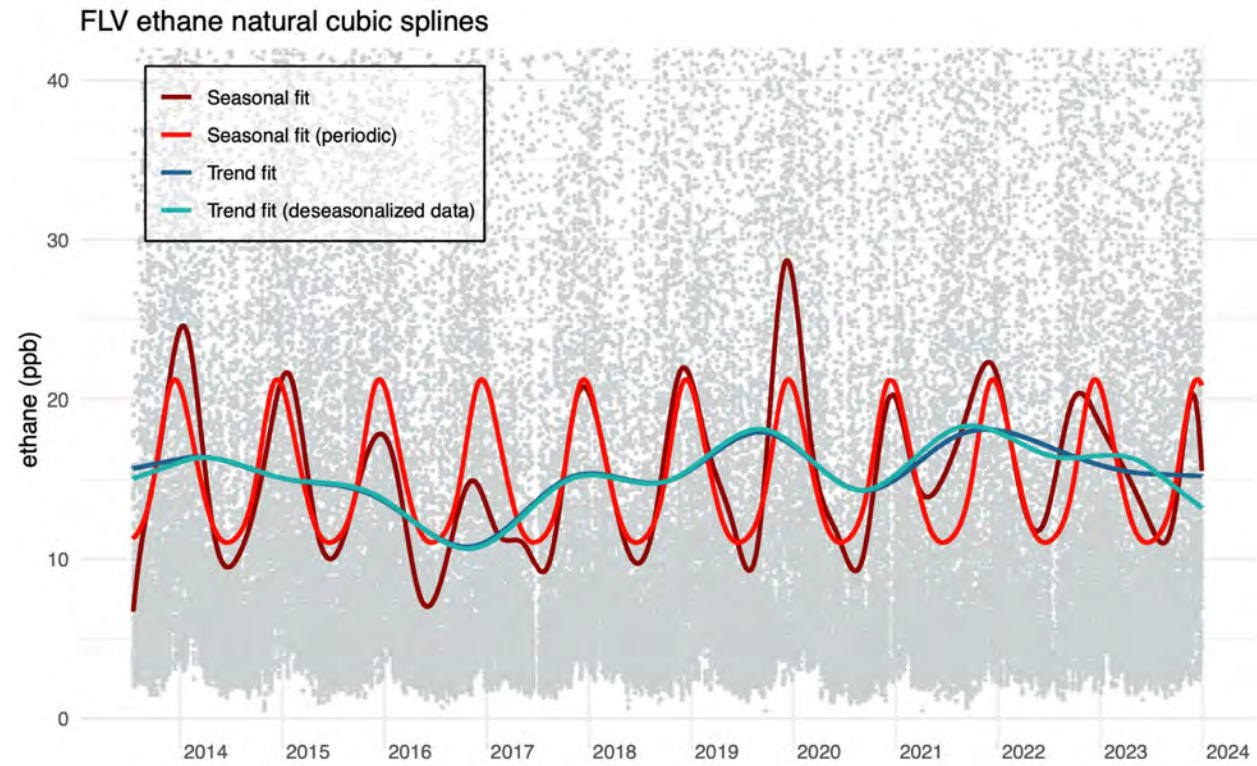
a.



b.

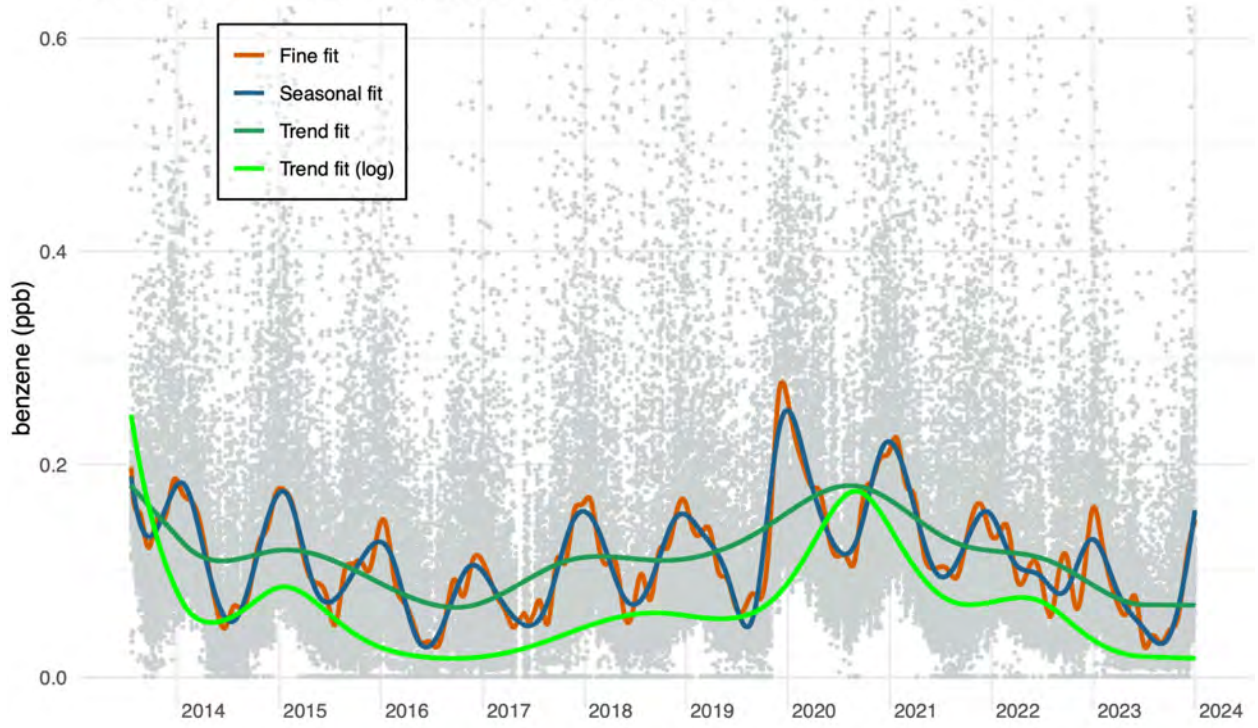


c.



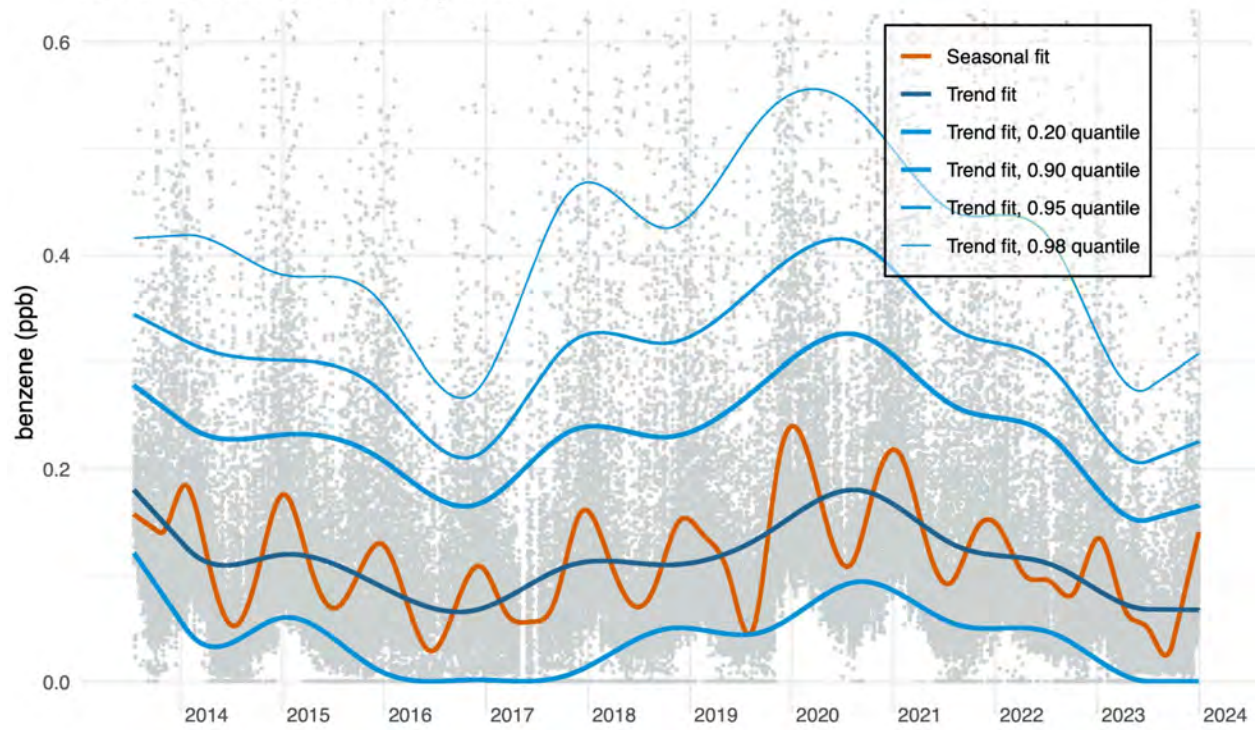
d.

FLV benzene cubic splines; with trend fit on log scale



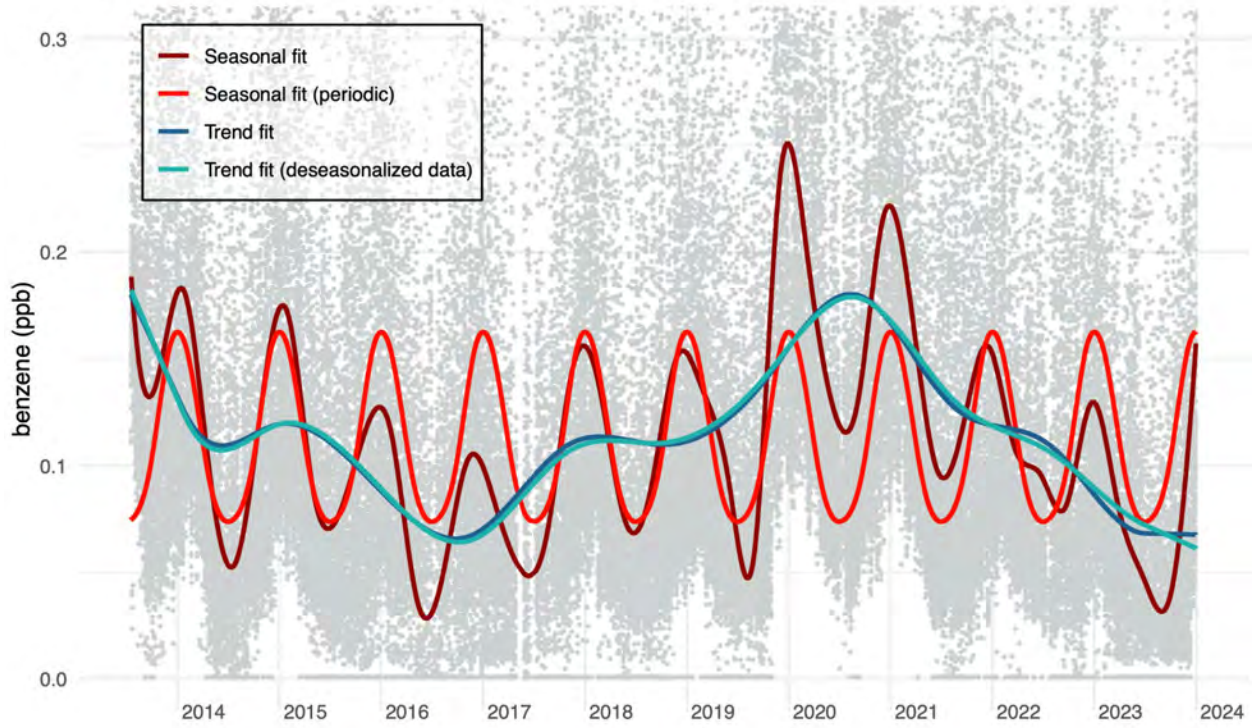
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FLV benzene natural cubic splines



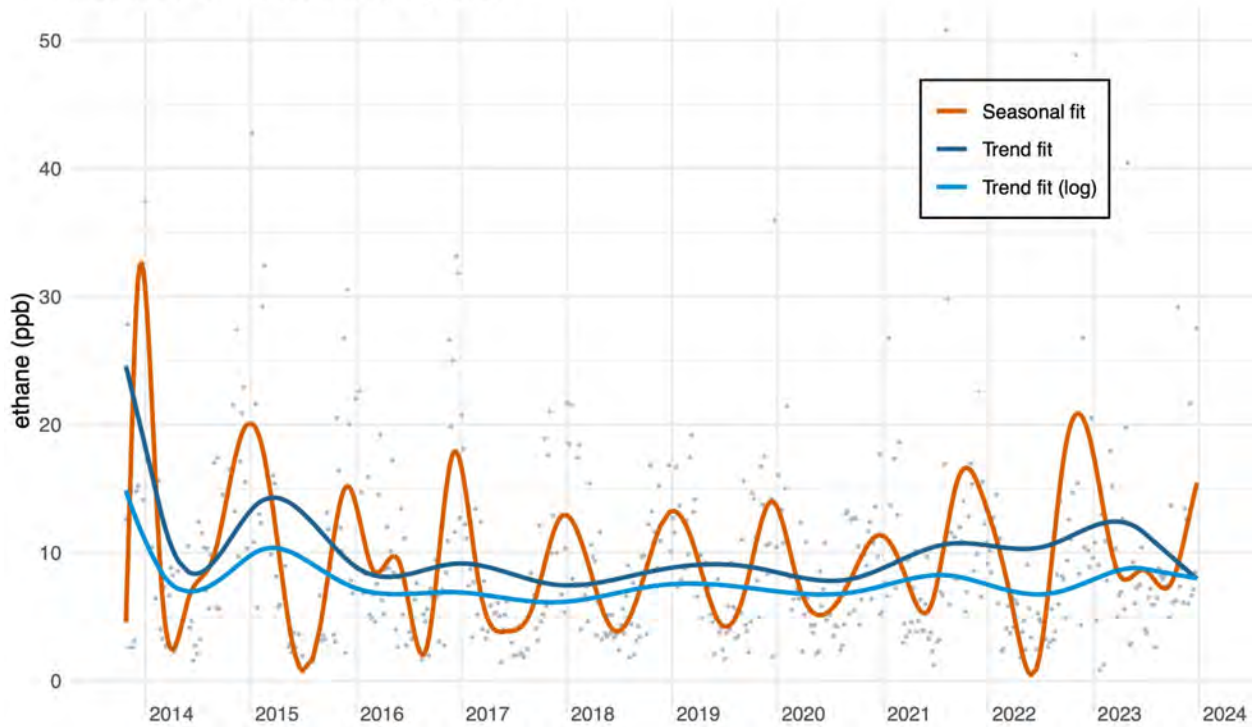
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FLV benzene natural cubic splines



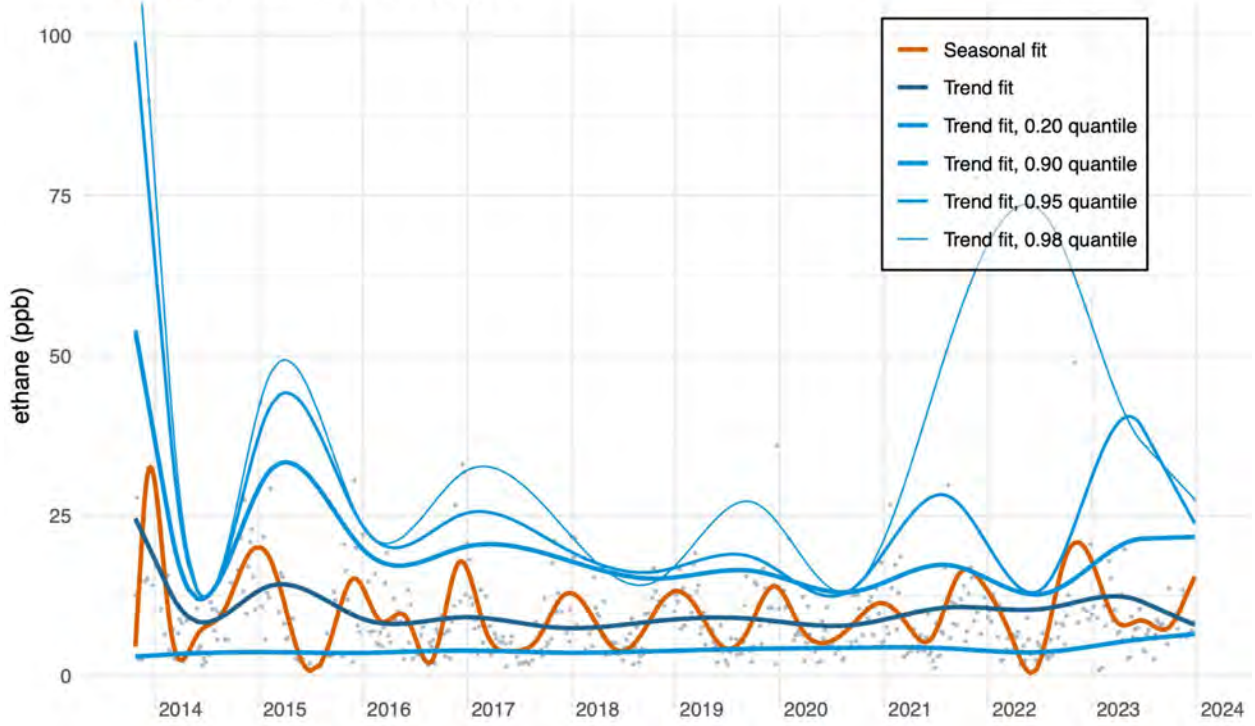
g.

MWL ethane natural cubic splines



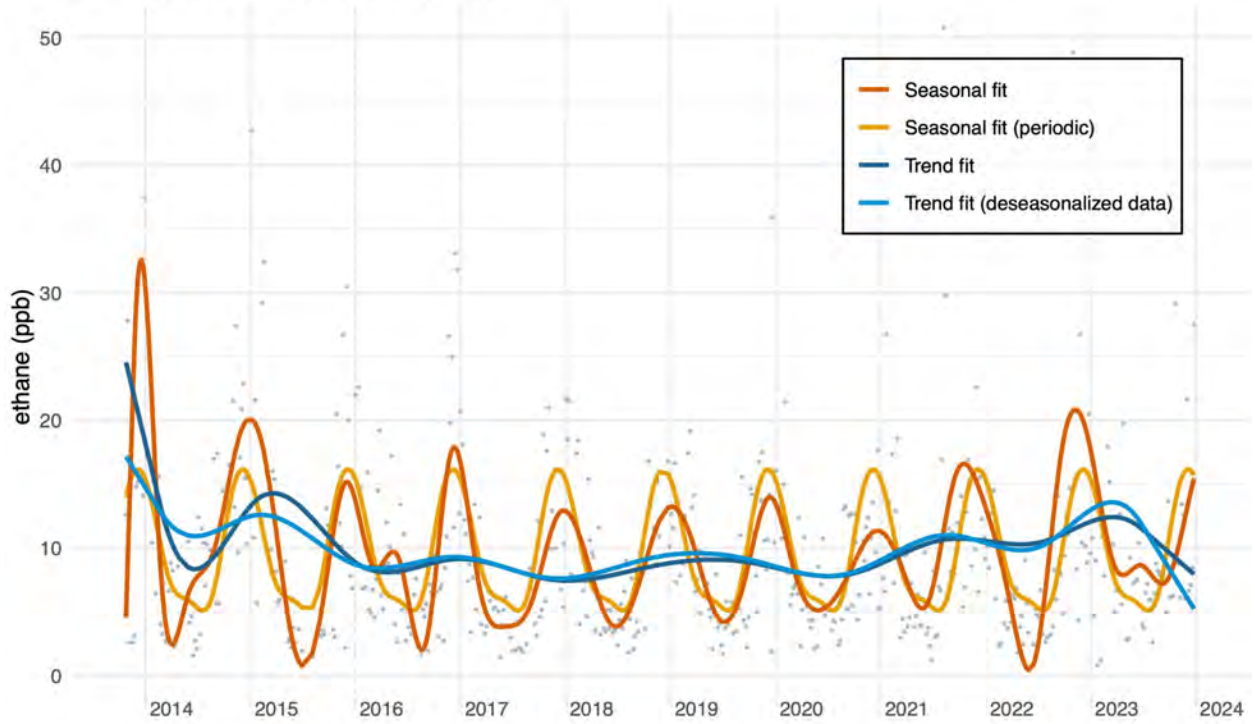
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MWL ethane natural cubic splines



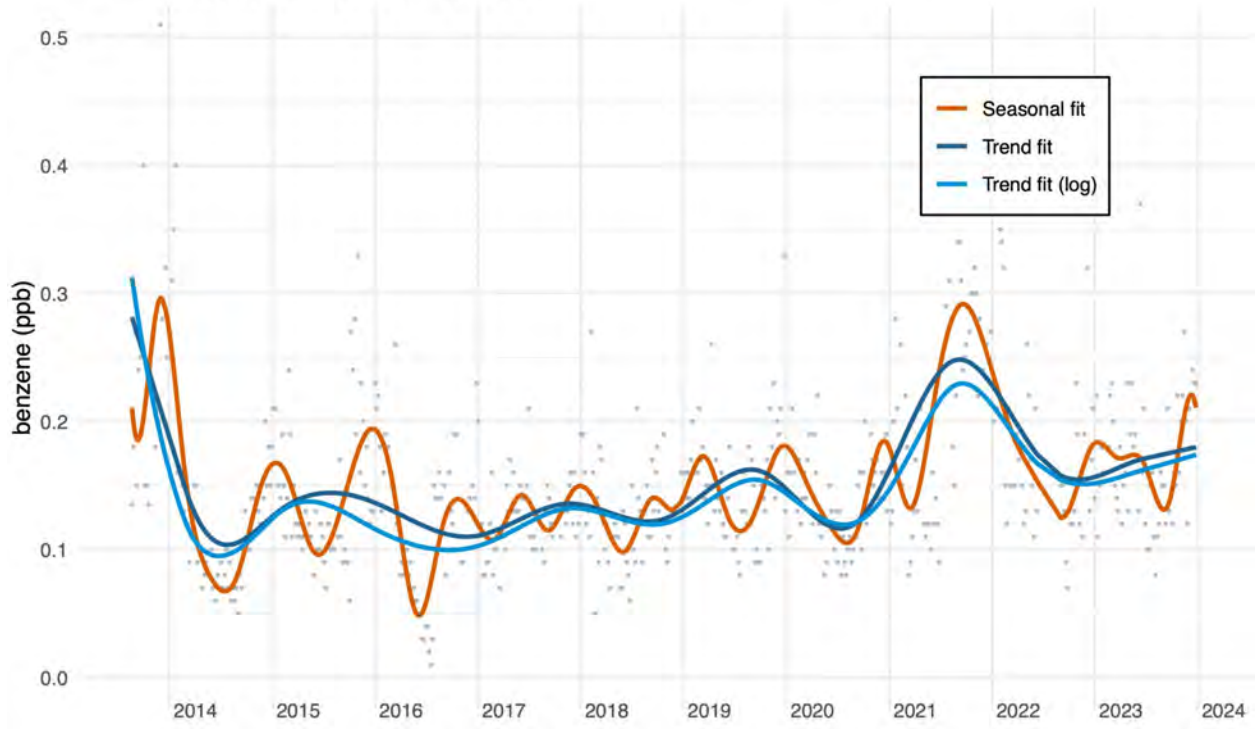
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MWL ethane natural cubic splines



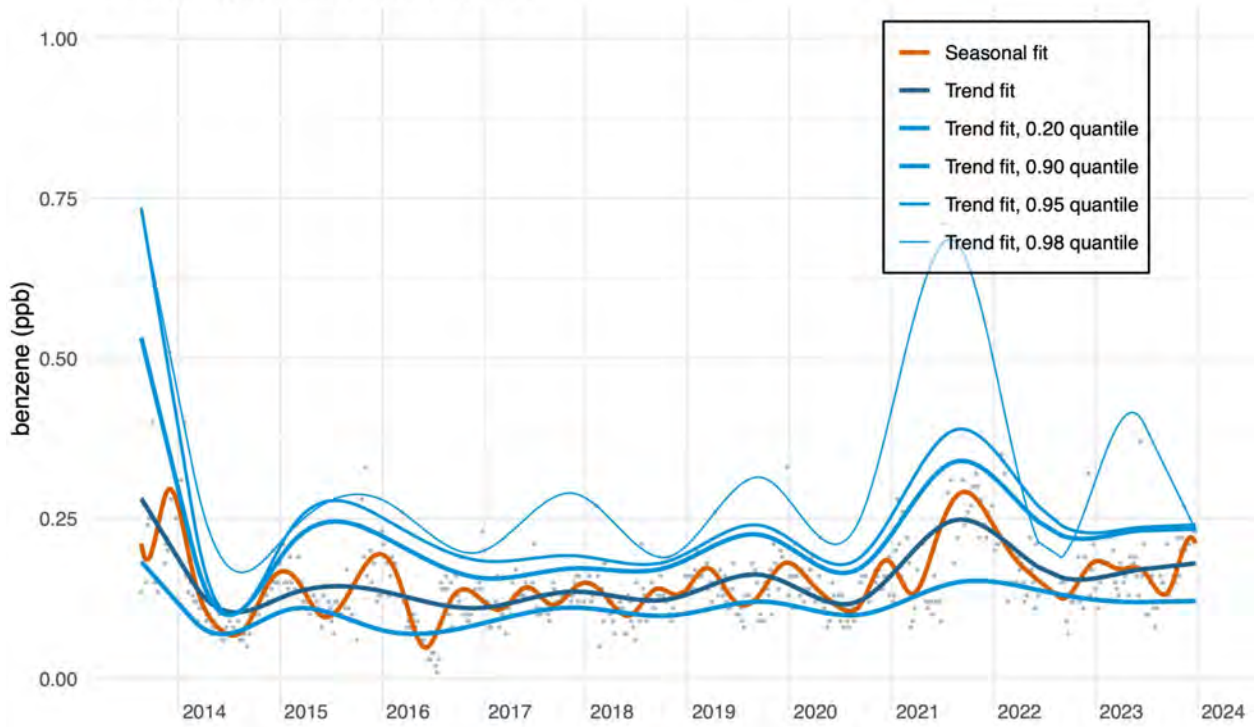
j.

MWL benzene natural cubic splines



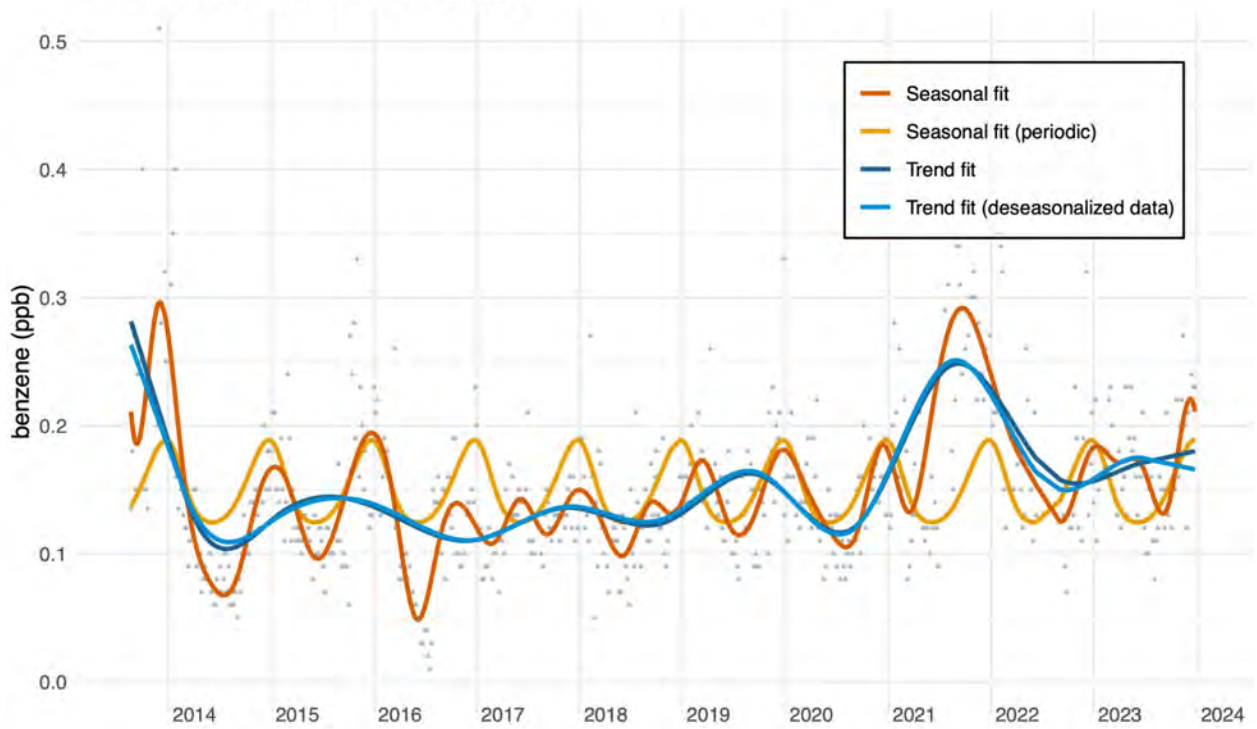
k.

MWL benzene natural cubic splines



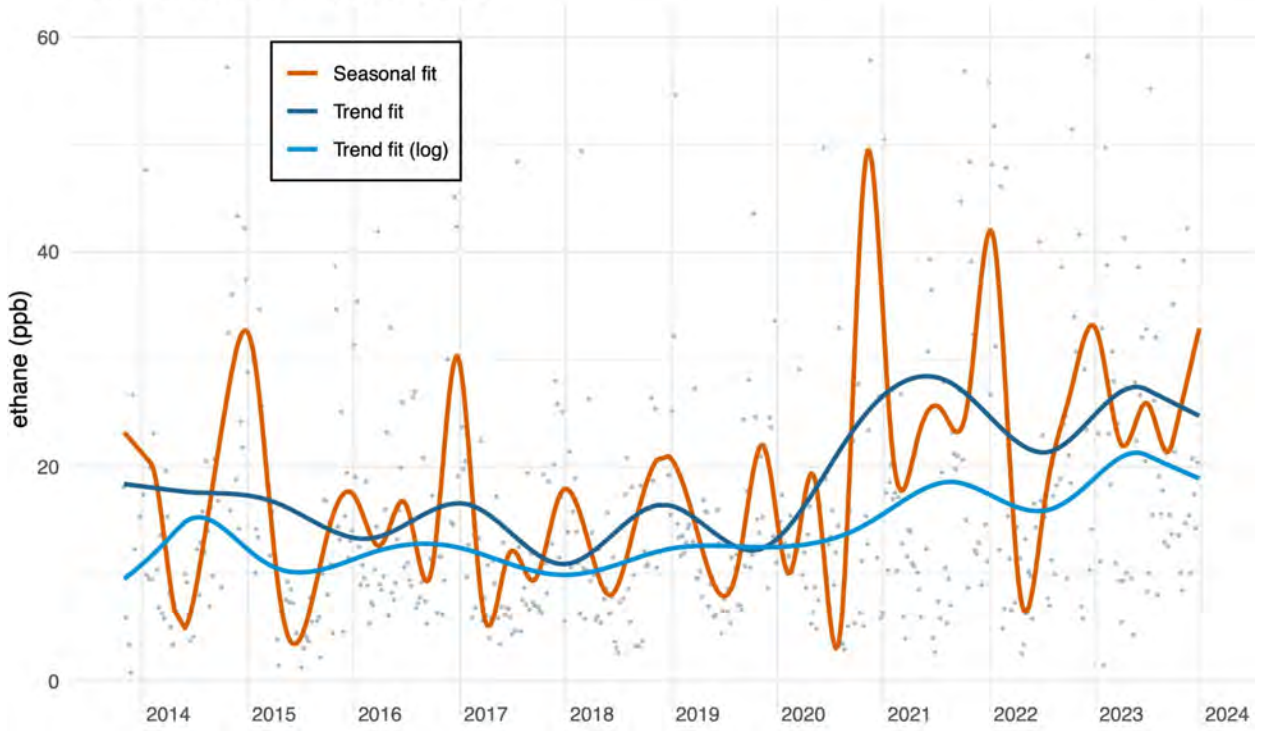
l.

MWL benzene natural cubic splines



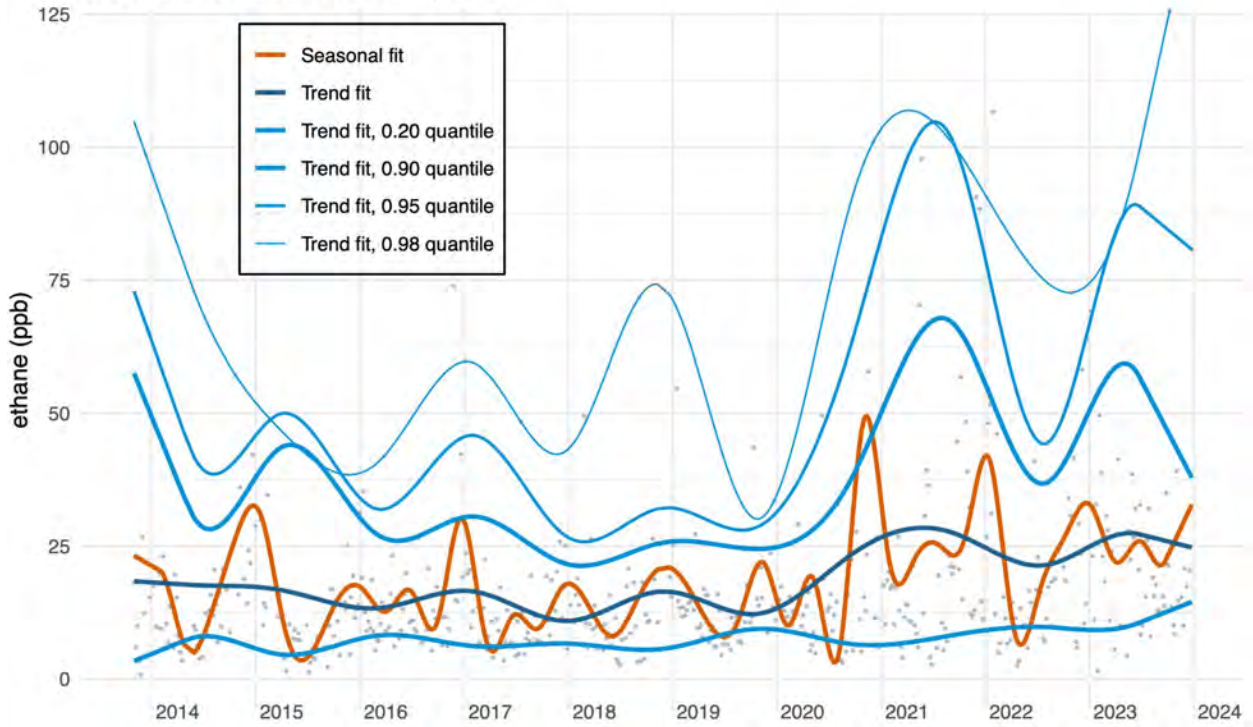
m.

BWP ethane natural cubic splines



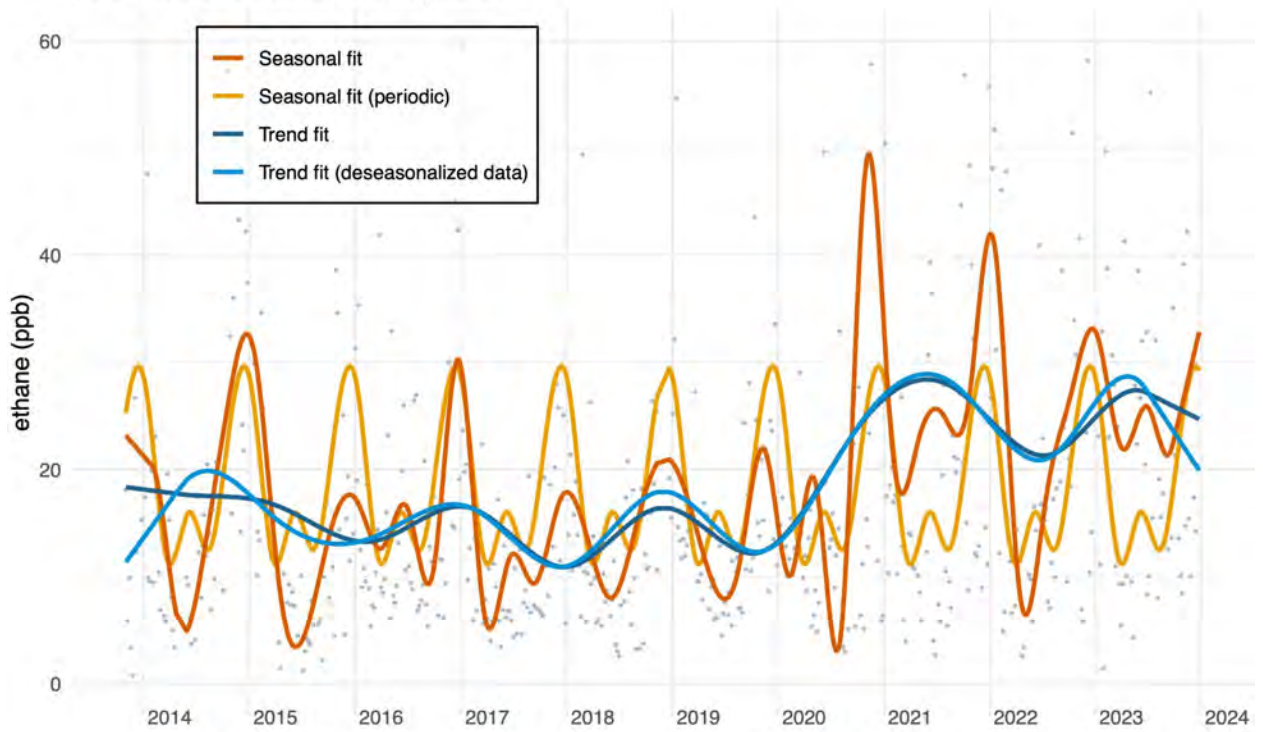
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BWP ethane natural cubic splines



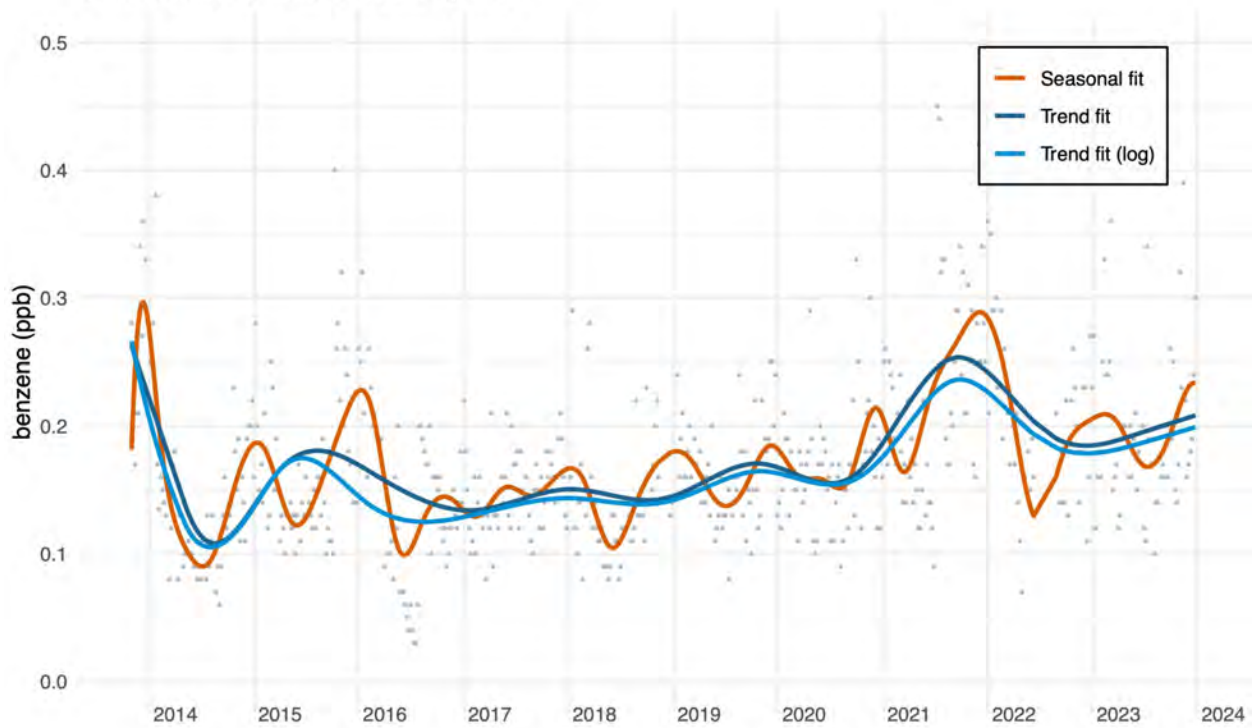
o.

BWP ethane natural cubic splines



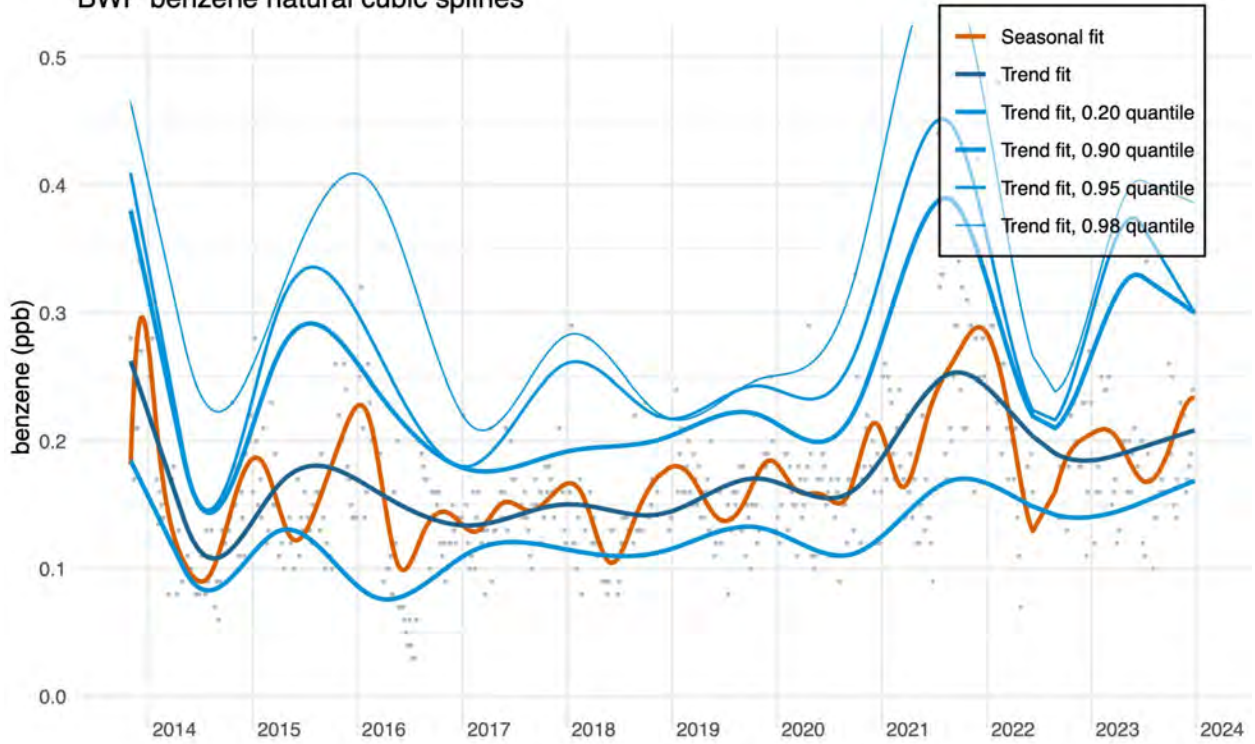
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BWP benzene natural cubic splines



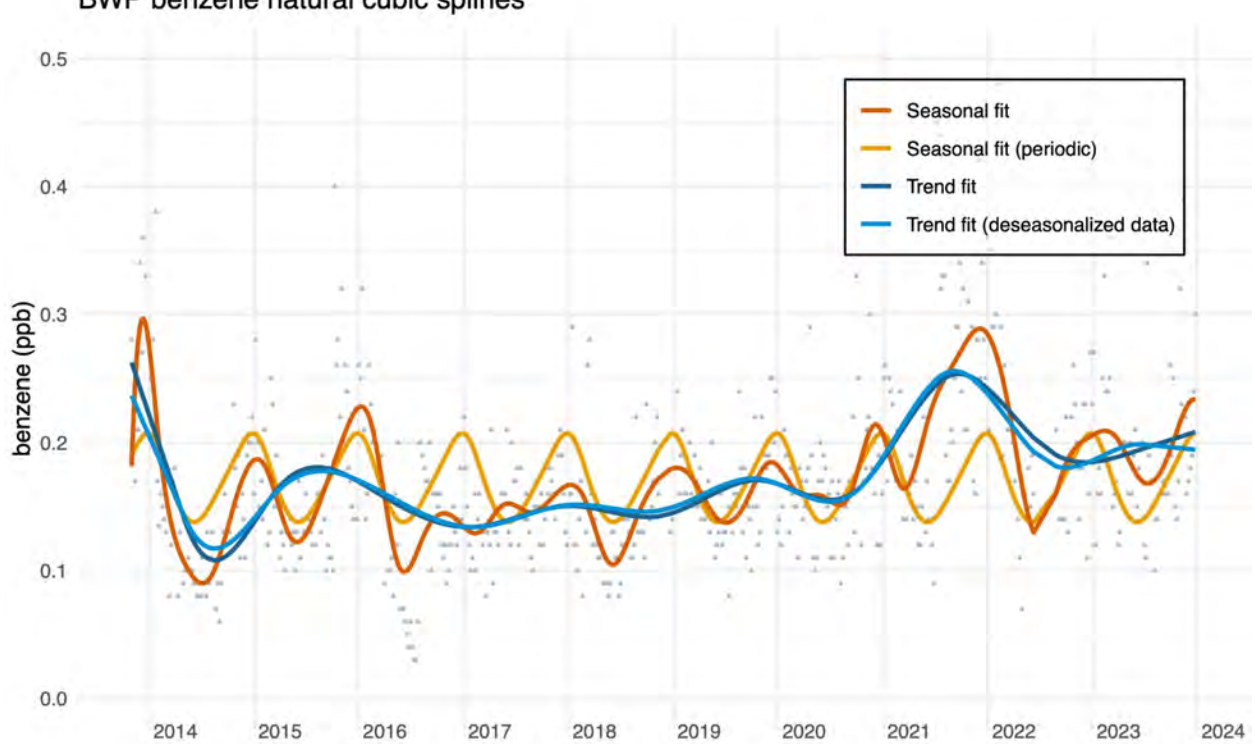
q.

BWP benzene natural cubic splines



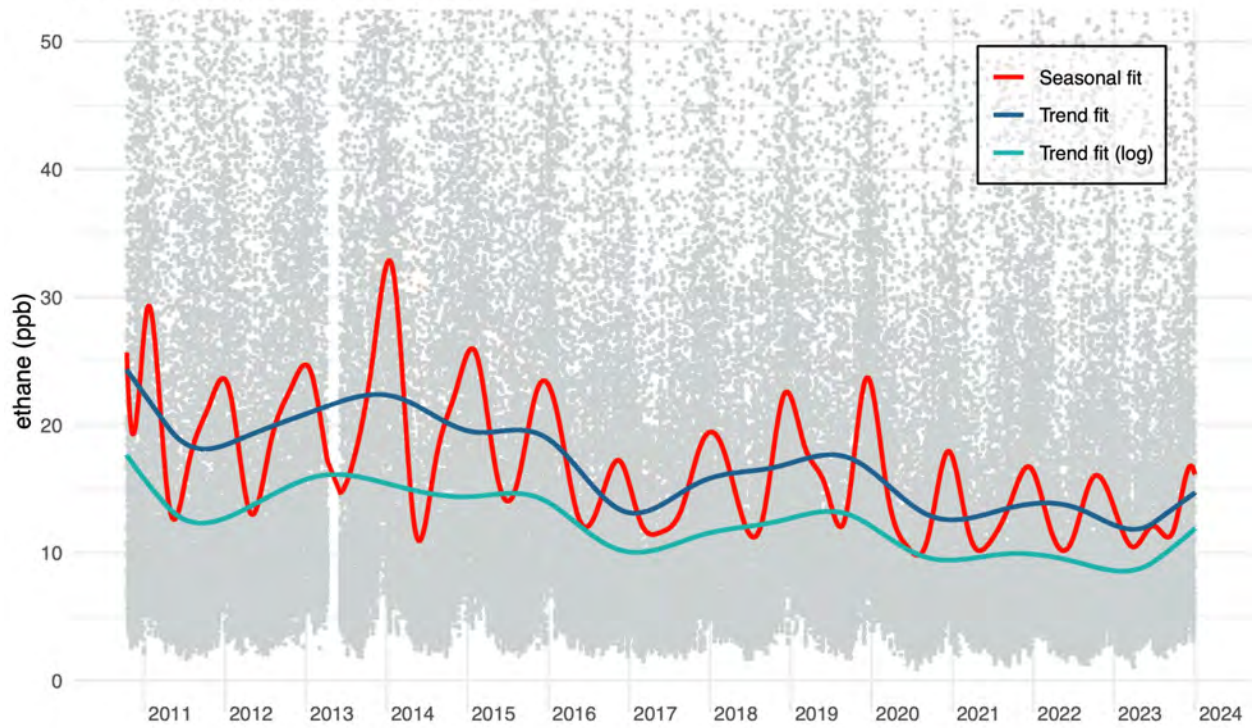
r.

BWP benzene natural cubic splines



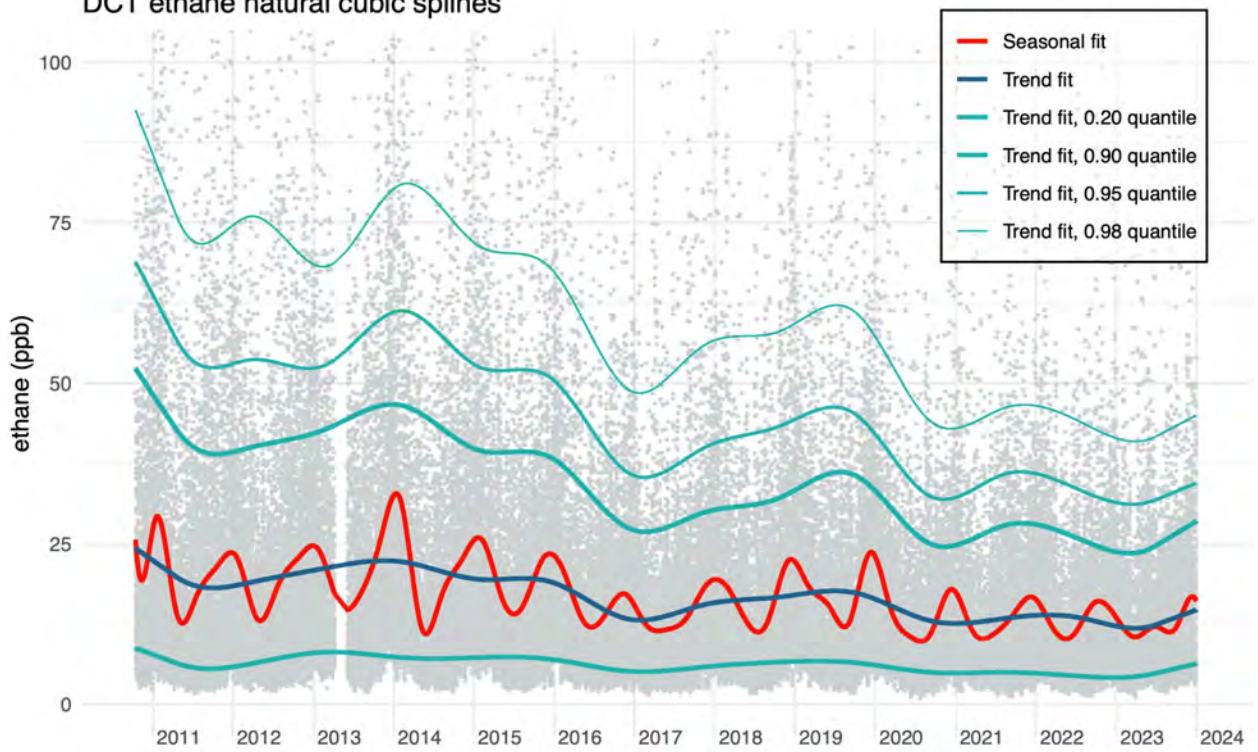
s.

DCT ethane natural cubic splines



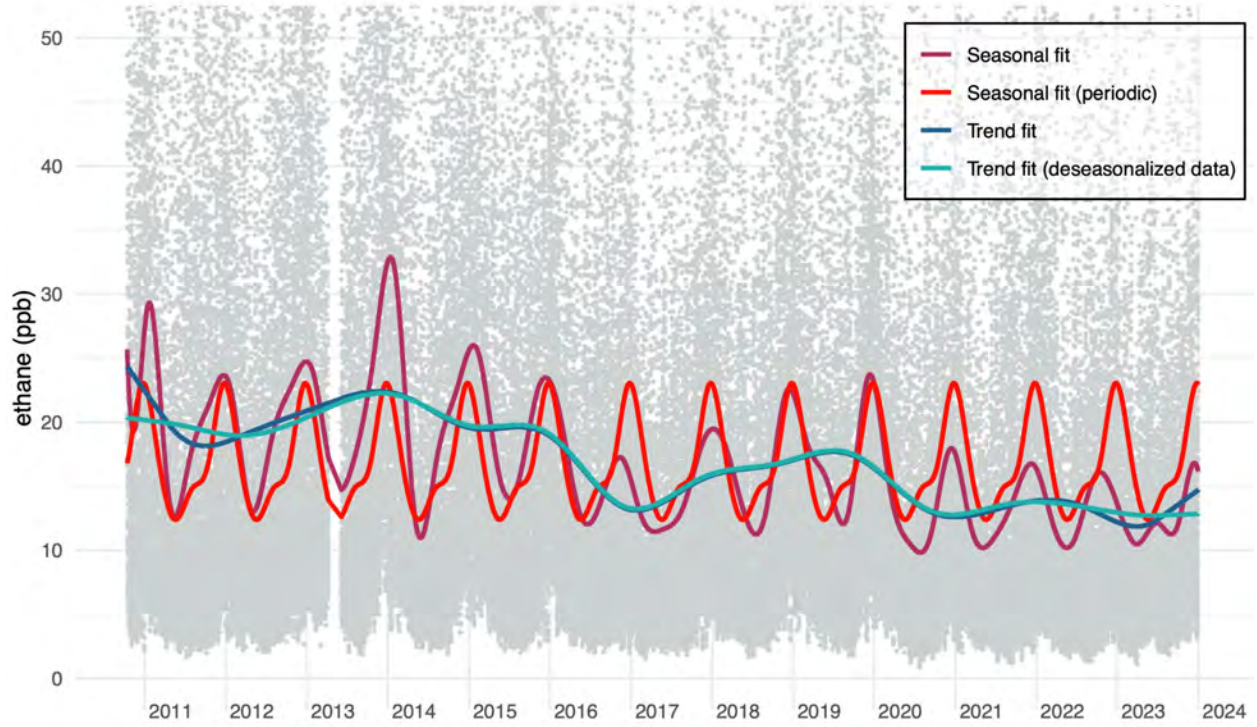
t.

DCT ethane natural cubic splines



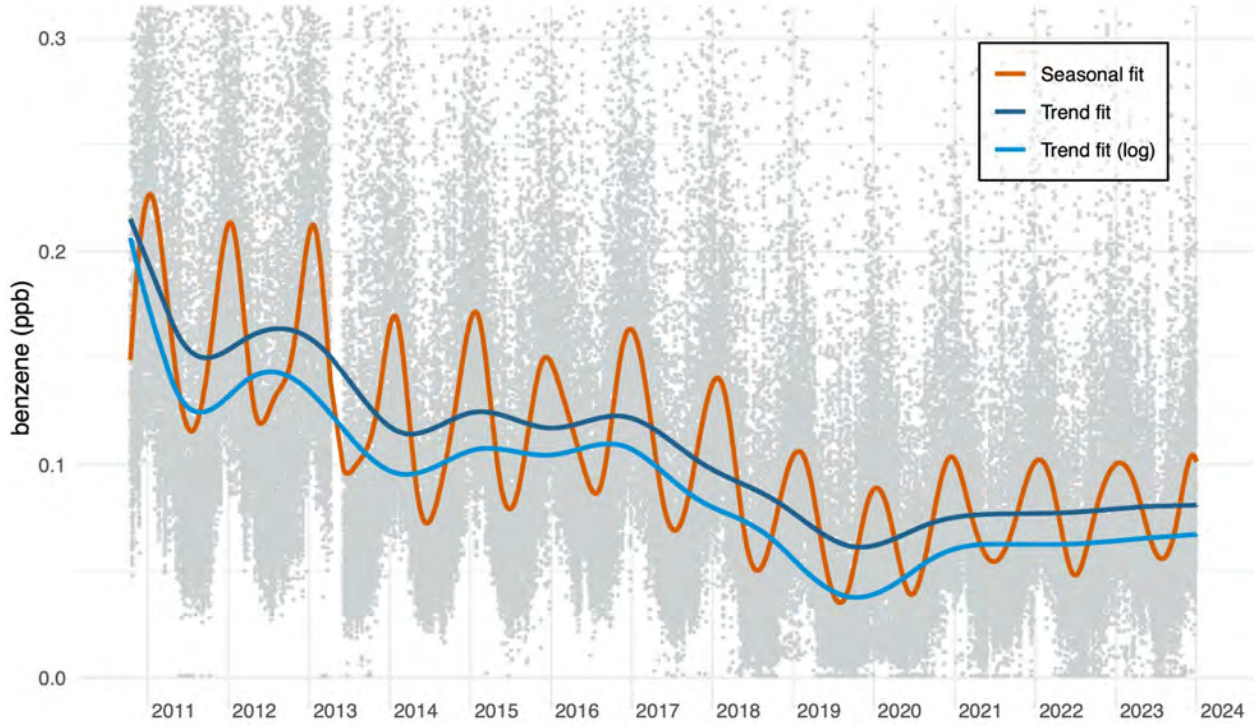
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DCT ethane natural cubic splines



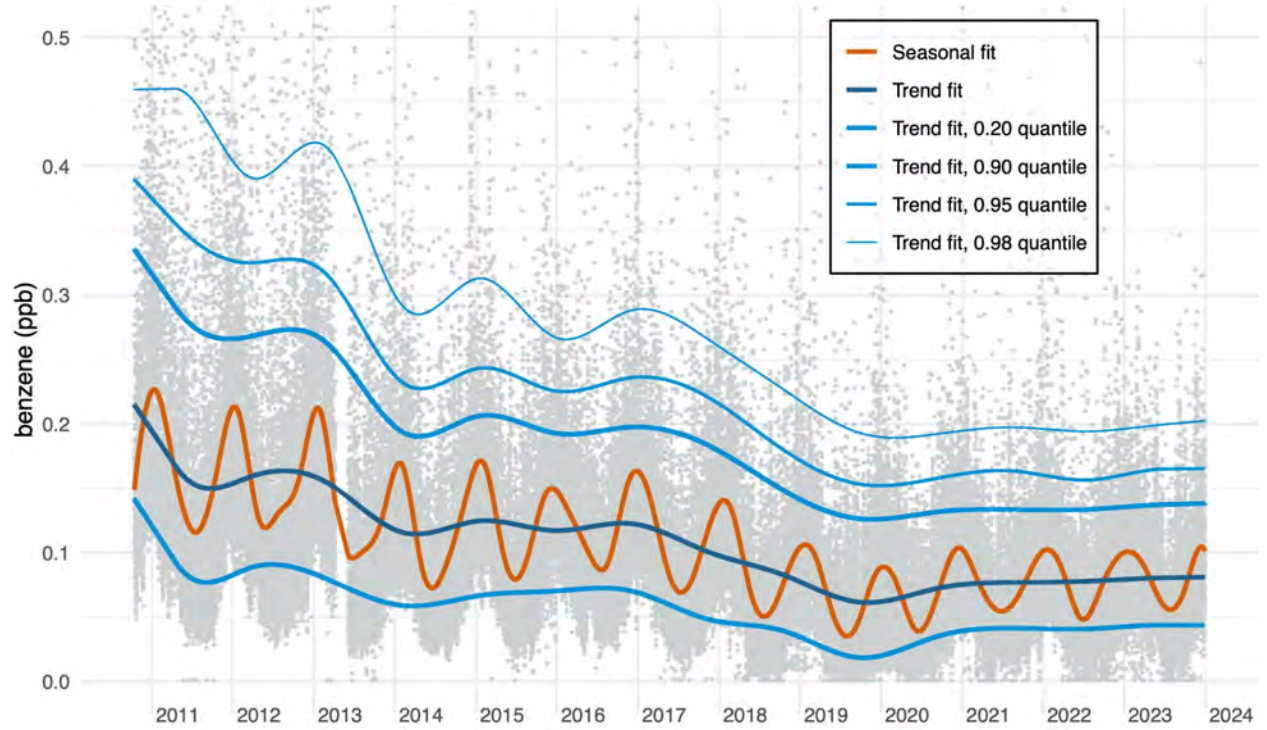
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DCT benzene natural cubic splines



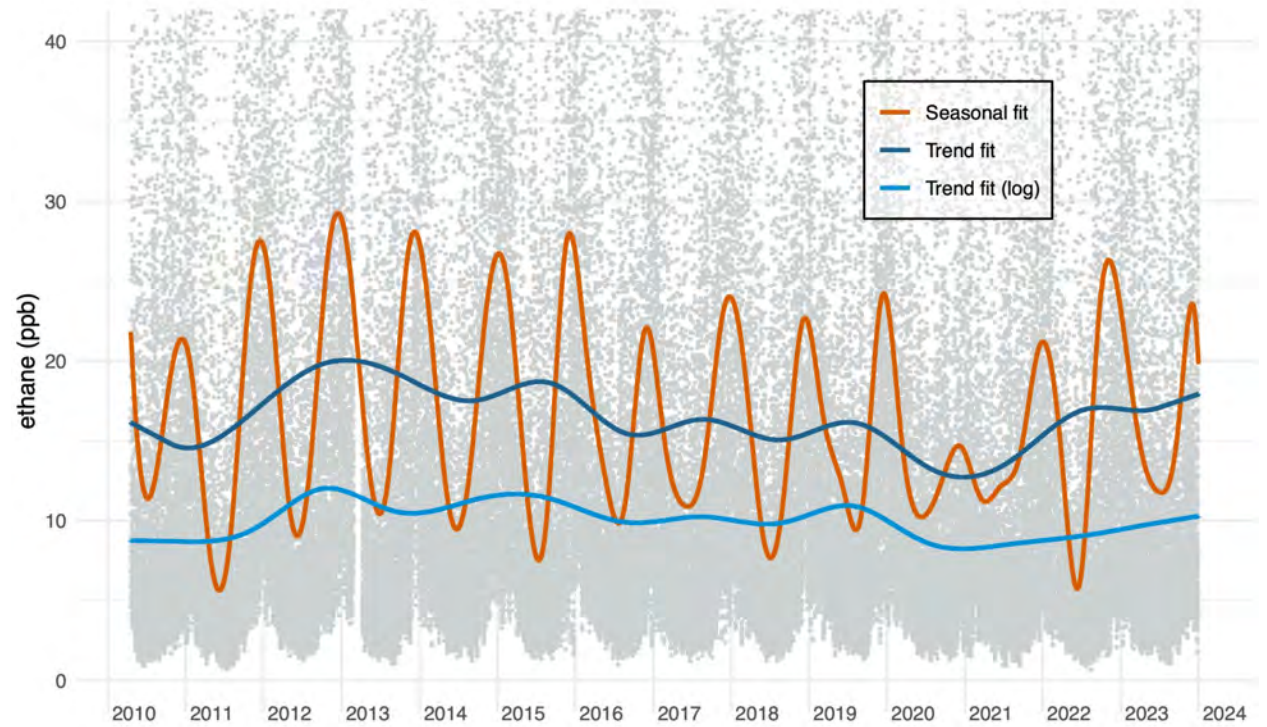
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DCT benzene natural cubic splines

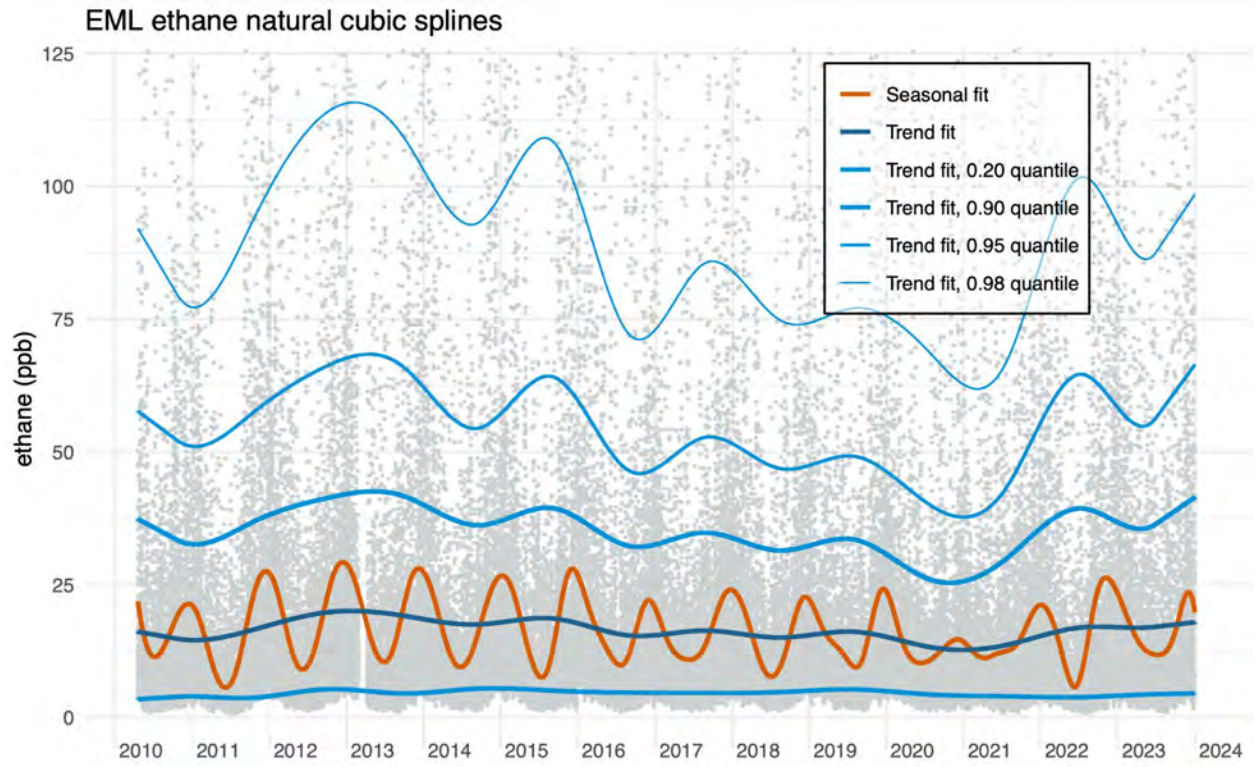


x.

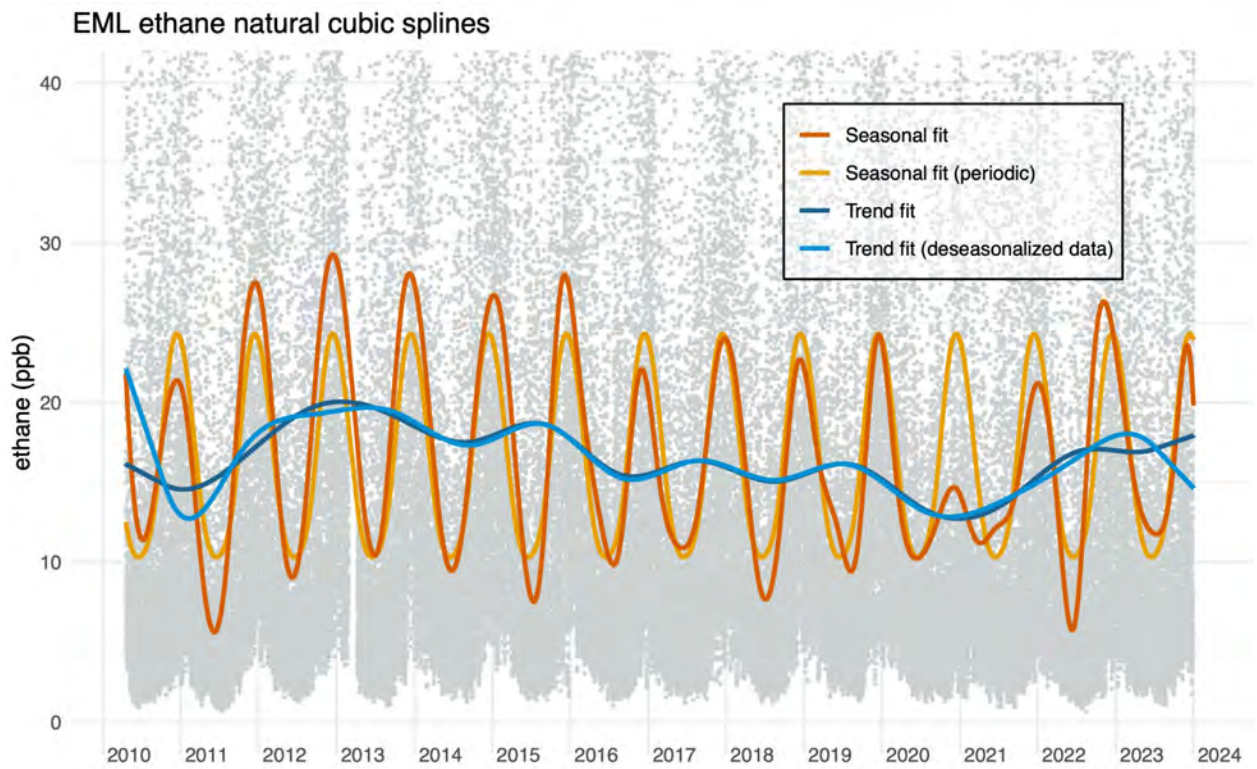
EML ethane natural cubic splines



y.

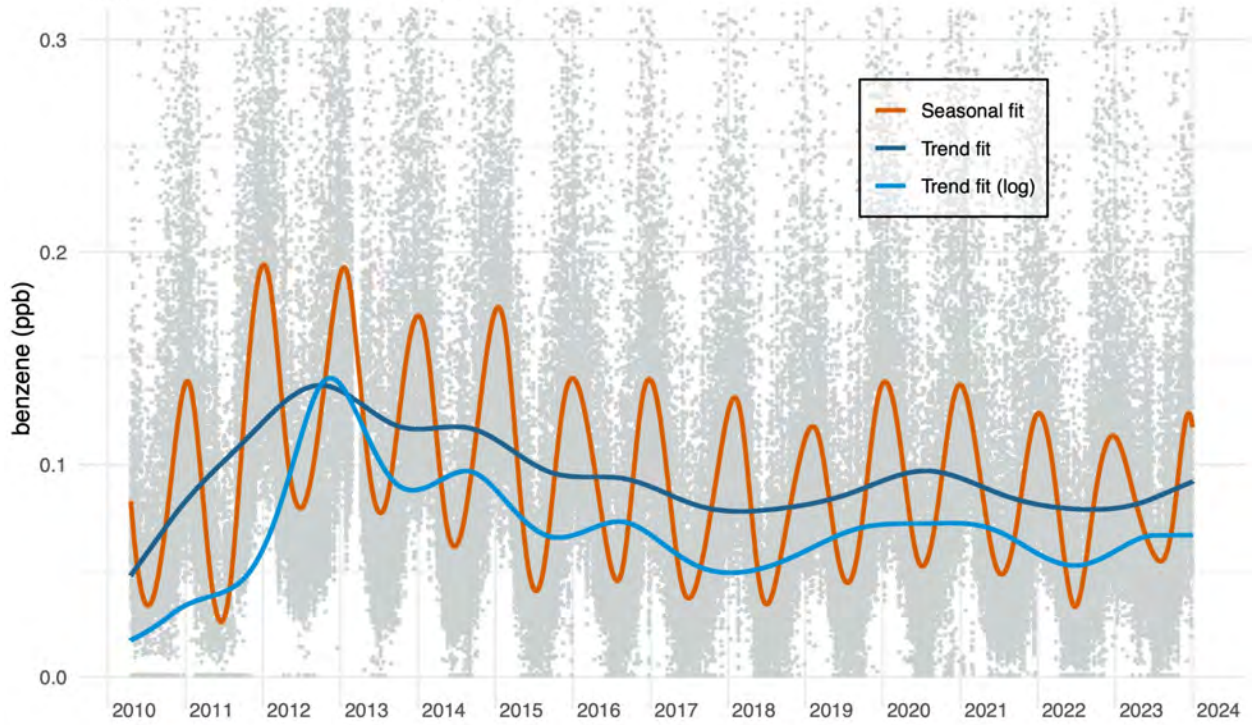


z.



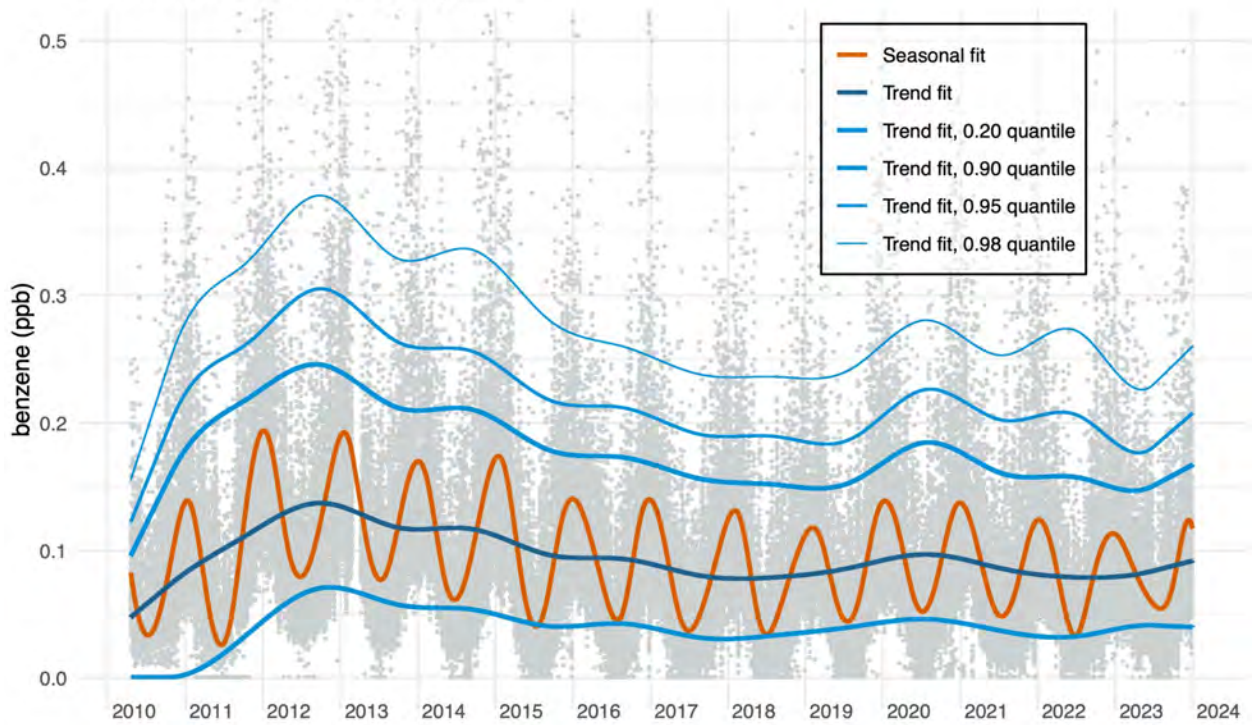
aa.

EML benzene natural cubic splines

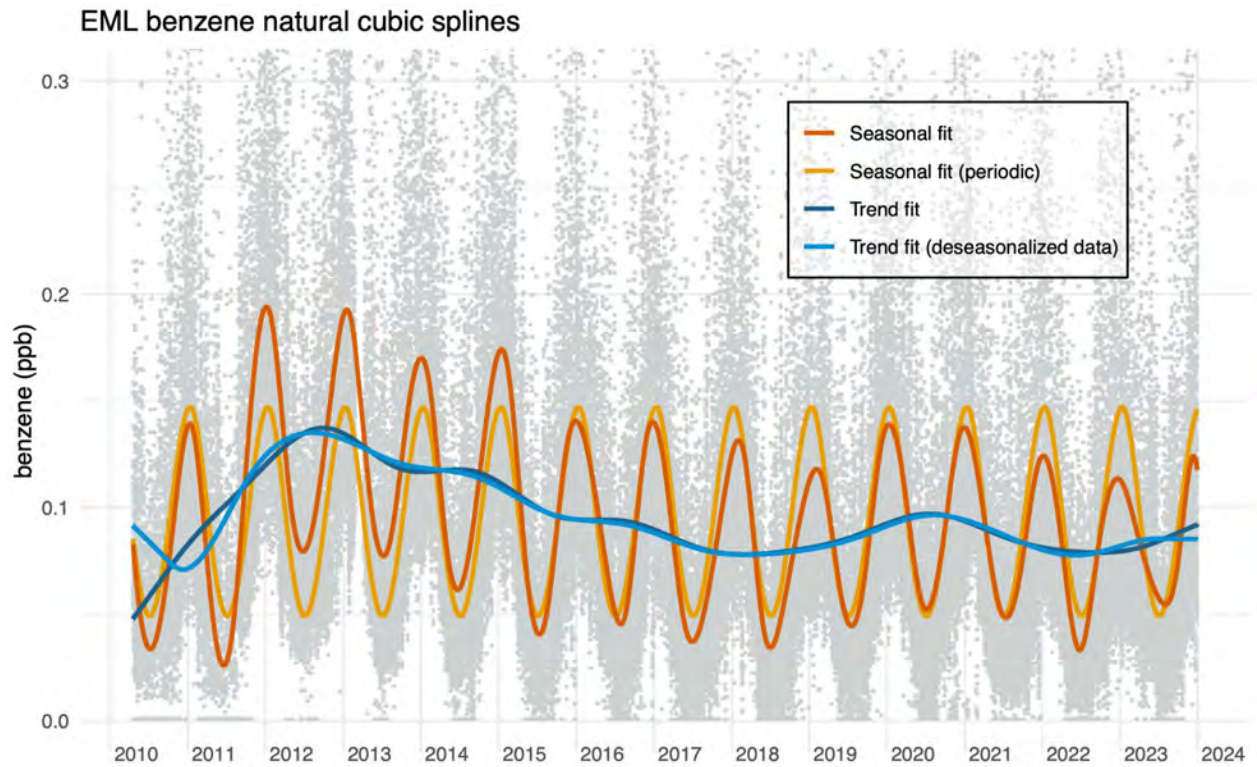


bb.

EML benzene natural cubic splines



cc.

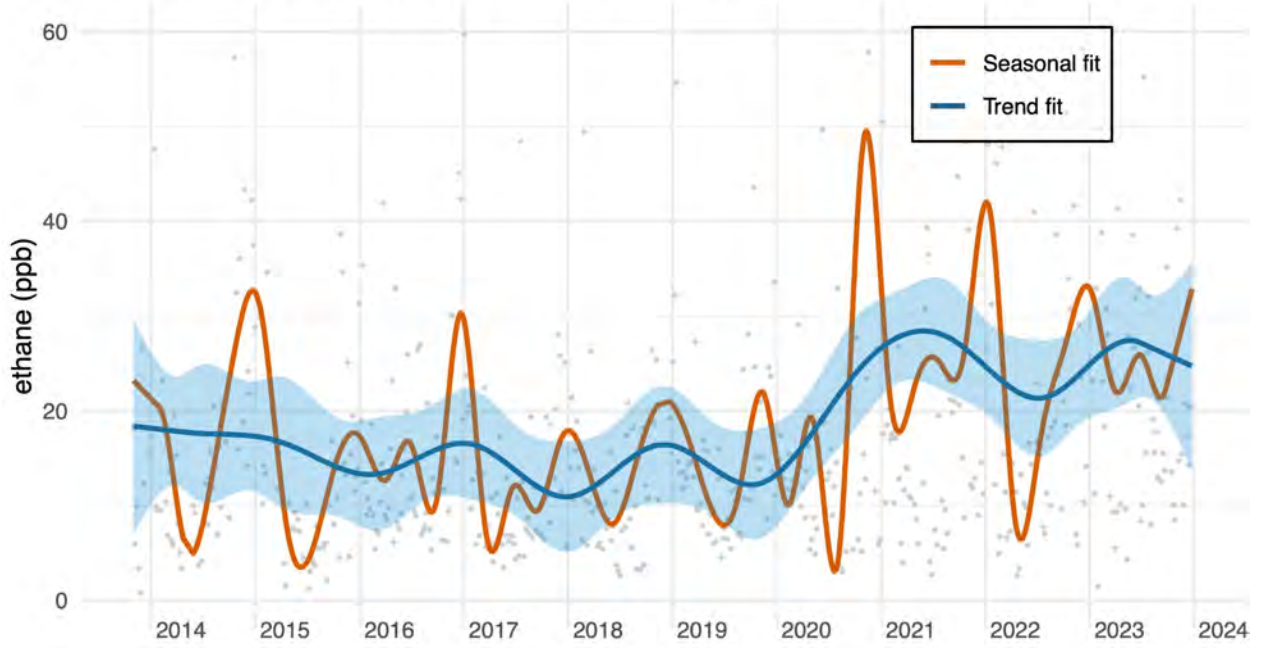


### Natural Cubic Spline Fits

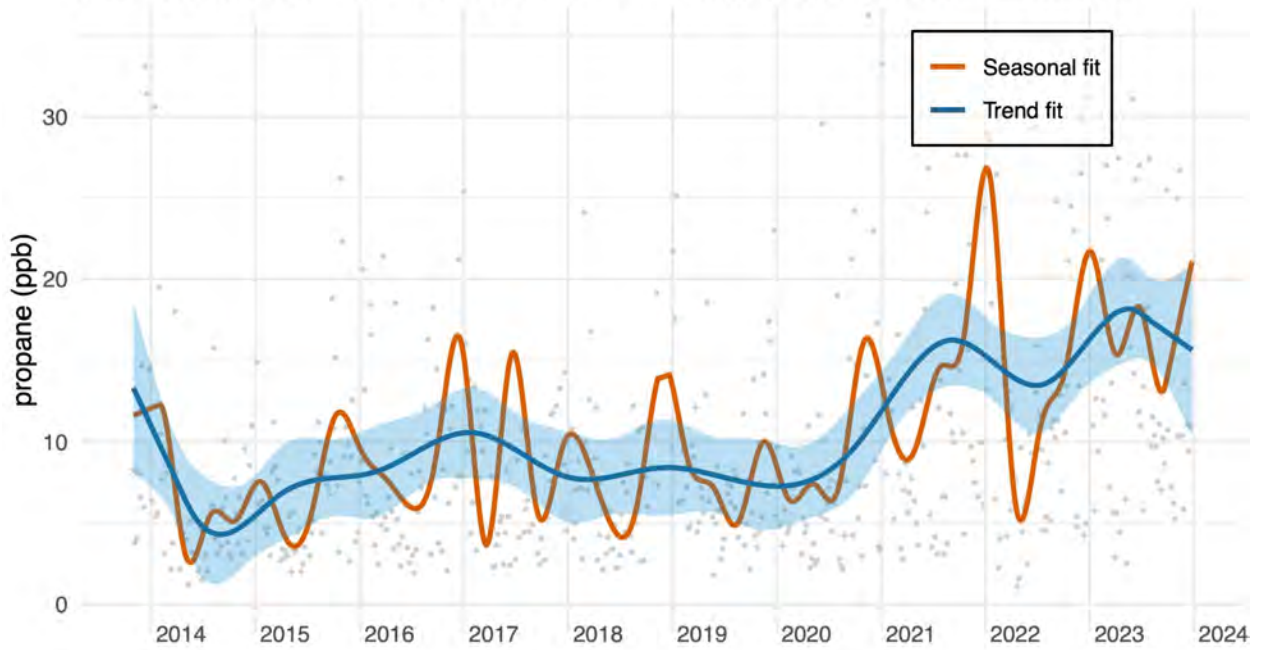
**Figure CI-3.** Long-term trends and seasonal spline fits for the 11 Texas sites for ethane, propane, and benzene. (Note that the fine spline fits are less relevant to the timescales of this study and have been left off of these plots for clarity.)

**a.** Barnett Shale: BWP, DCT, EML, MWL, WFD

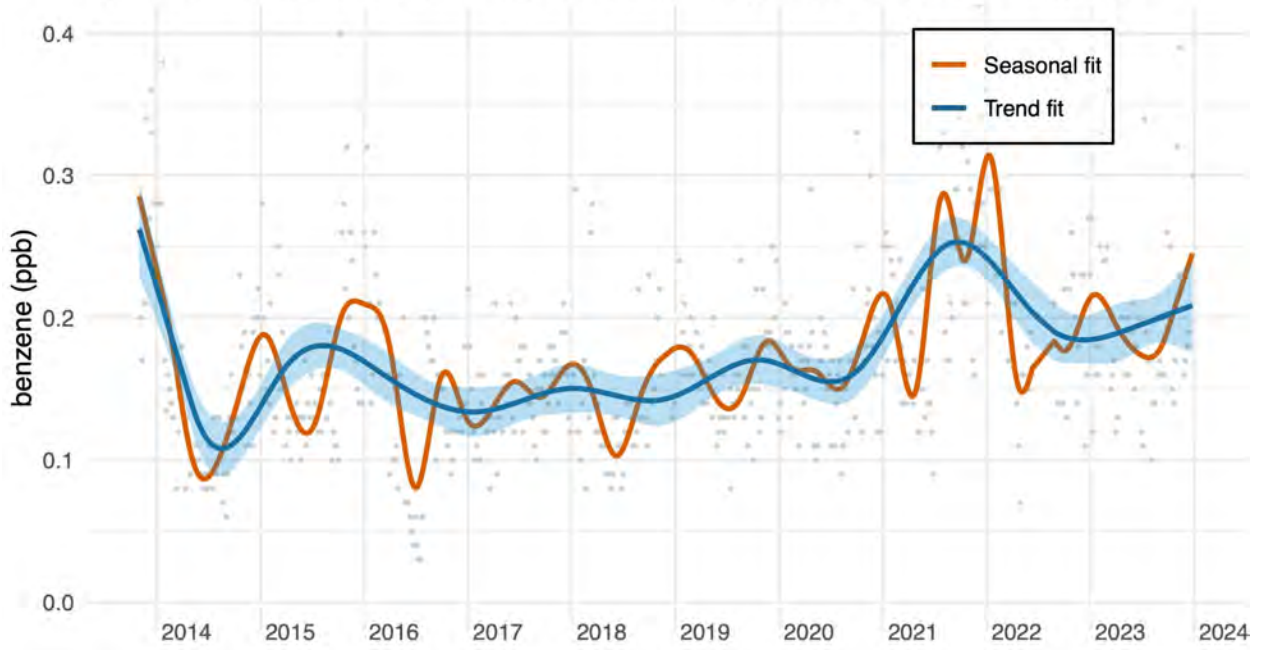
BWP ethane natural cubic splines; trend fit with 95% confidence interval



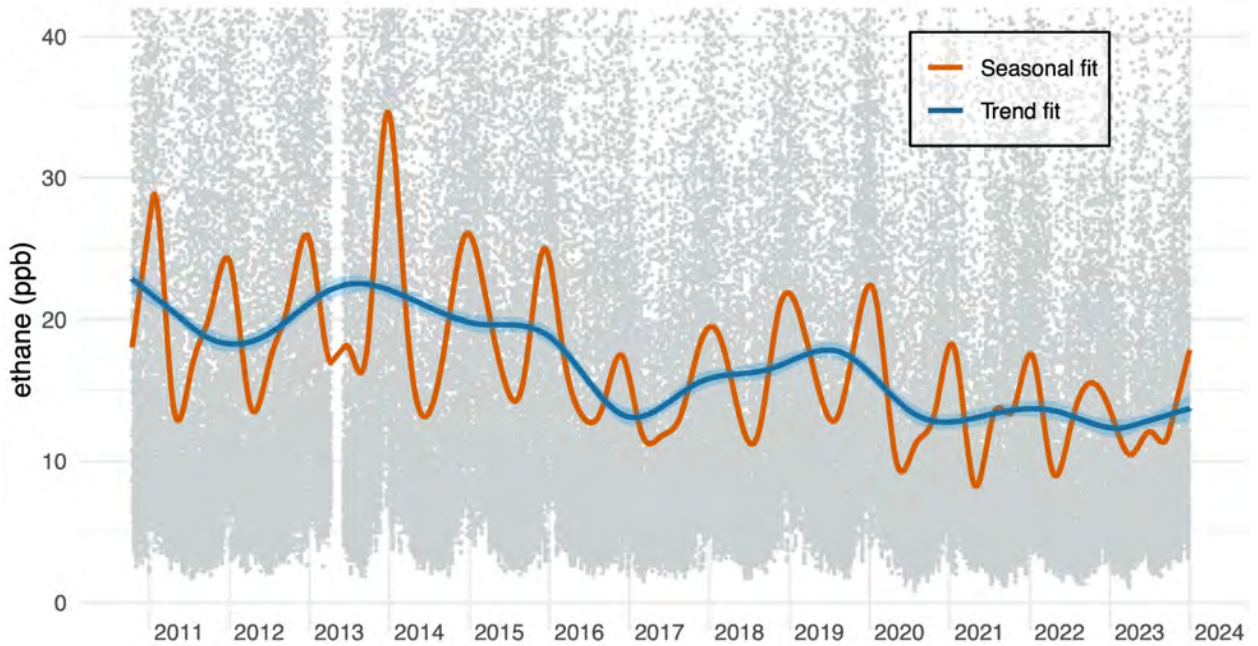
BWP propane natural cubic splines; trend fit with 95% confidence interval



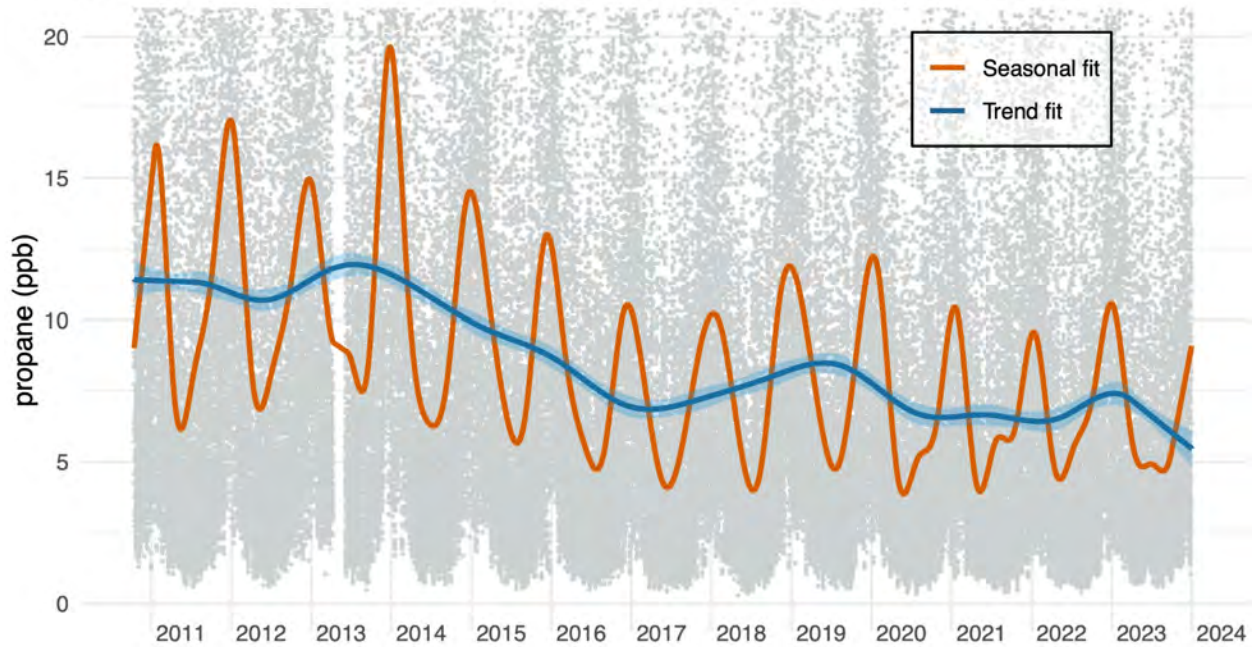
BWP benzene natural cubic splines; trend fit with 95% confidence interval



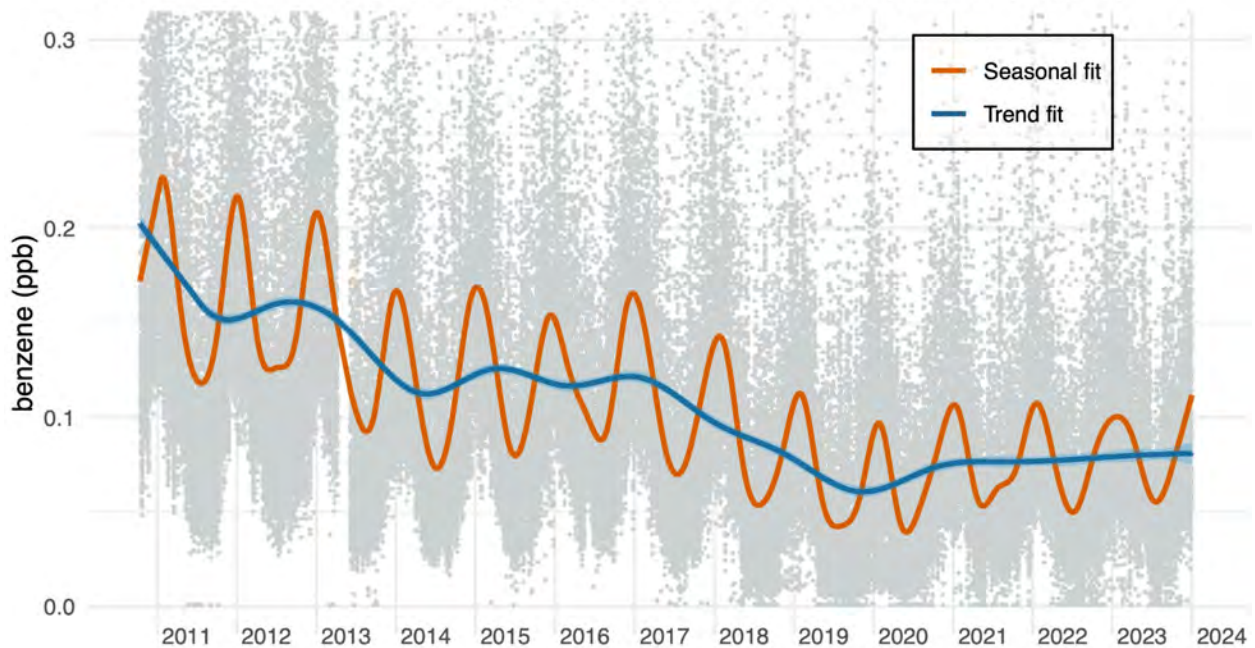
DCT ethane natural cubic splines; trend fit with 95% confidence interval



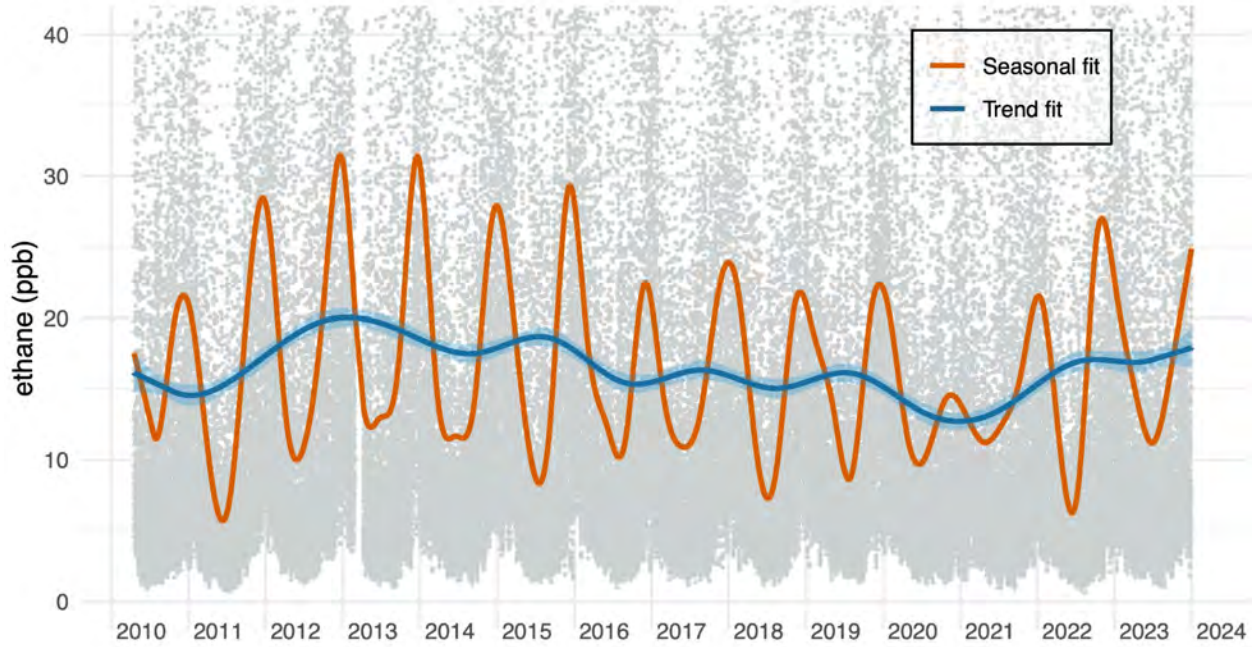
DCT propane natural cubic splines; trend fit with 95% confidence interval



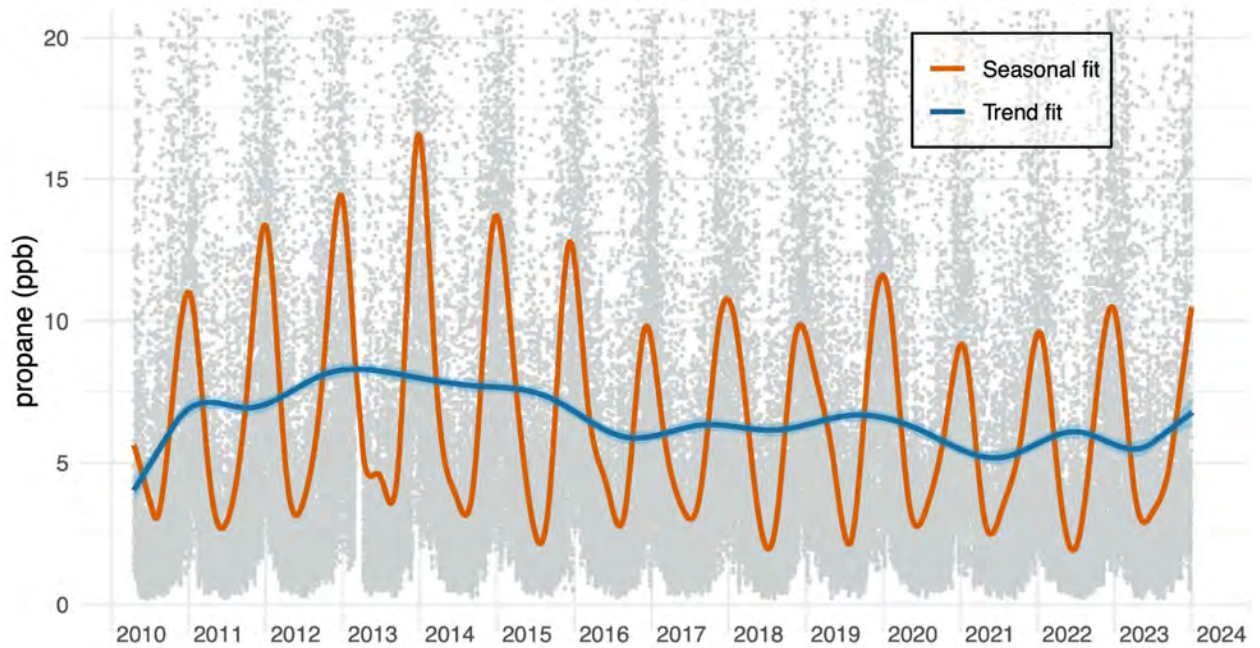
DCT benzene natural cubic splines; trend fit with 95% confidence interval



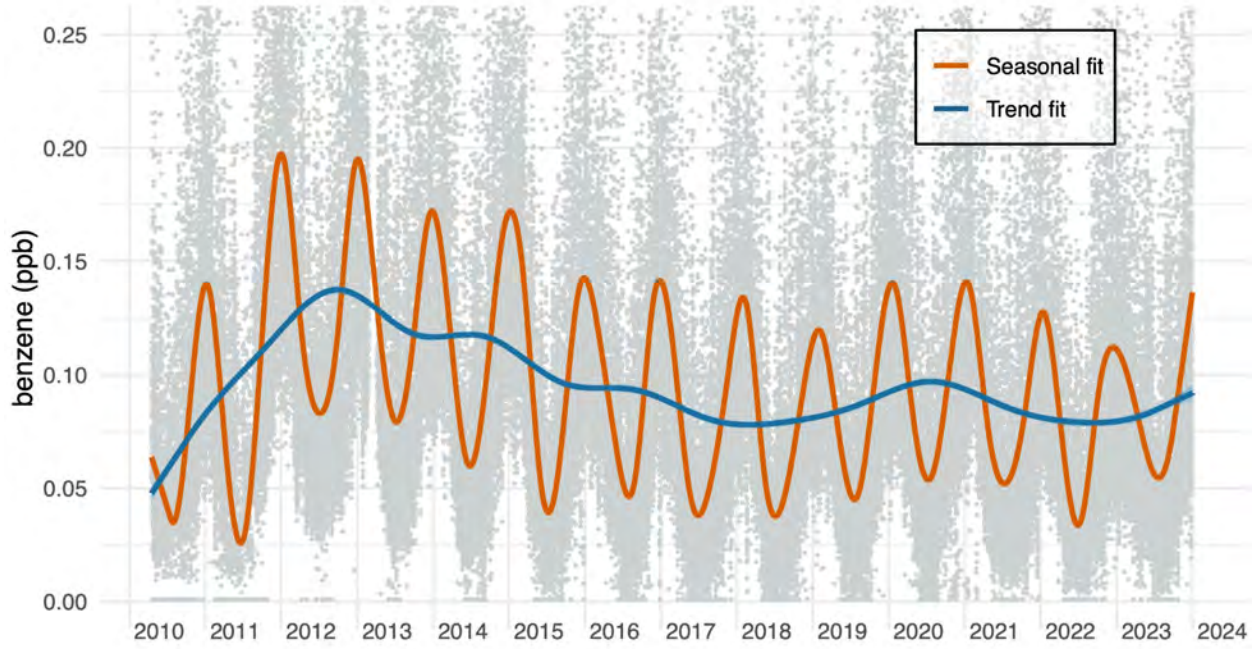
EML ethane natural cubic splines; trend fit with 95% confidence interval



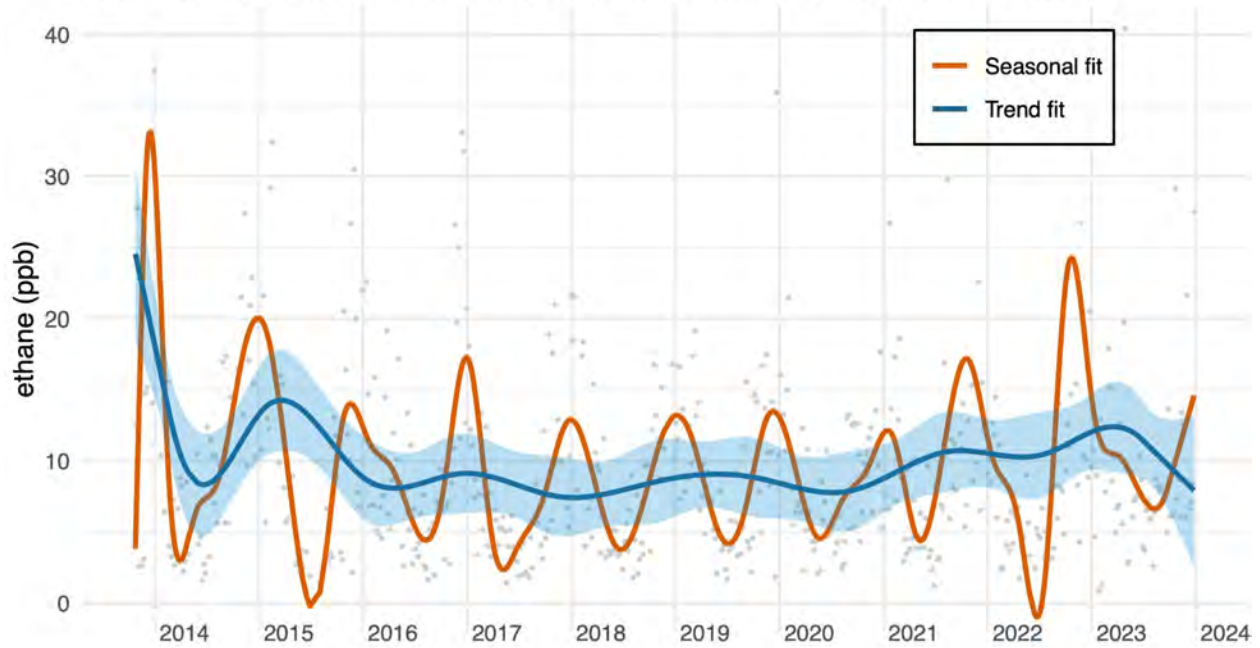
EML propane natural cubic splines; trend fit with 95% confidence interval



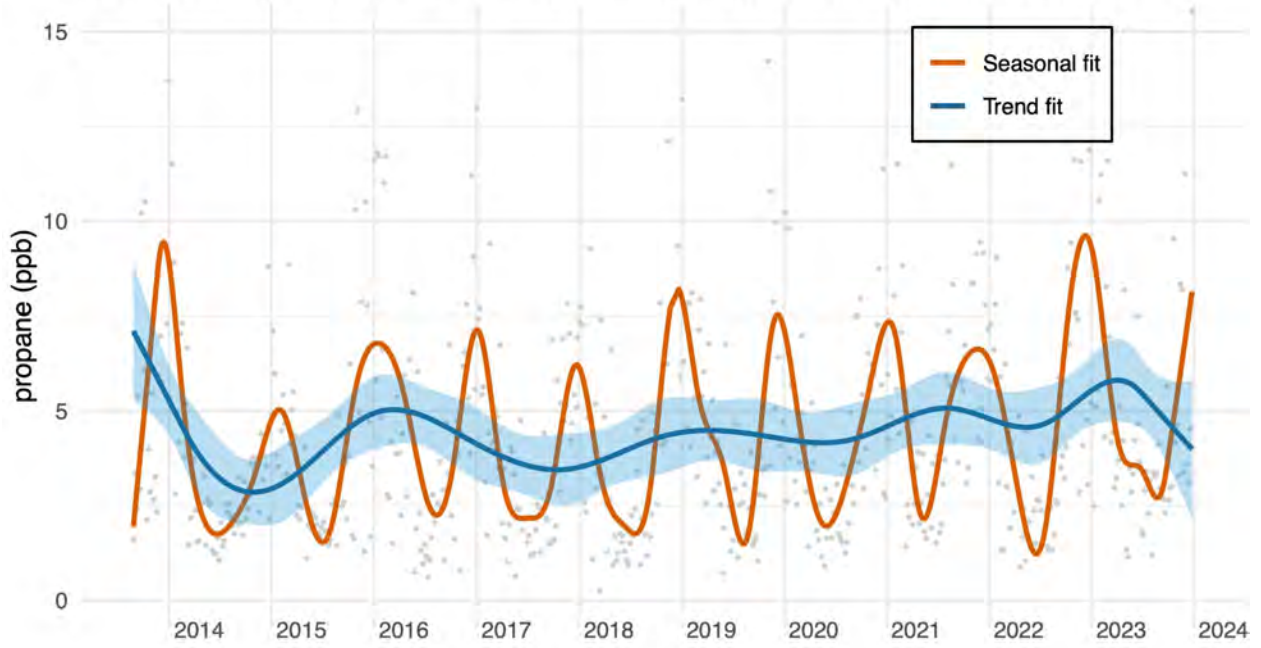
EML benzene natural cubic splines; trend fit with 95% confidence interval



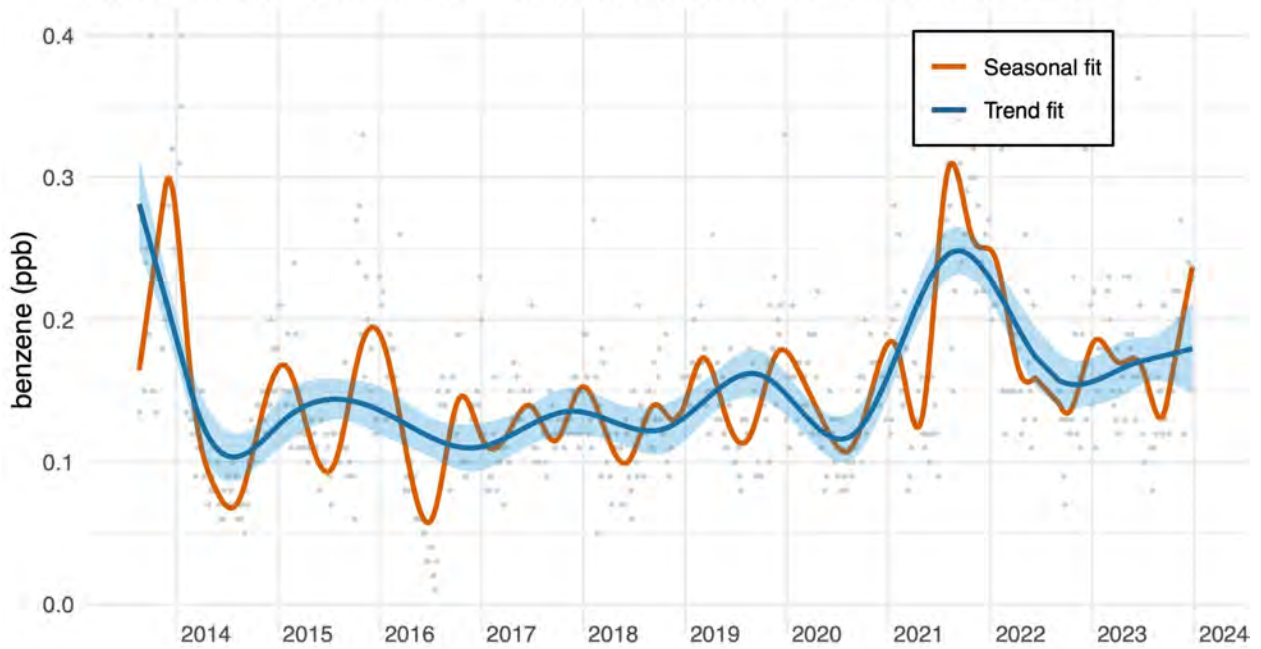
MWL ethane natural cubic splines; trend fit with 95% confidence interval



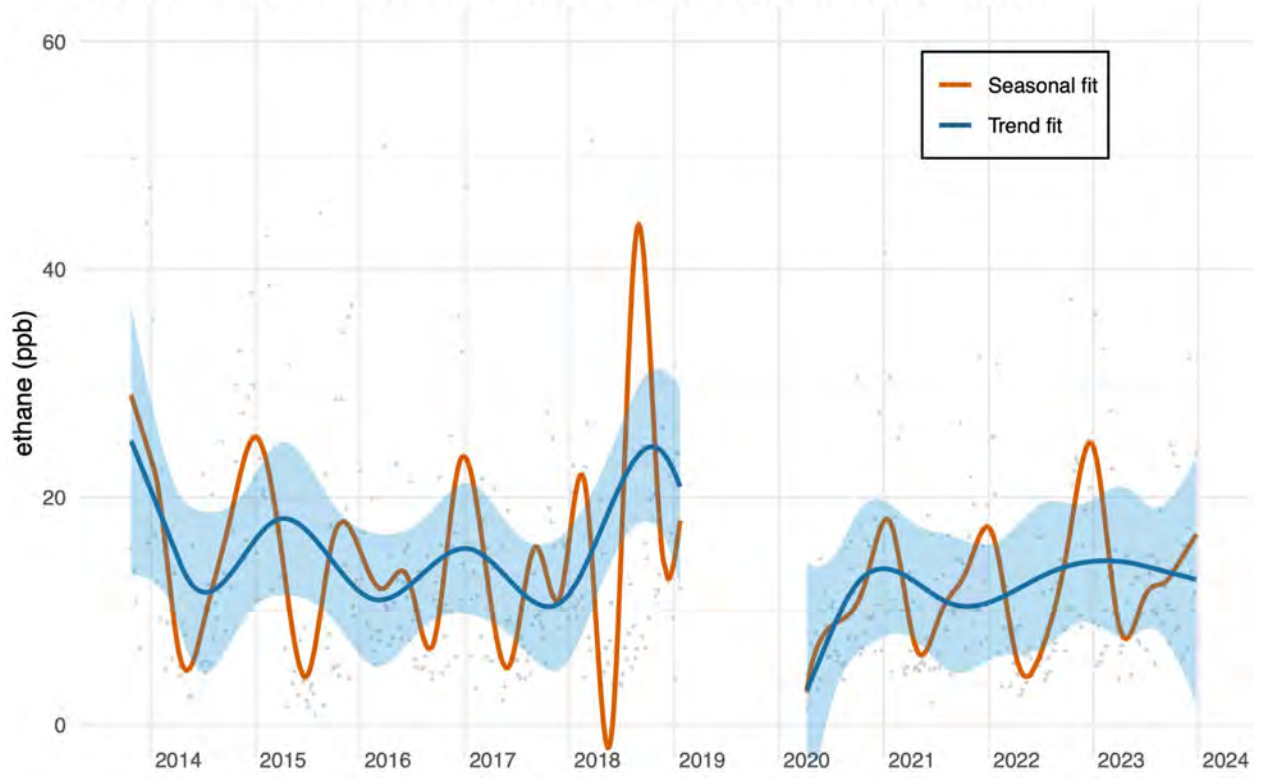
MWL propane natural cubic splines; trend fit with 95% confidence interval



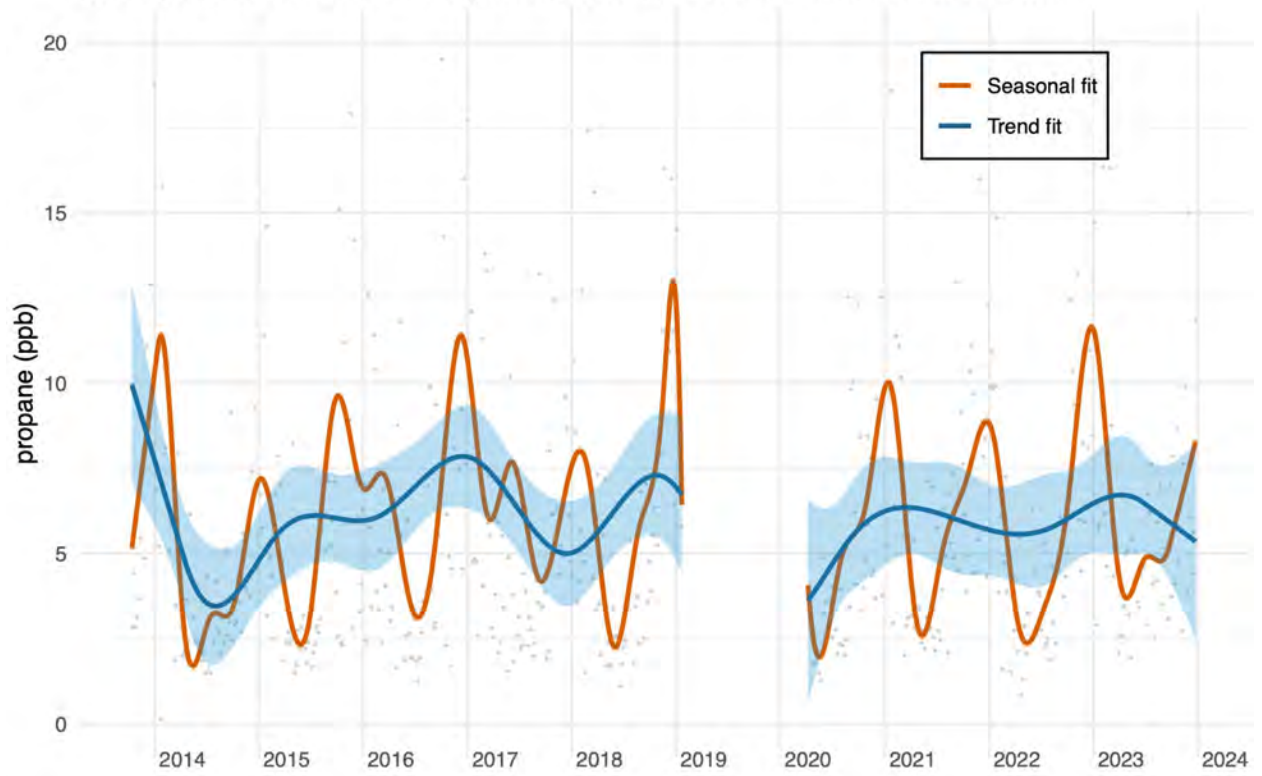
MWL benzene natural cubic splines; trend fit with 95% confidence interval



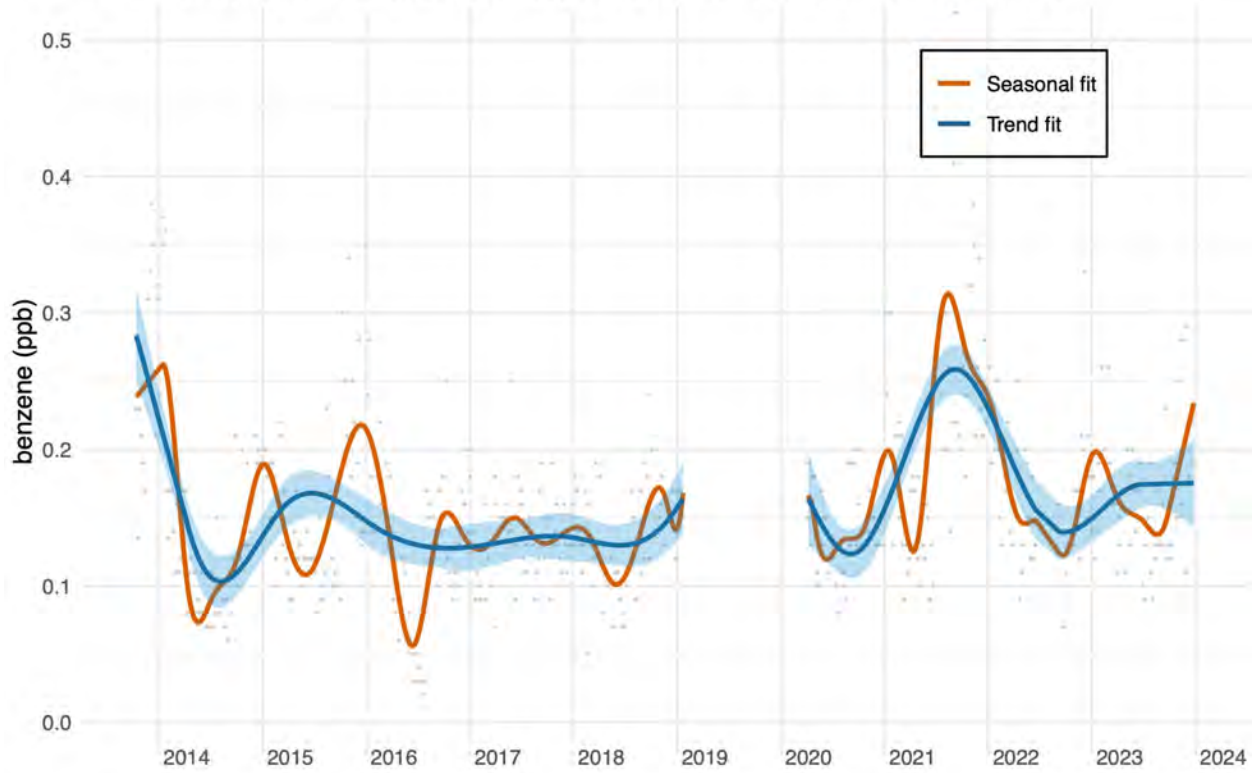
WFD ethane natural cubic splines; trend fit with 95% confidence interval



WFD propane natural cubic splines; trend fit with 95% confidence interval

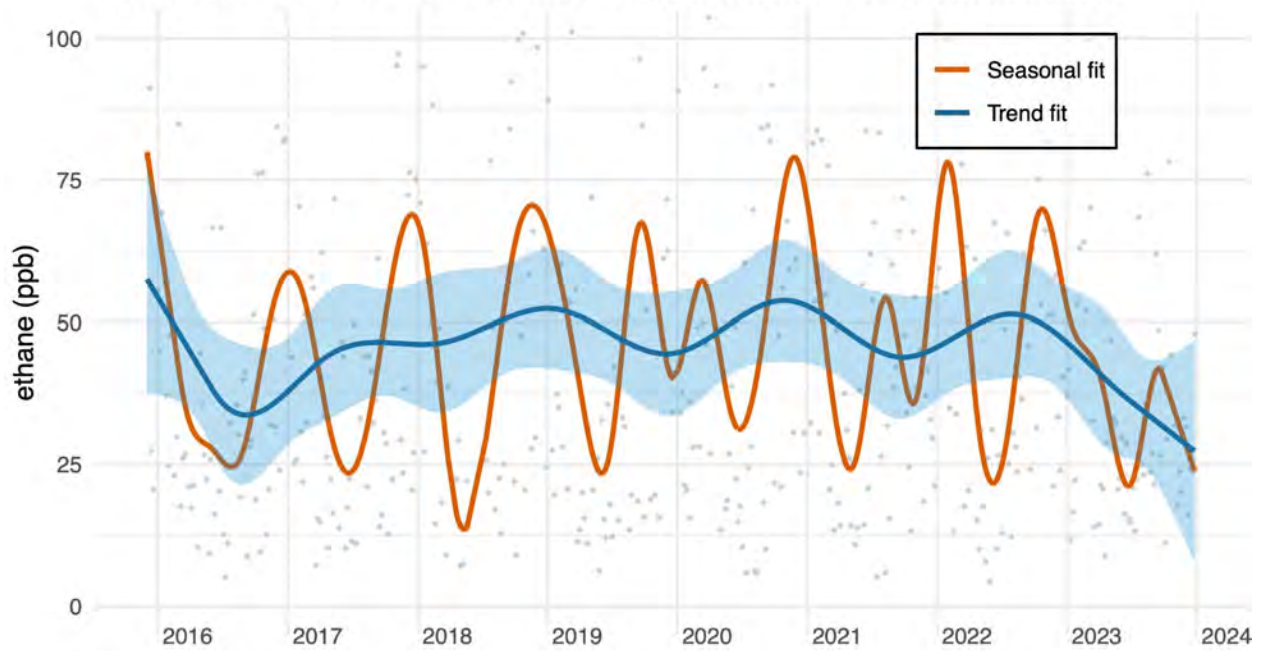


WFD benzene natural cubic splines; trend fit with 95% confidence interval

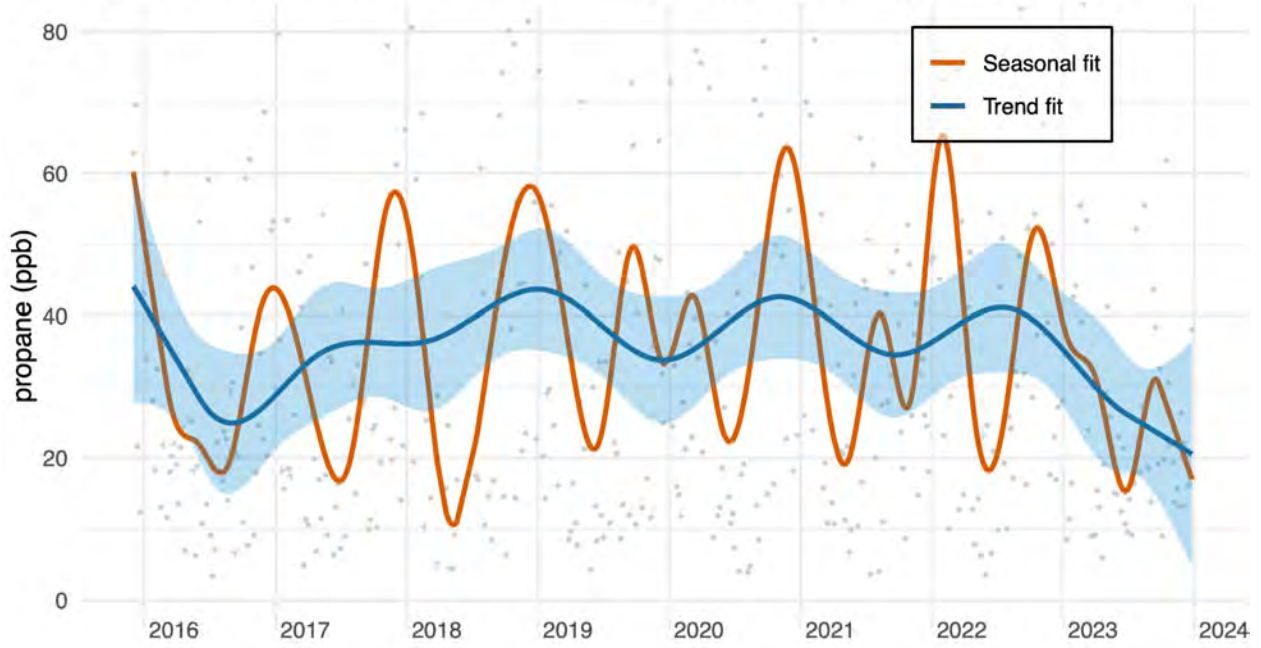


**b. Permian Basin: OHE**

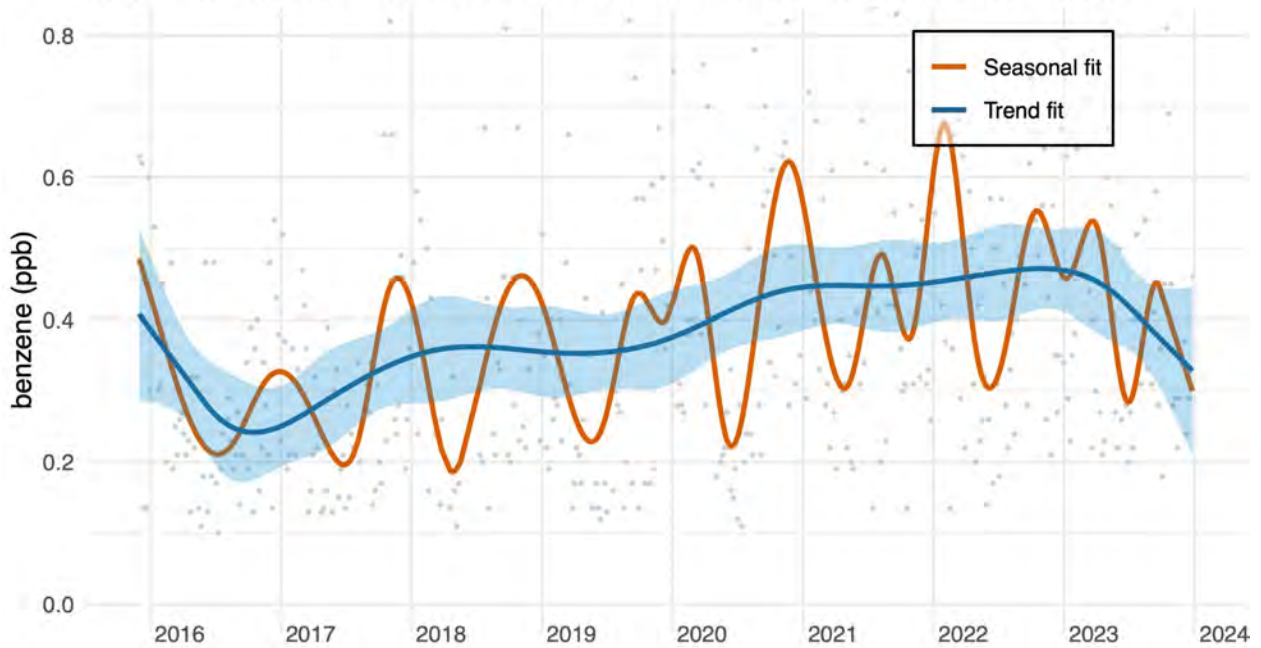
OHE ethane natural cubic splines; trend fit with 95% confidence interval



OHE propane natural cubic splines; trend fit with 95% confidence interval

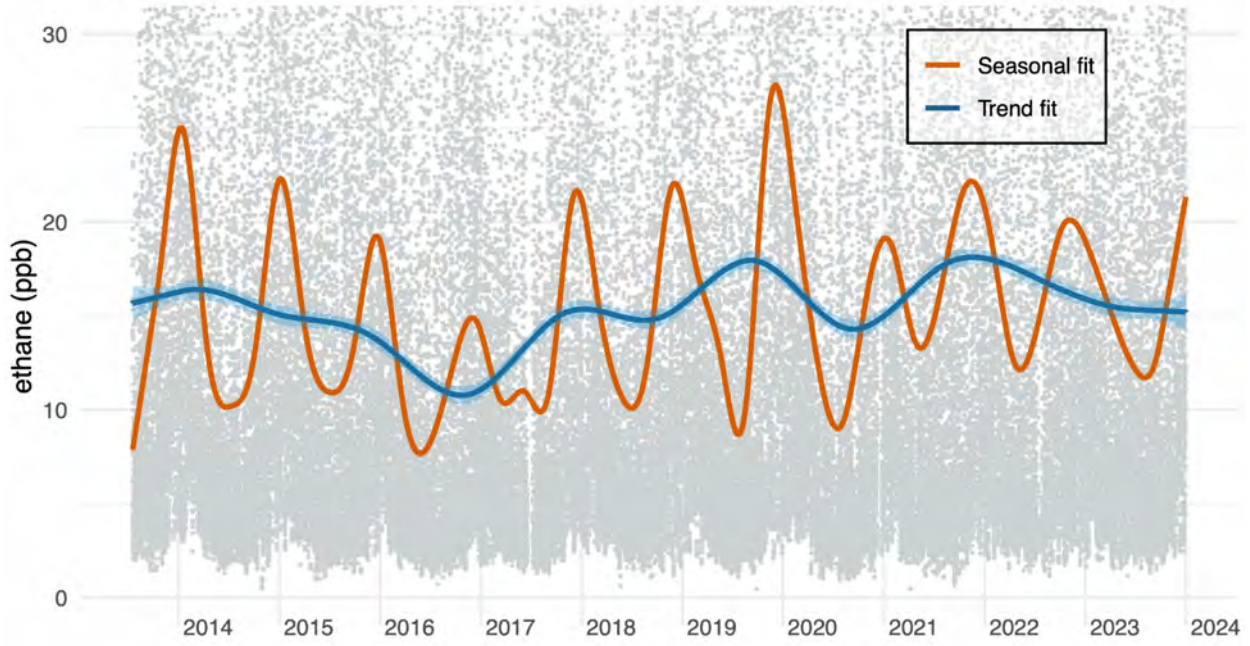


OHE benzene natural cubic splines; trend fit with 95% confidence interval

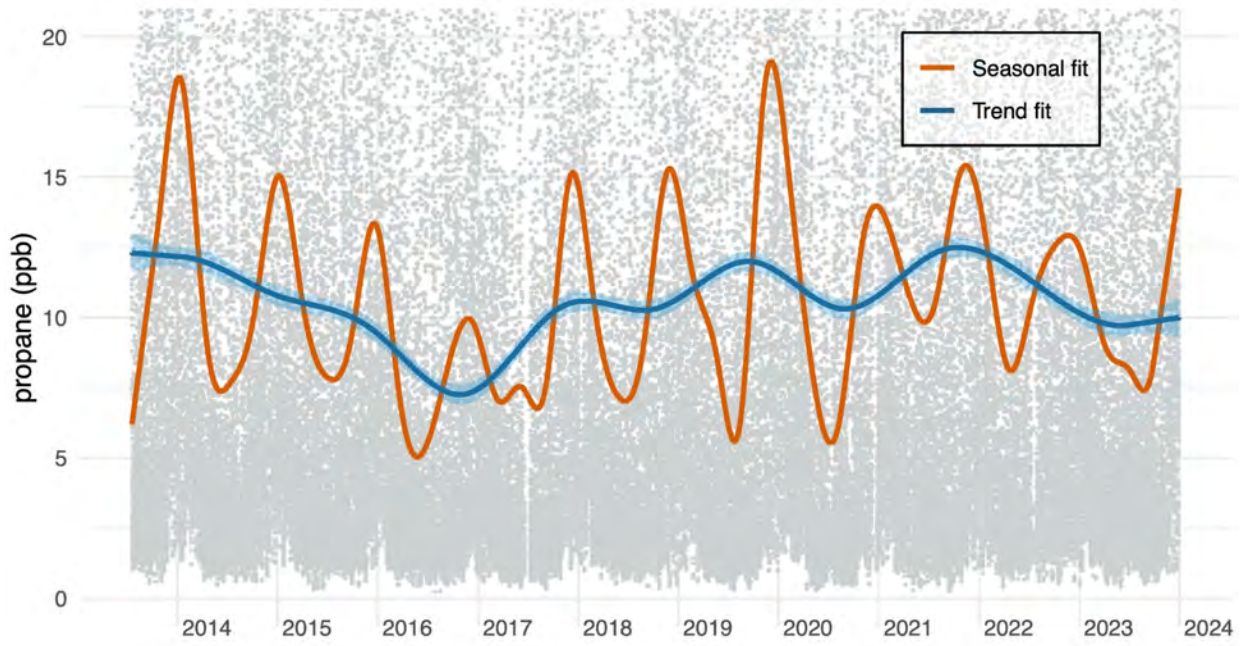


c. Eagle Ford Shale: FLV, LRB, OLN

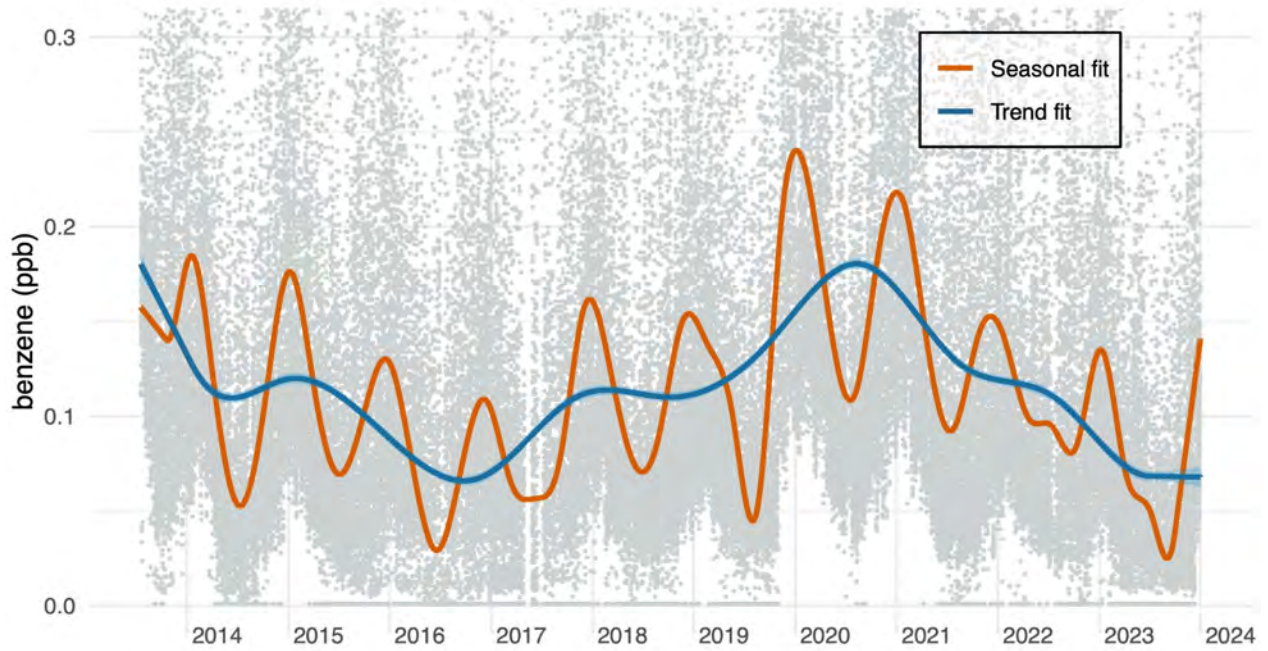
FLV ethane natural cubic splines; trend fit with 95% confidence interval



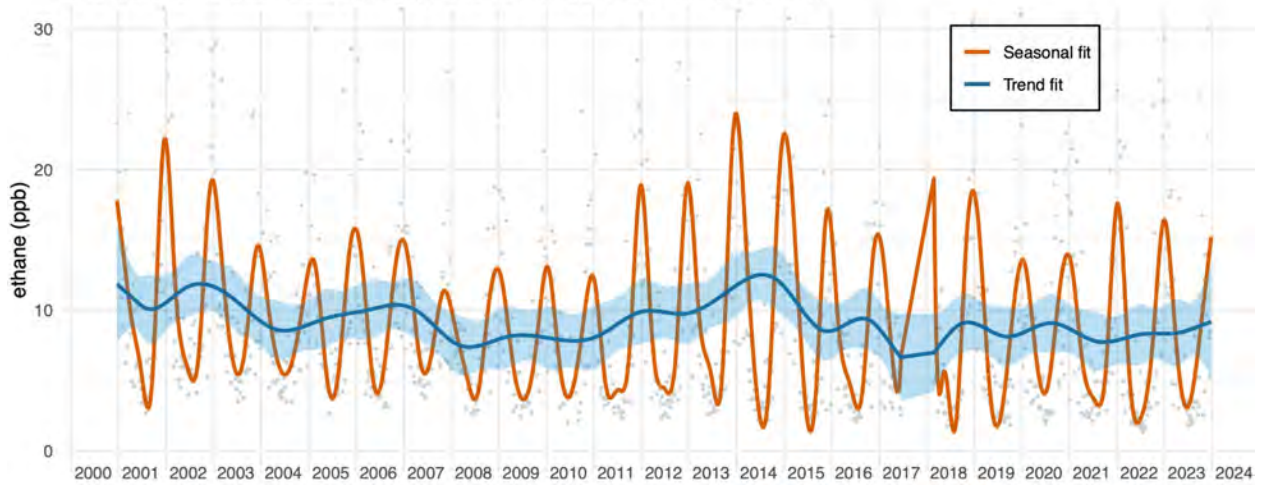
FLV propane natural cubic splines; trend fit with 95% confidence interval



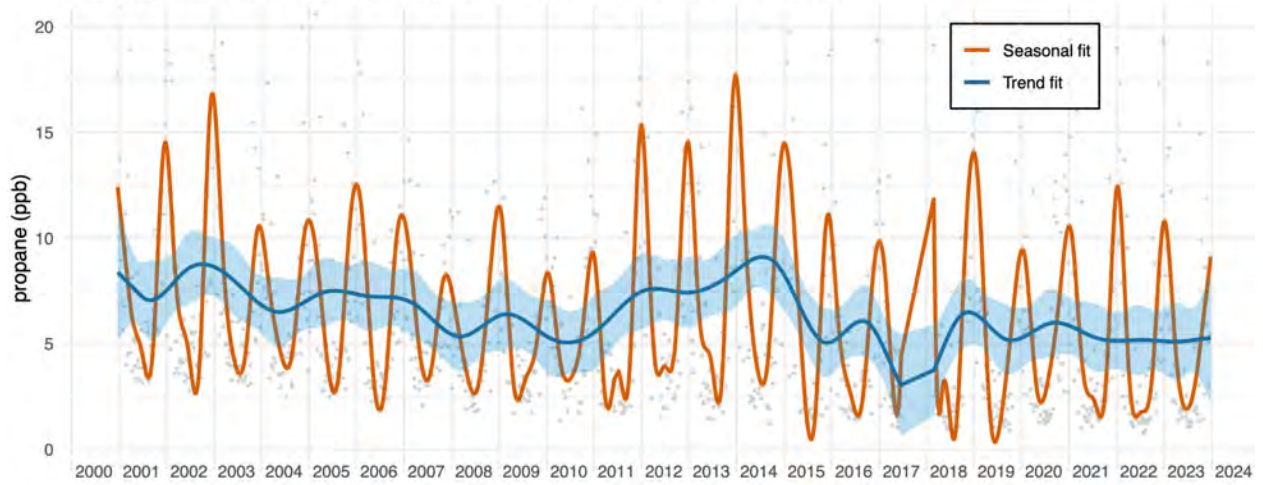
FLV benzene natural cubic splines; trend fit with 95% confidence interval



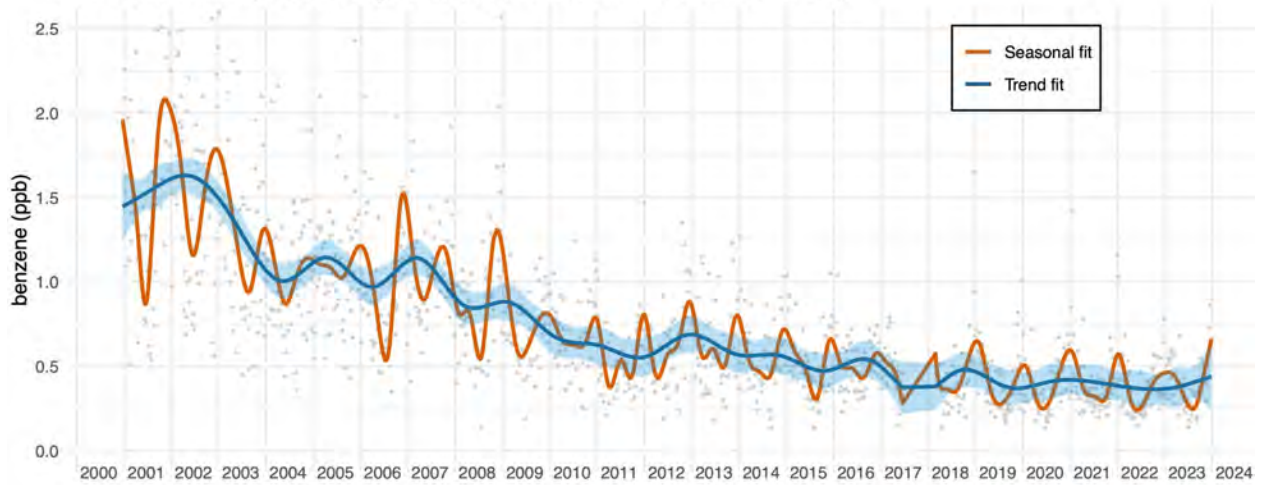
LRB ethane natural cubic splines; trend fit with 95% confidence interval



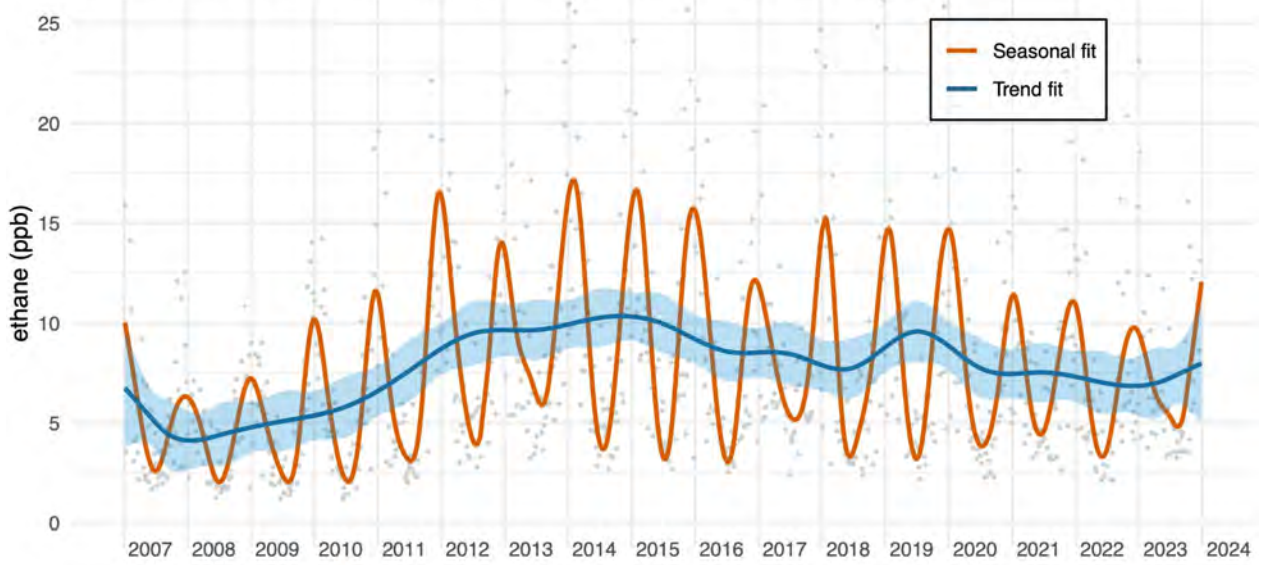
LRB propane natural cubic splines; trend fit with 95% confidence interval



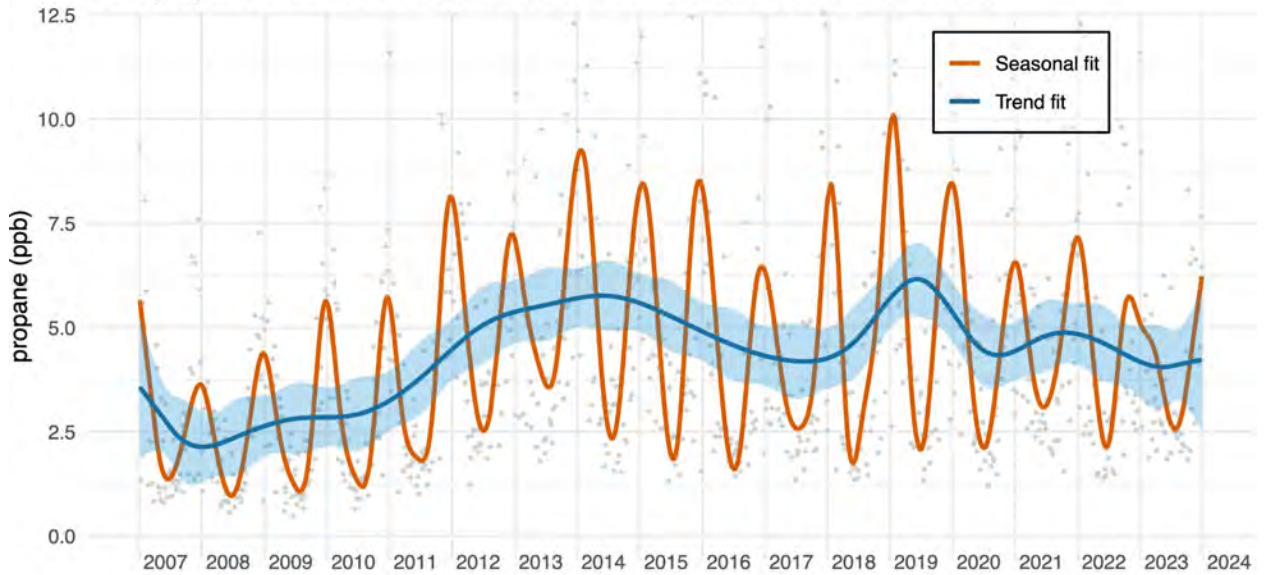
LRB benzene natural cubic splines; trend fit with 95% confidence interval



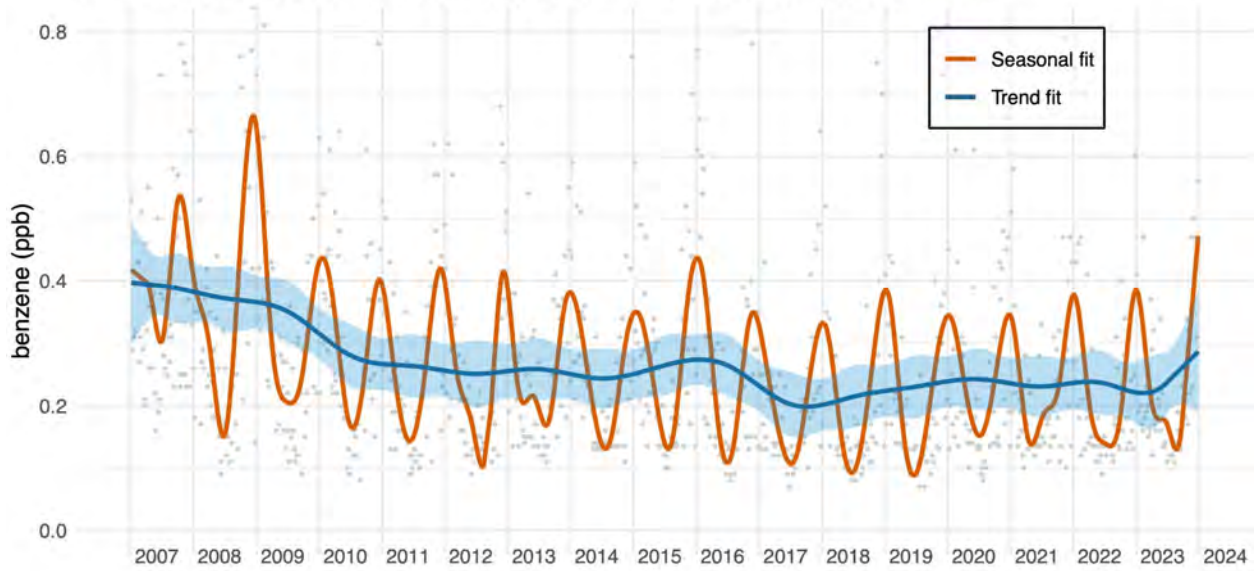
OLN ethane natural cubic splines; trend fit with 95% confidence interval



OLN propane natural cubic splines; trend fit with 95% confidence interval

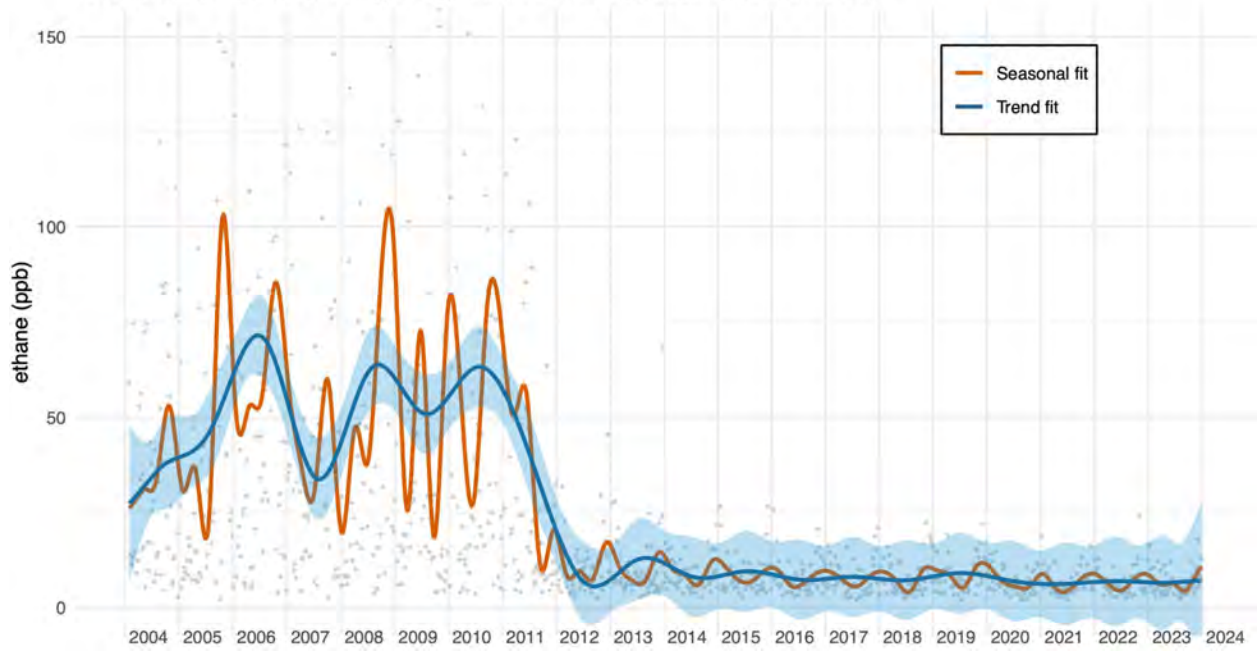


OLN benzene natural cubic splines; trend fit with 95% confidence interval

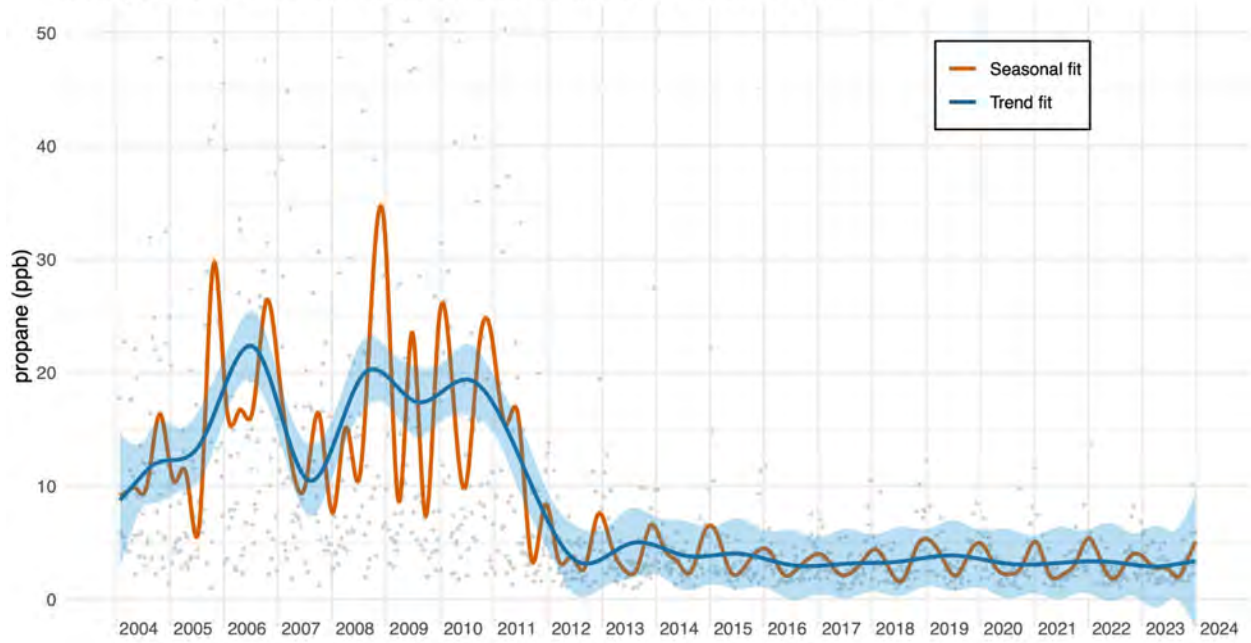


**d. Haynesville Shale: KNK, LGV**

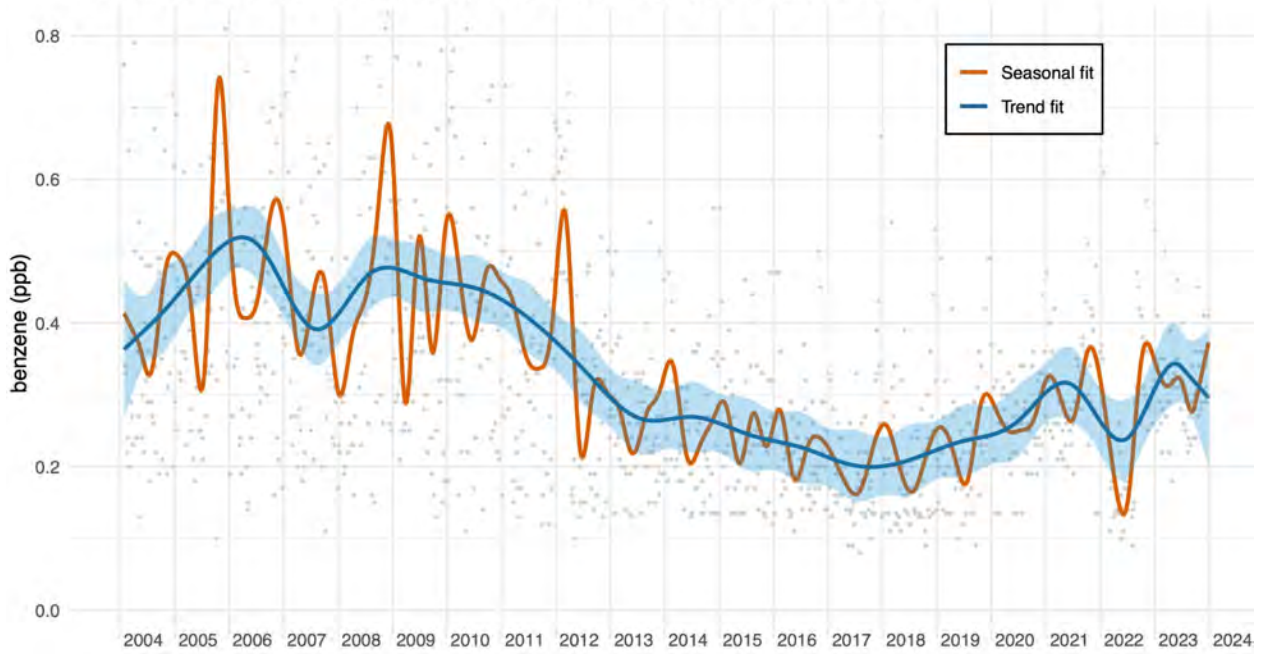
KNK ethane natural cubic splines; trend fit with 95% confidence interval



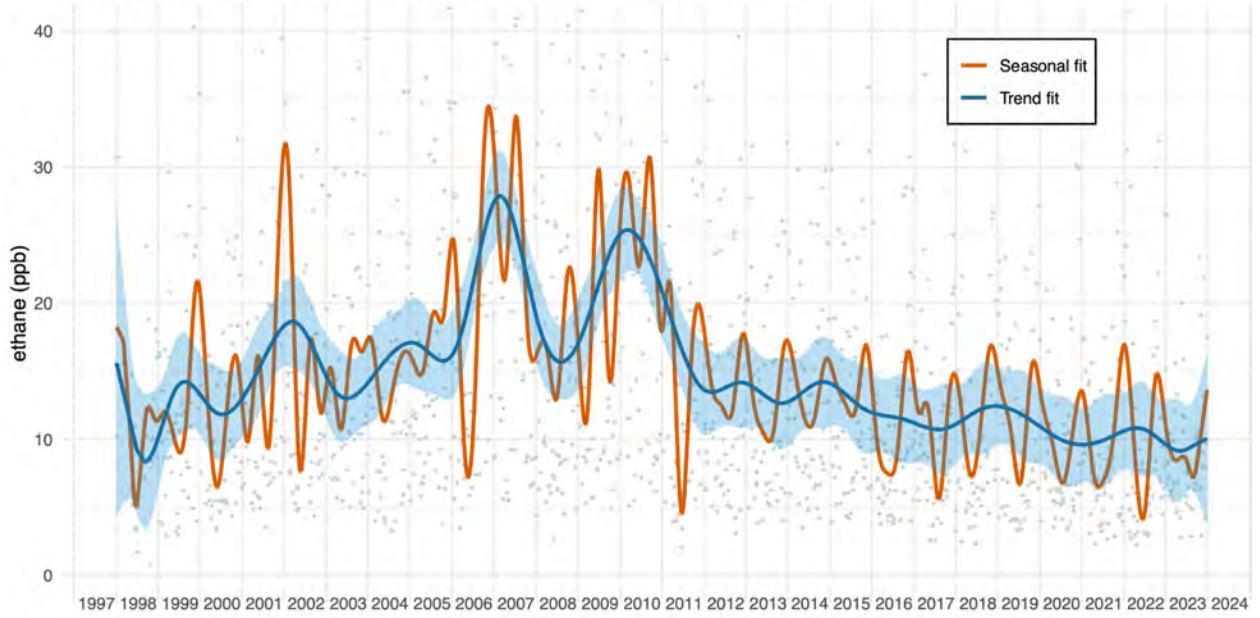
KNK propane natural cubic splines; trend fit with 95% confidence interval



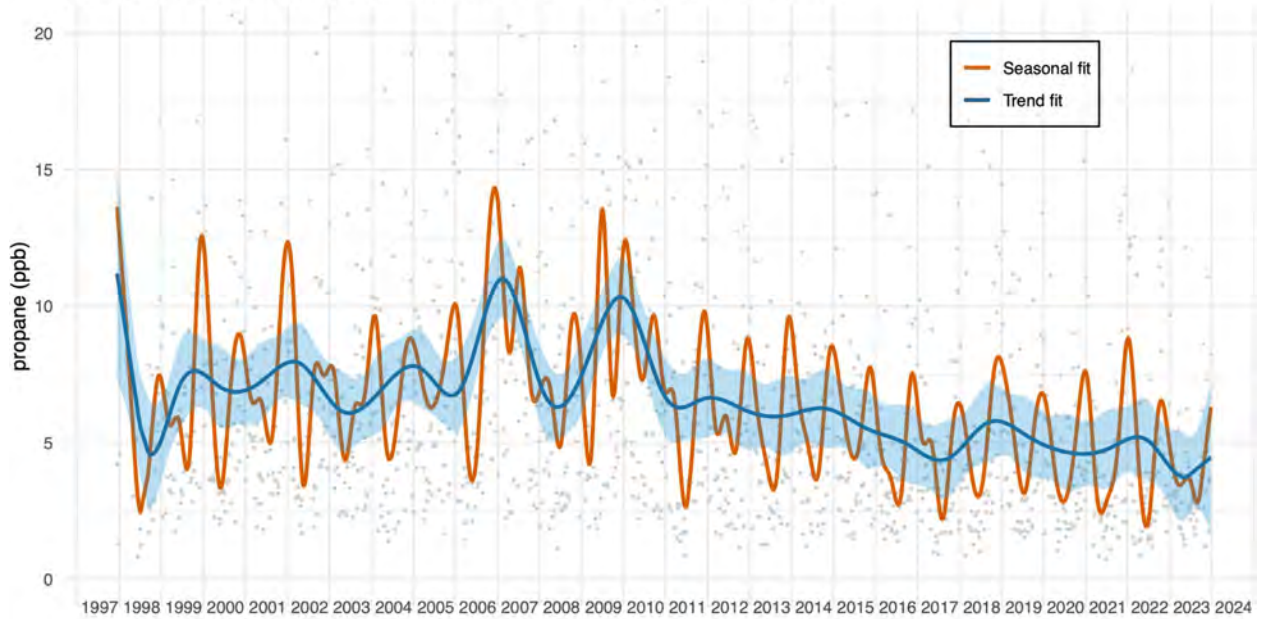
KNK benzene natural cubic splines; trend fit with 95% confidence interval



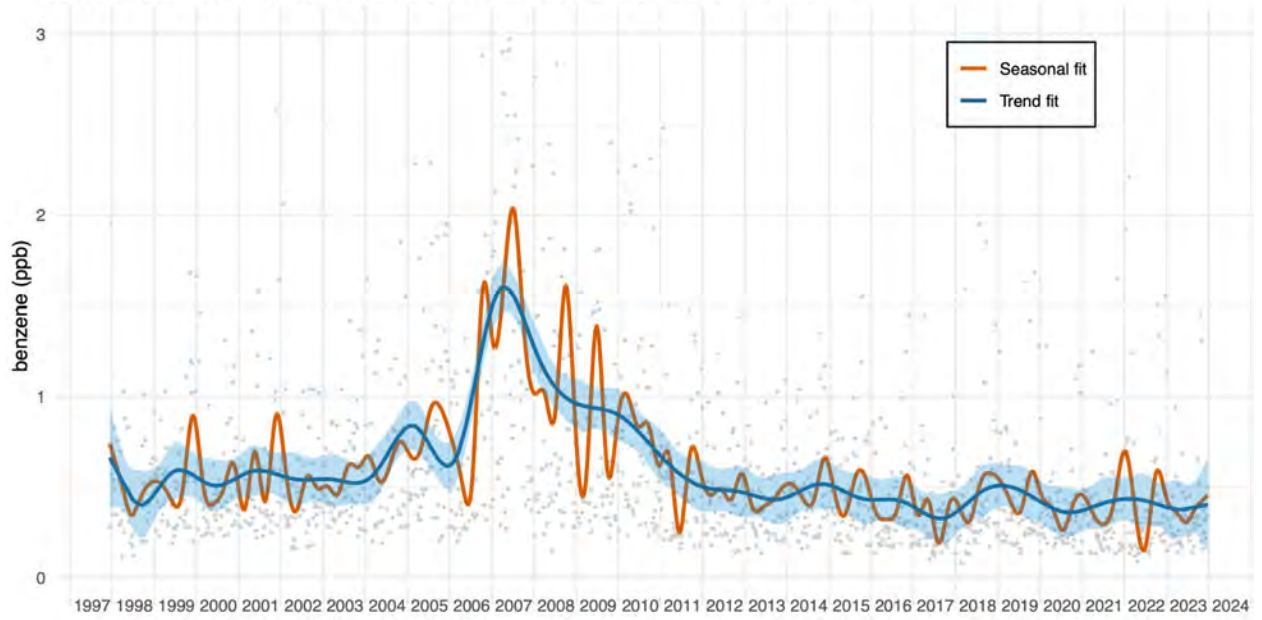
LGV ethane natural cubic splines; trend fit with 95% confidence interval



LGV propane natural cubic splines; trend fit with 95% confidence interval



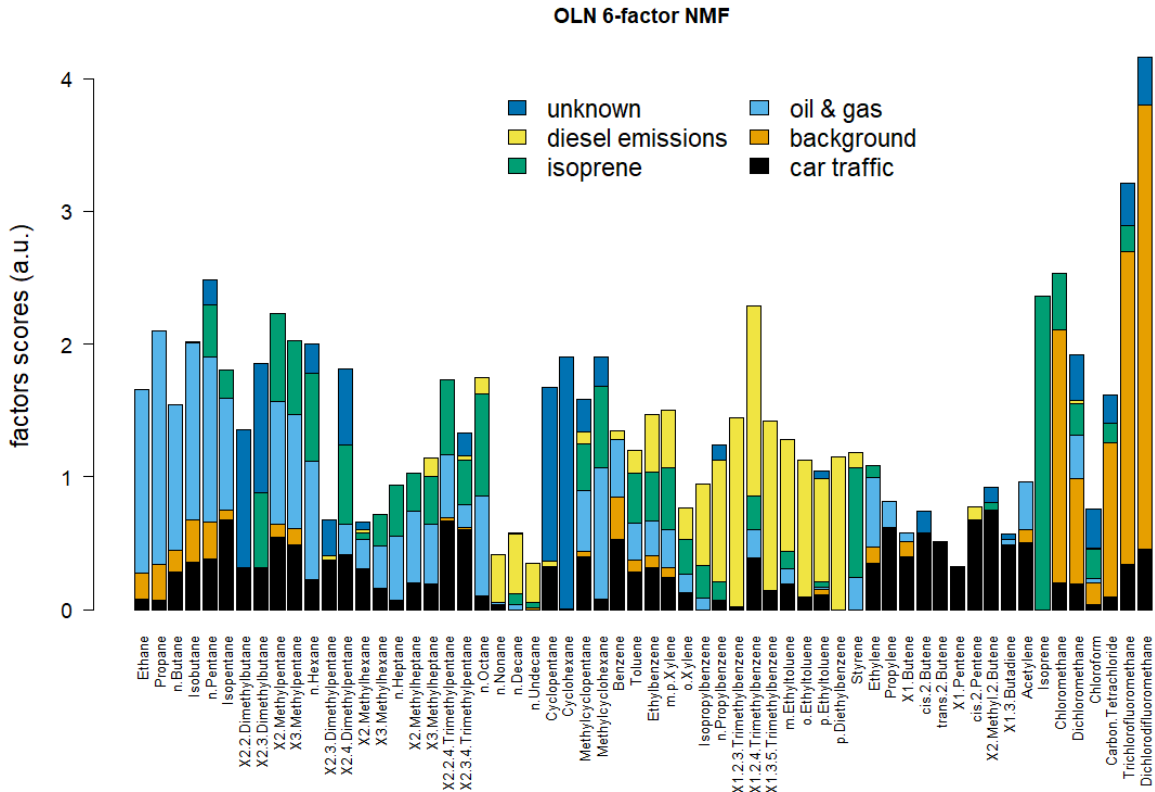
LGV benzene natural cubic splines; trend fit with 95% confidence interval



## NMF Analyses

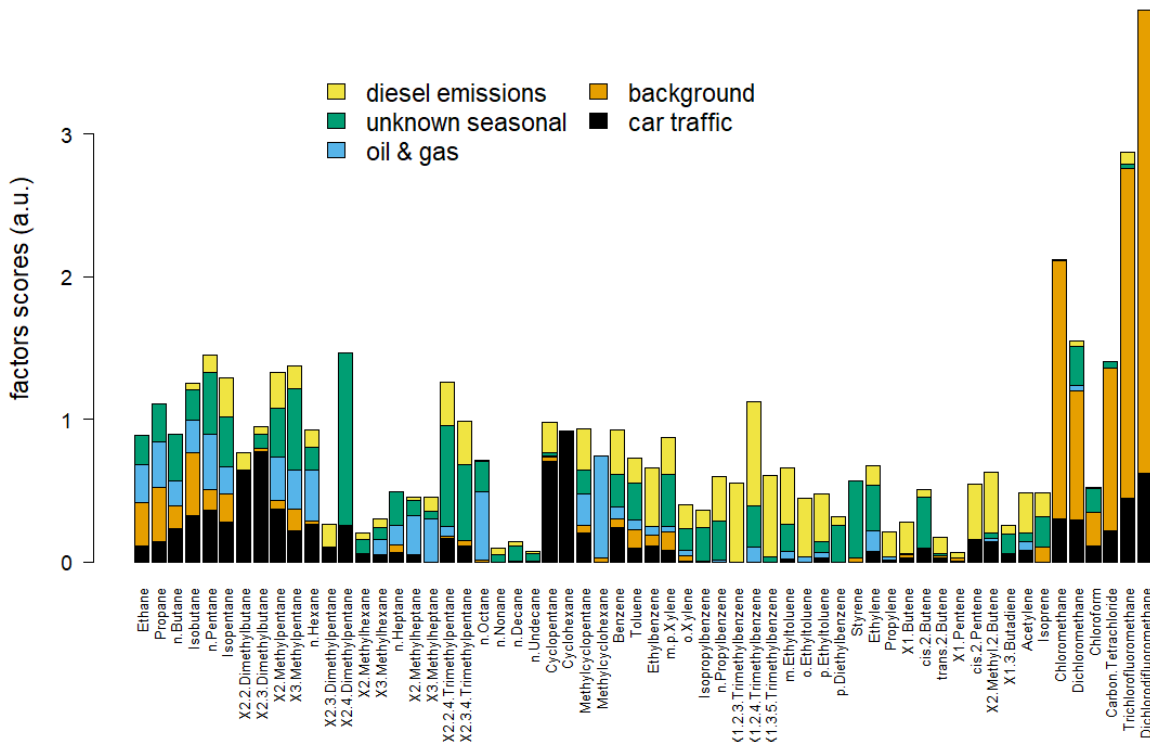
This section shows the determined factor distributions for each site for which an NMF analysis was performed. Captions specify the seeding method and algorithm; factor identifications are provided in the legend of each plot (colors are plot-specific, not assigned to one source versus another).

Some additional example factor time series are included to illustrate the sought-after trends over time, used to aid in the interpretation of the assigned “O&G factor” shown in the main report.

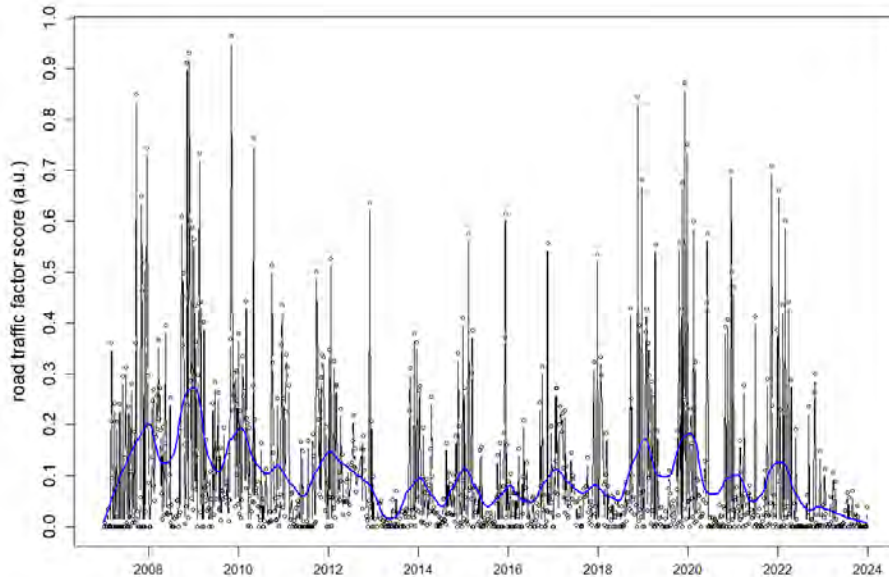


**Figure C1-4.1a.** OLN site NMF factors and scores, downwind of the Eagle Ford shale in southwest San Antonio. Note the moderate scores of non-background factors on the predefined background (orange bars) species on the far right of the bar plot, suggesting significant uncertainty in this calculation. (Brunet algorithm, un-weighted NMF with singular value decomposition (svd) seeding; not used in main report)

OLN site 5-factor NMF

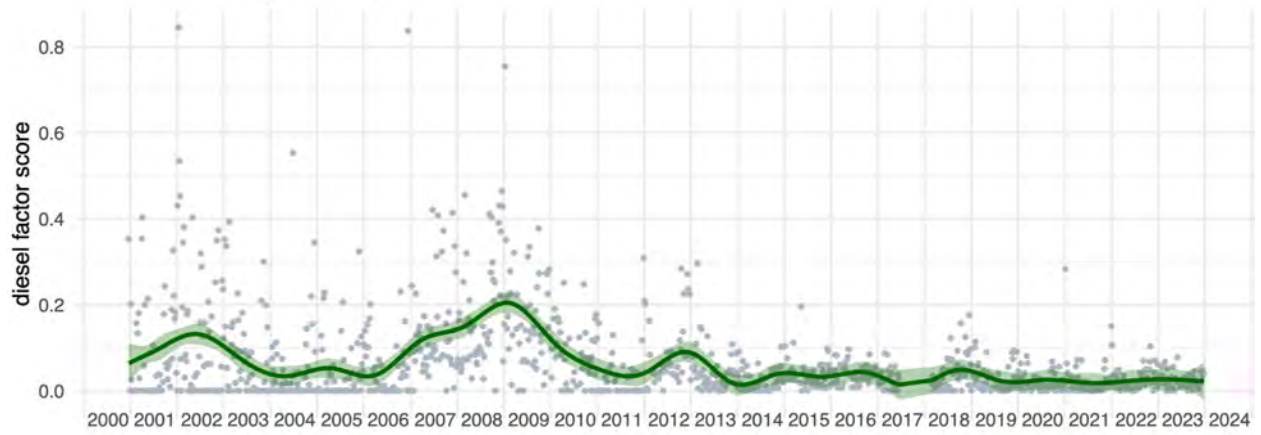


**Figure C1-4.1b.** The OLN site's NMF factors and scores, downwind of the Eagle Ford shale. Note small to moderate scores of non-background factors on the predefined background (orange bars) species on the far right of the bar plot, suggesting medium uncertainty in this calculation. (Least-squares error-weighted NMF with svd seeding; results from this NMF were used in the main report.)

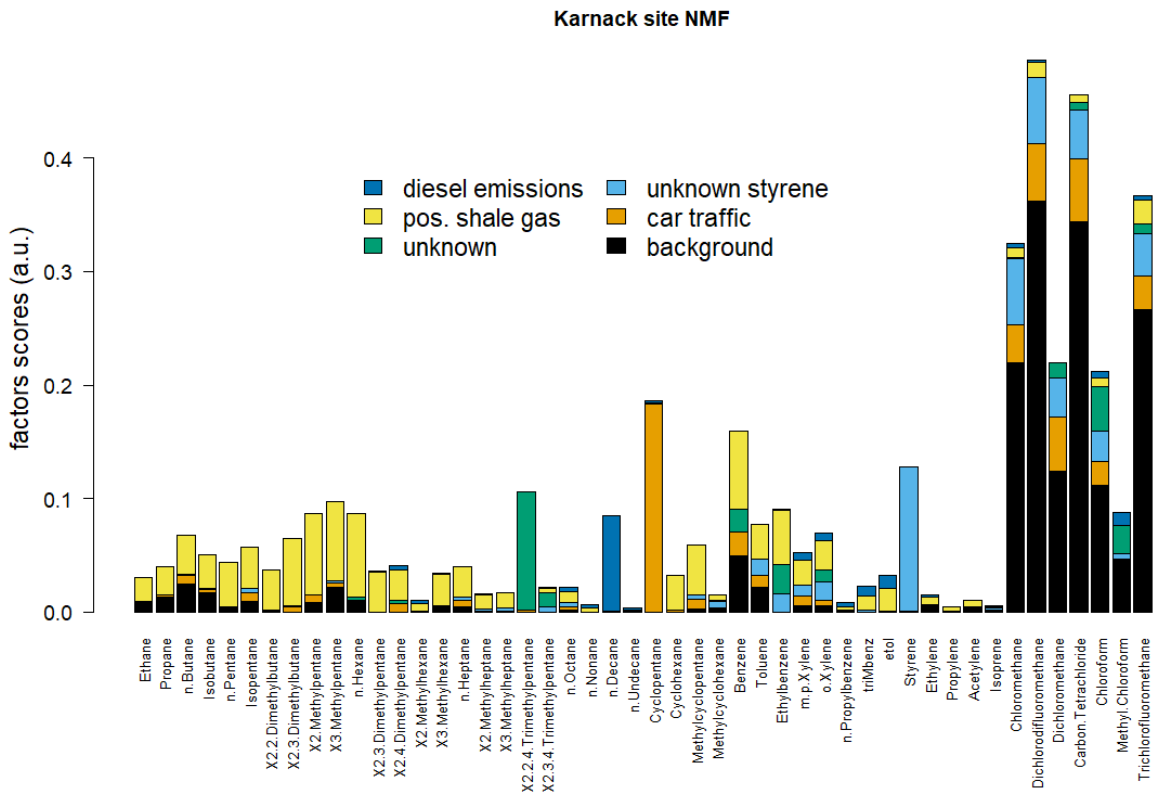


**Figure C4-4.1b.1.** Derived time trend of traffic emissions impacts at OLN site in San Antonio.

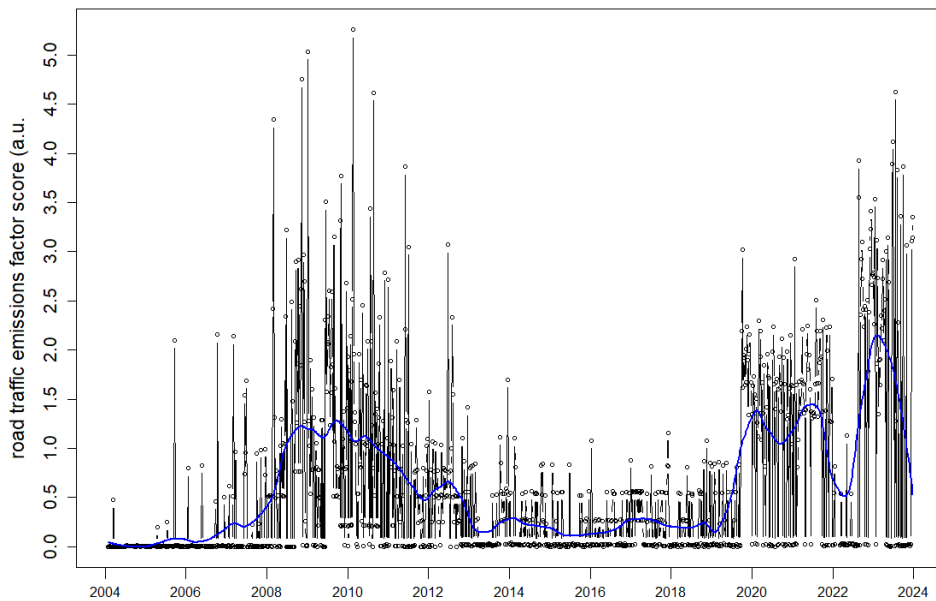




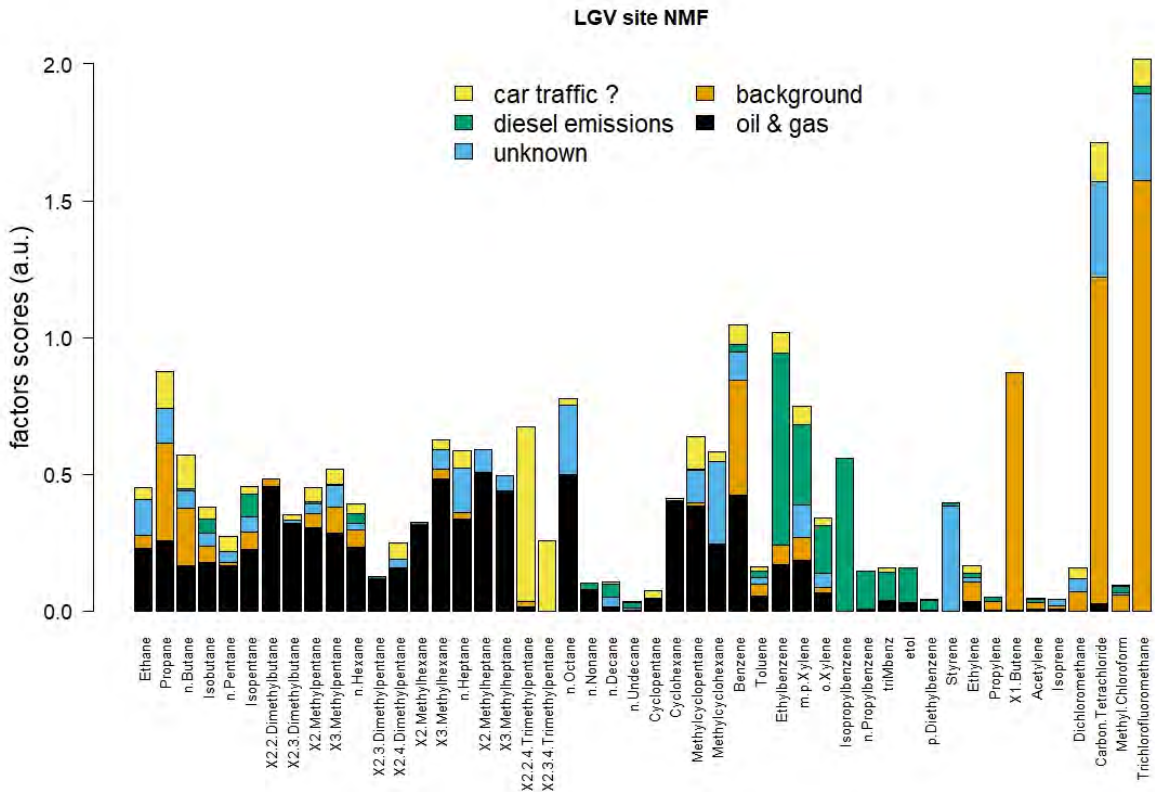
**Figure C1-4.2.2.** Time series and spline-based trend analysis of the NMF-based factor identified as the diesel emissions factor at the LRB site based on its compound composition (heavy aromats dominant).



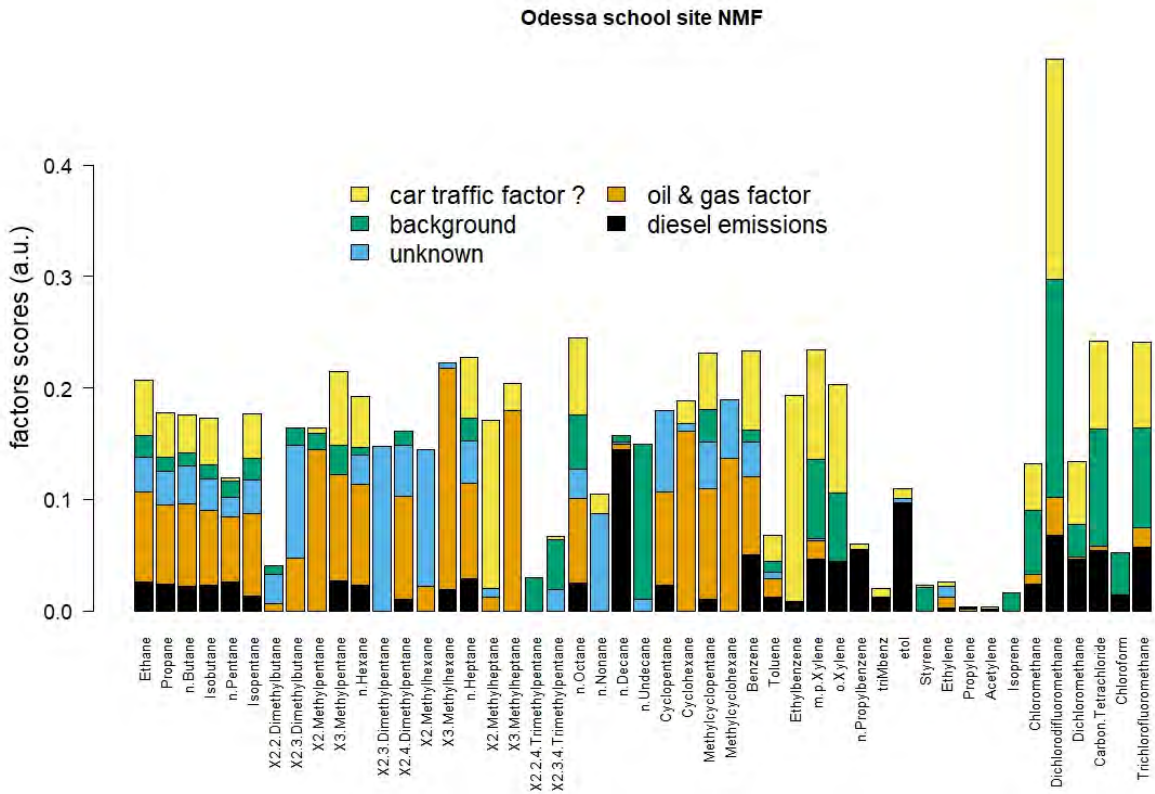
**Figure C1-5.1.** Haynesville Shale’s Karnak site NMF factors and scores. Note the moderate scores of non-background factors on the predefined background (black bars) species on the far right of the bar plot, suggesting significant uncertainty in this calculation. (Least-squares error-weighted NMF with random seeding.)



**Figure C1-5.1.1.** Derived time trend of traffic emissions impacts at the rural Karnack site in northeast Texas.



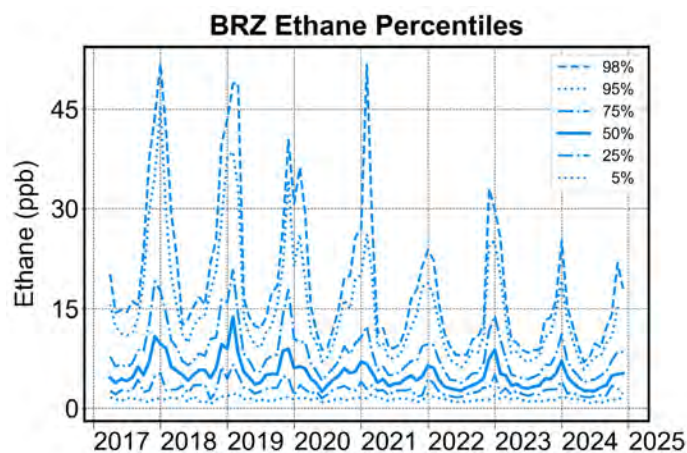
**Figure C1-5.2.** Haynesville Shale's Longview site NMF factors and scores. Note scores of non-background factors on the predefined background (orange bars) species on the far right of the bar plot, suggesting medium fidelity in this calculation. (Least-squares error-weighted NMF with svd seeding.)



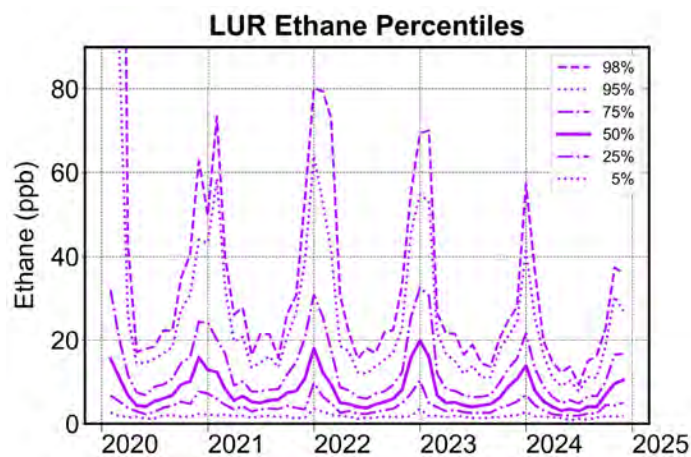
**Figure C1-6.** Permian basin's Odessa Elementary school (OHE) NMF factors and scores. Note the relatively high scores of non-background factors on the predefined background (green bars) species on the far right of the bar plot, suggesting a lower fidelity of this calculation.

## C2. Additional Results from Analyses of AQM Station Data from Colorado

Monthly Statistics Plots: Ethane Percentiles



**Figure C2-1.** Time series of monthly 5th, 25th, 50th, 75th, 95th, and 98th percentiles for BRZ ethane. Different line styles indicate each percentile.



**Figure C2-2.** Same as C2-1, but for LUR ethane. The y-axis maximum was fixed at 90 ppb.

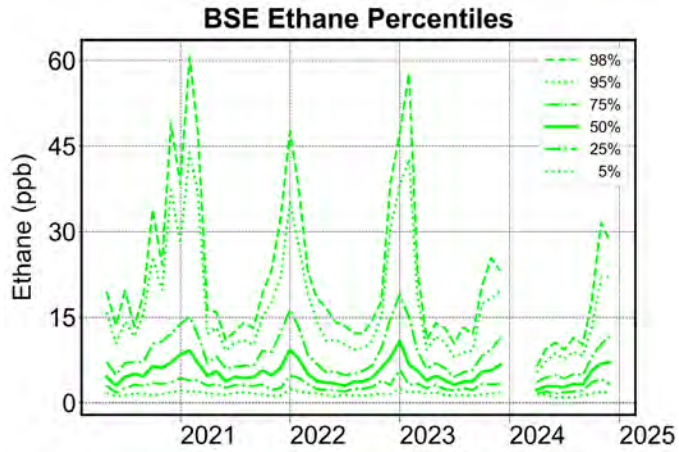


Figure C2-3. Same as C2-1, but for BSE ethane.

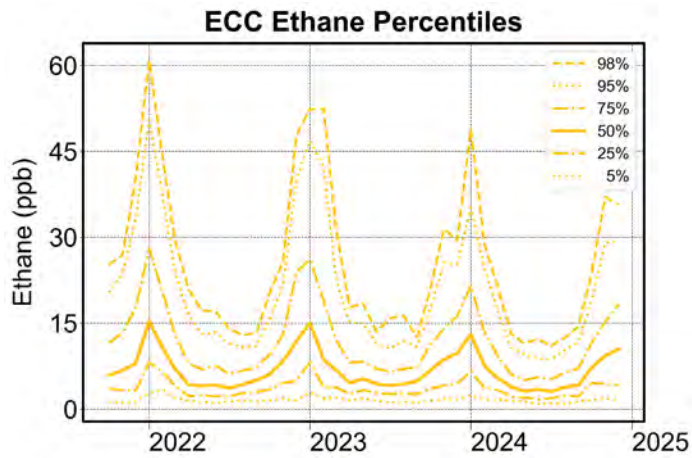


Figure C2-4. Same as C2-1, but for ECC ethane.

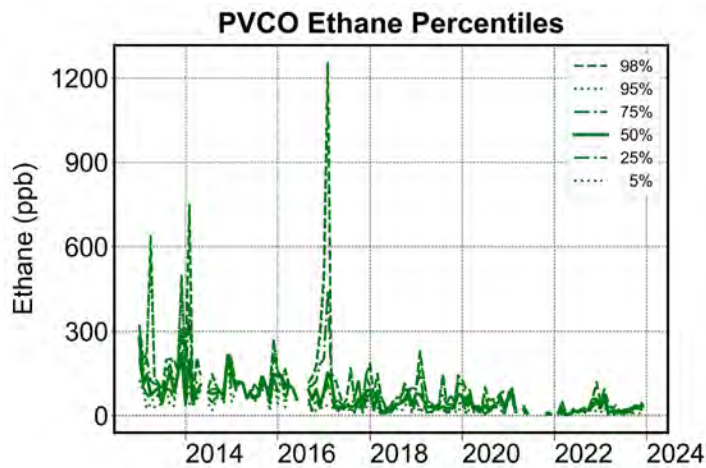
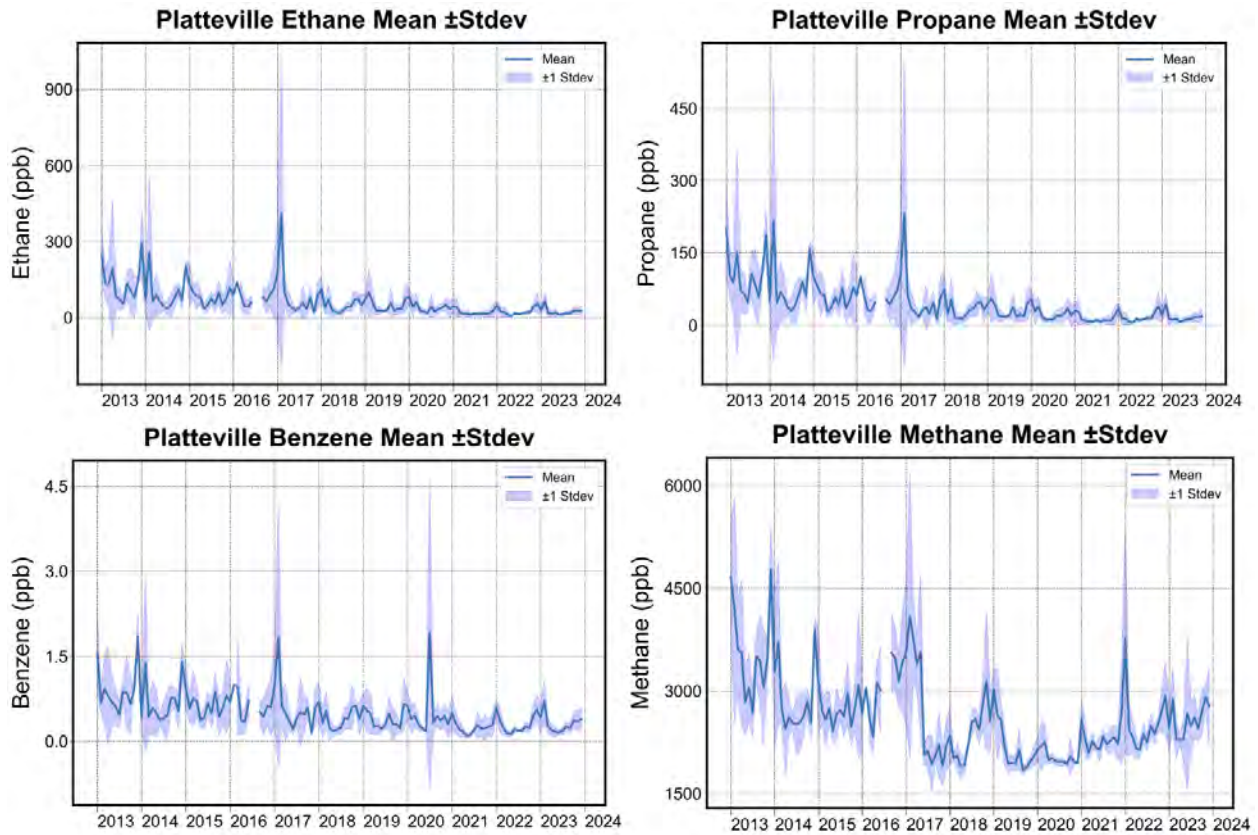


Figure C2-5. Same as C2-1, but for PVCO ethane.

## Monthly Statistics Plots: Mean and Standard Deviation

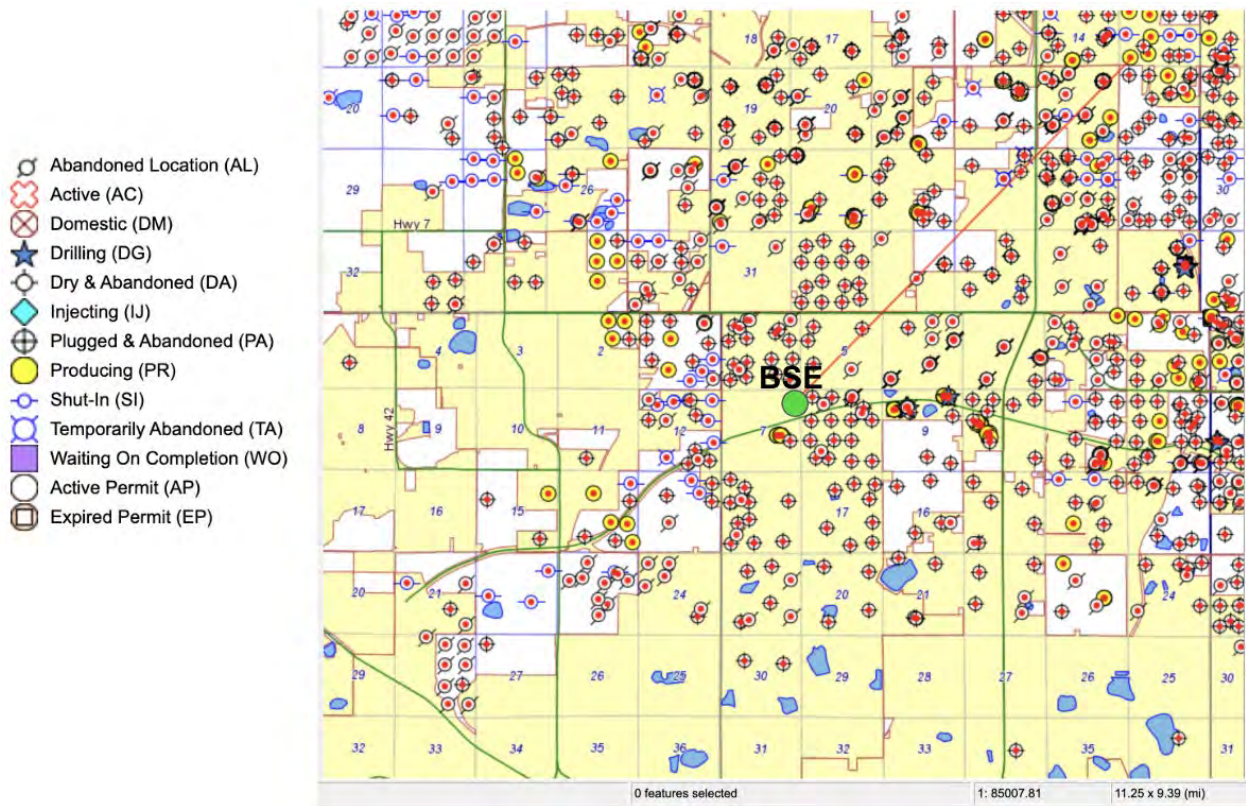


**Figure C2-6.** Example time series of monthly means (blue line) and standard deviations (light blue swath) for the PVC0 site measurements.

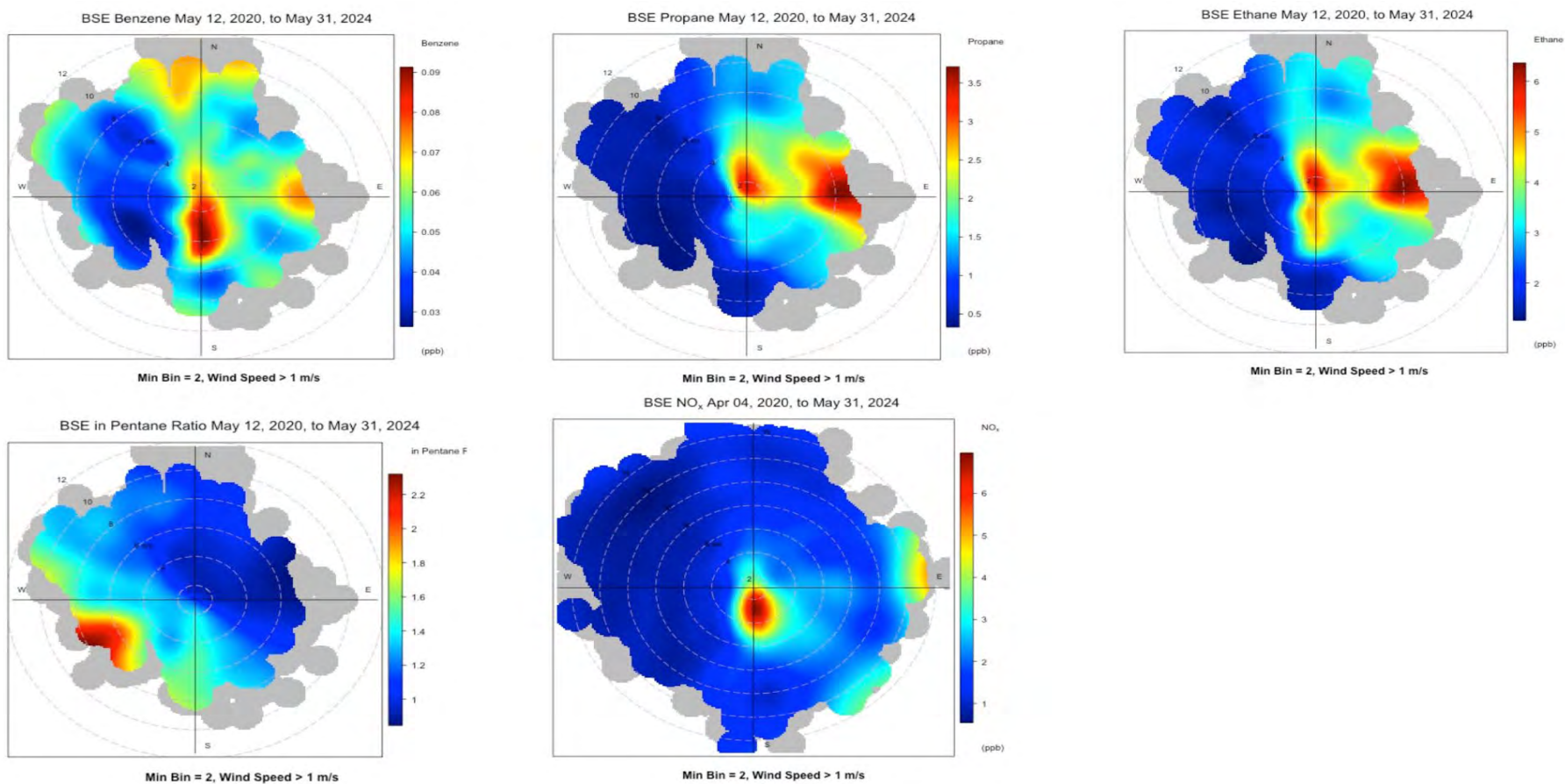
Sector Analysis Plots: BSE, Western: 190°–290°, O&G: 330°–110°

For each site, maps of oil and gas (O&G) wells, obtained from the Colorado Oil and Gas Conservation Commission (COGCC, [https://cogccmap.state.co.us/cogcc\\_gis\\_online/](https://cogccmap.state.co.us/cogcc_gis_online/)), have been analyzed to support O&G sector determination.

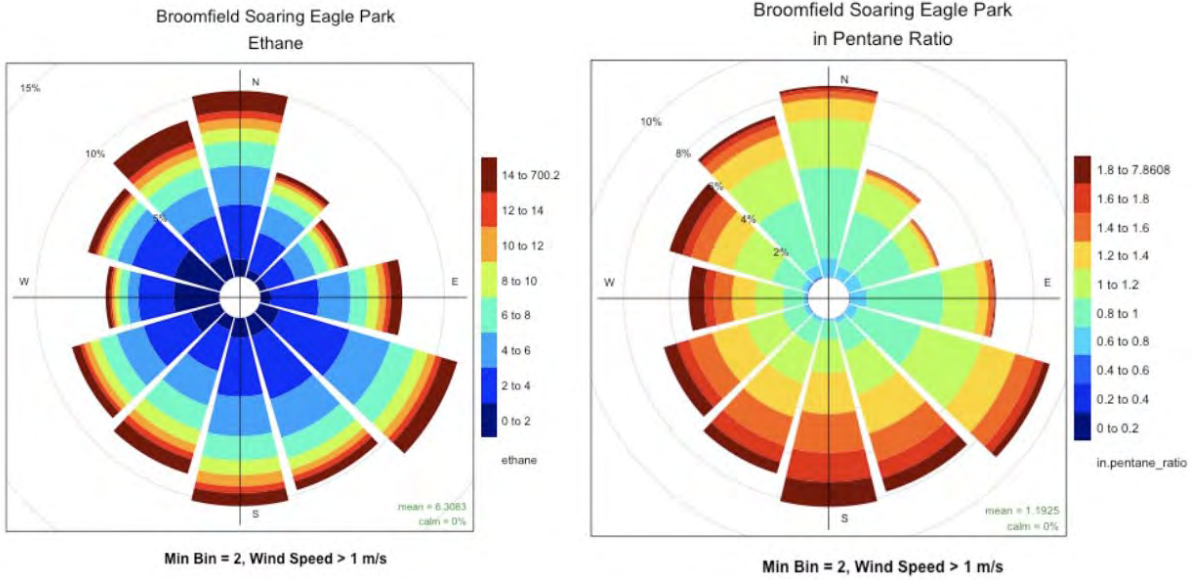
Bivariate polar plots were generated using the R (Version 4.3.1) package *Openair* (Version 2.17.0) to show the median chemical mole fraction as a function of wind speed and wind direction. Each directional bin spans 10° and 1/30th of the wind speed range. The *openair* plot function smooths the data using a generalized additive model (GAM), and bins with fewer than two points were omitted (are grayed out in the plots below). Wind speeds below 1 m/s and above 15 m/s were also excluded.



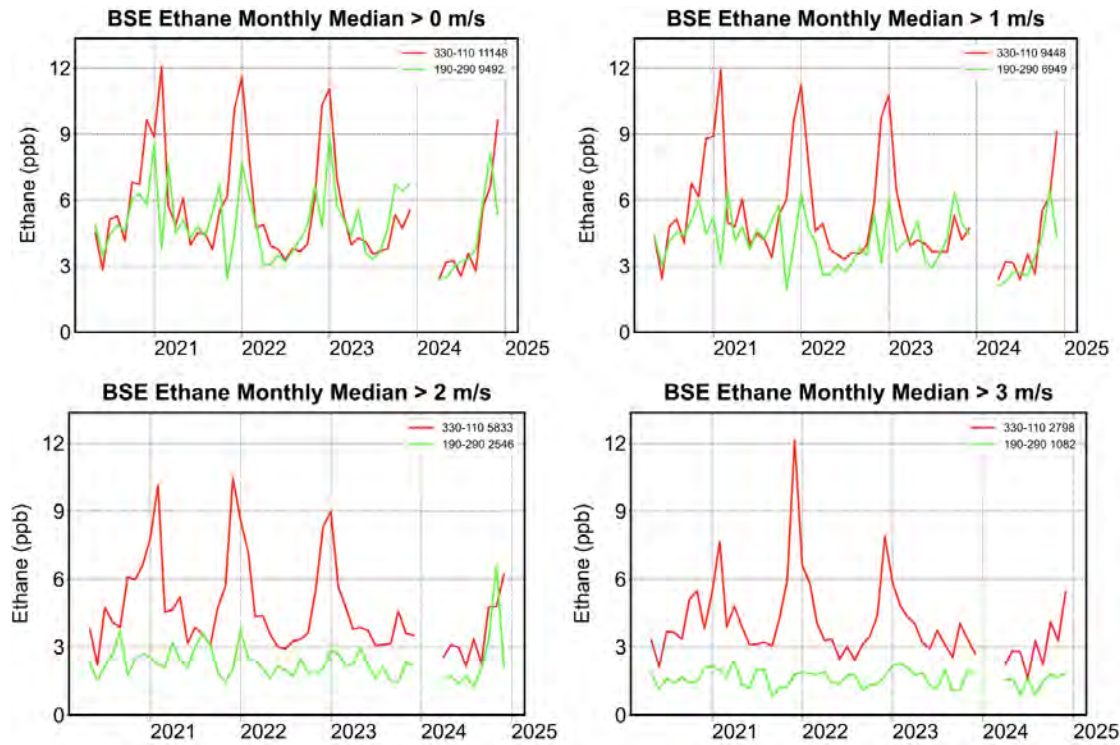
**Figure C2-7.** Well sites and their status near BSE. Yellow markers show currently producing wells at the time when these data were accessed (2024 July 15–17). The red line indicates a 5.9-mile distance. Source: [https://cogccmap.state.co.us/cogcc\\_gis\\_online/](https://cogccmap.state.co.us/cogcc_gis_online/).



*Figure C2-8a. Polar plots of various NMHCs and NO<sub>x</sub> measured at the BSE site.*



**Figure C2-8b.** Similar to Figure C2-8a, but data is plotted in the form of pollution roses (generated using the R Openair package), showing chemical mole fractions as a function of wind direction. Data collected at wind speeds below 1 m/s and above 15 m/s were excluded.



**Figure C2-9a.** Western (“clean”) vs. O&G sector comparisons for monthly median ethane at the BSE site when locally measured wind speeds exceeded different thresholds, including the number of observations available for each sector’s bounds.

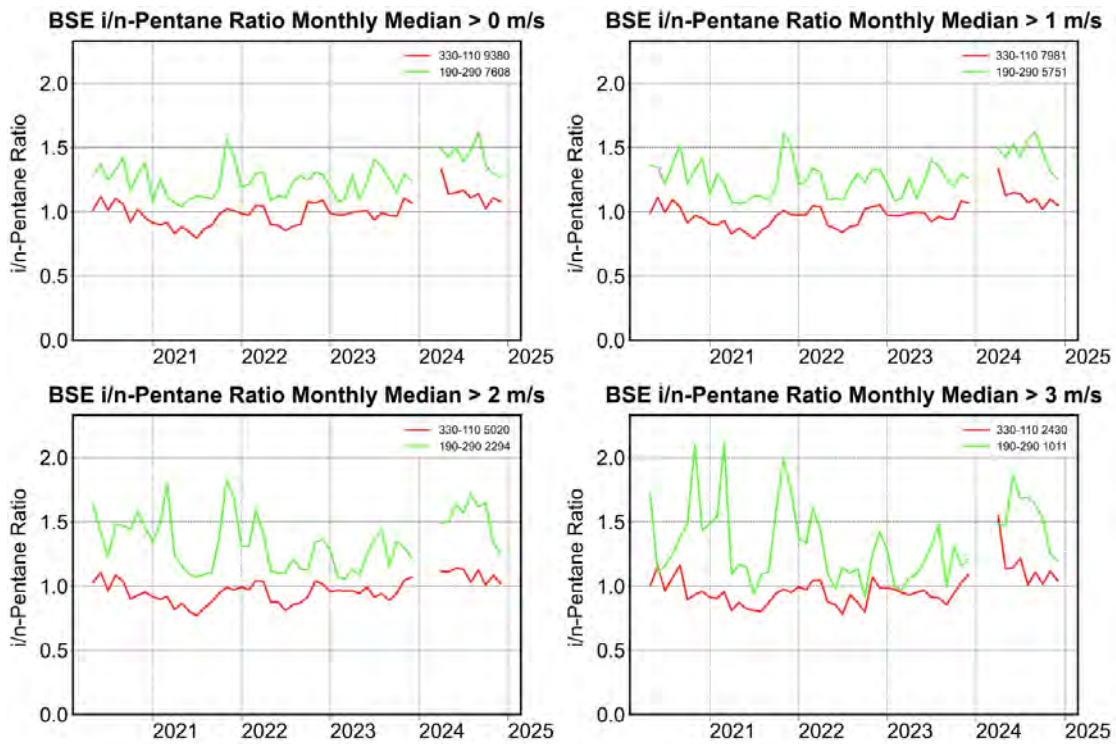


Figure C2-9b. Same as Figure C2-9a but for the i/n-pentane ratio.

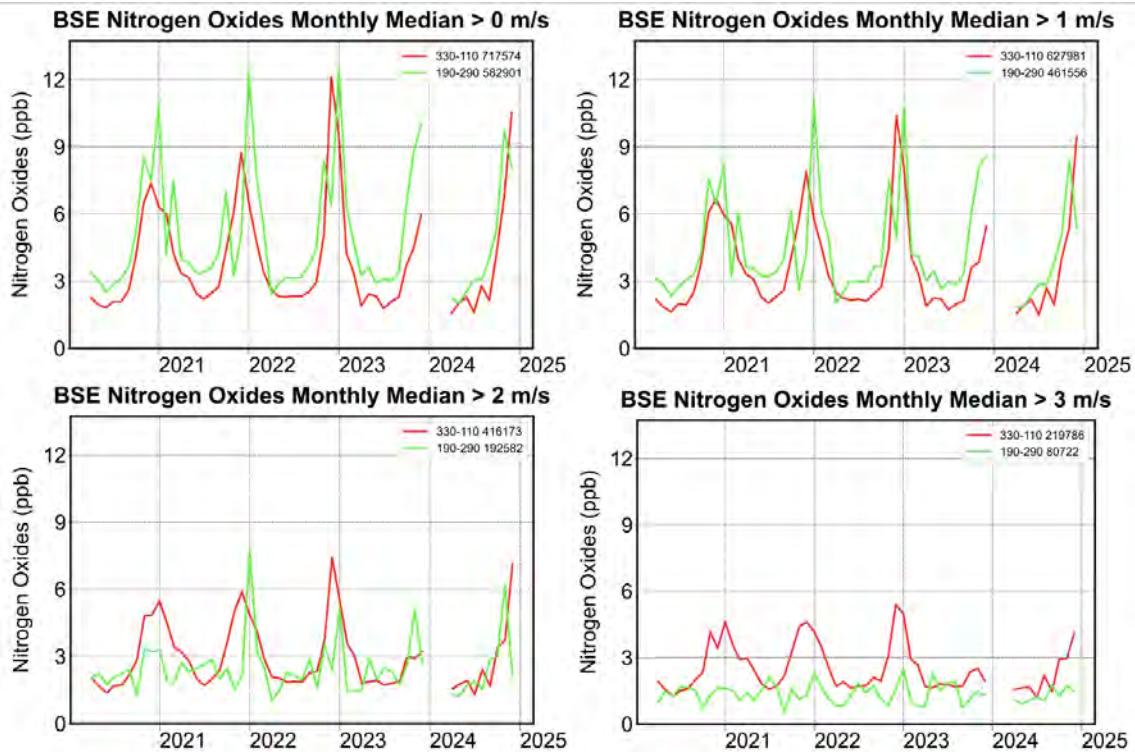
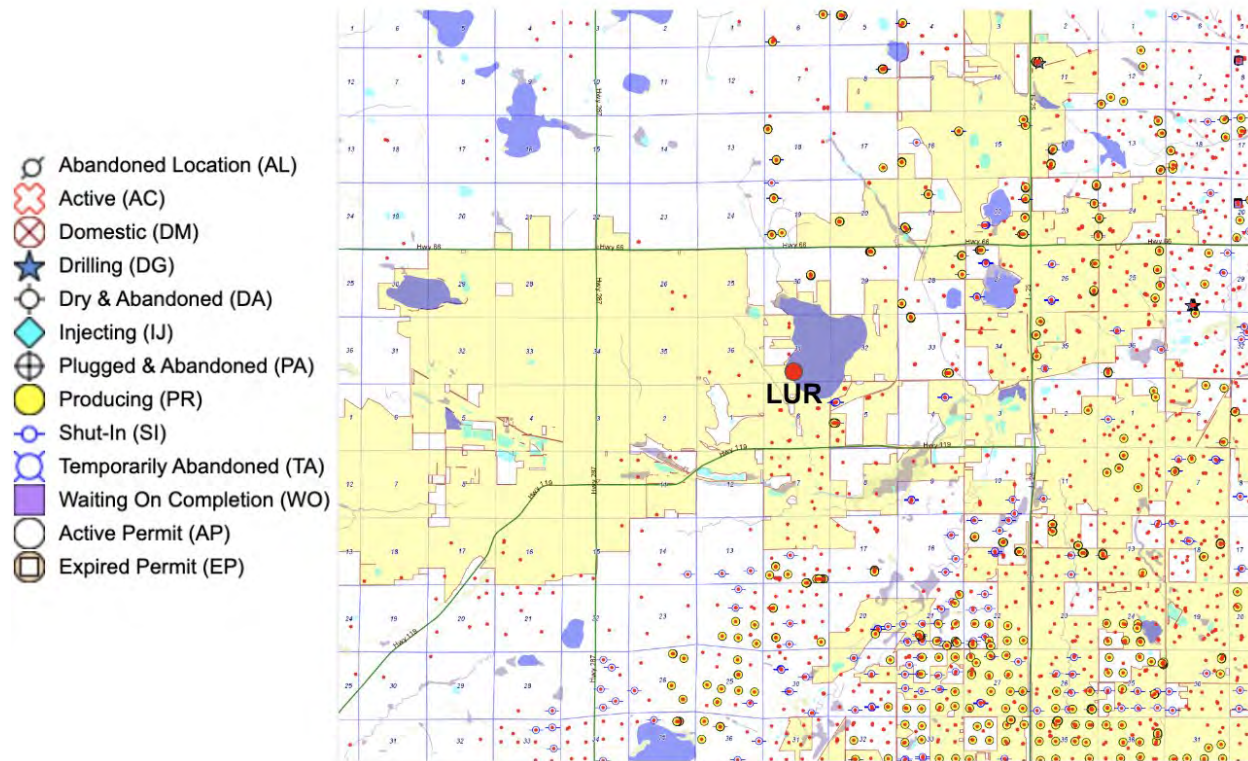
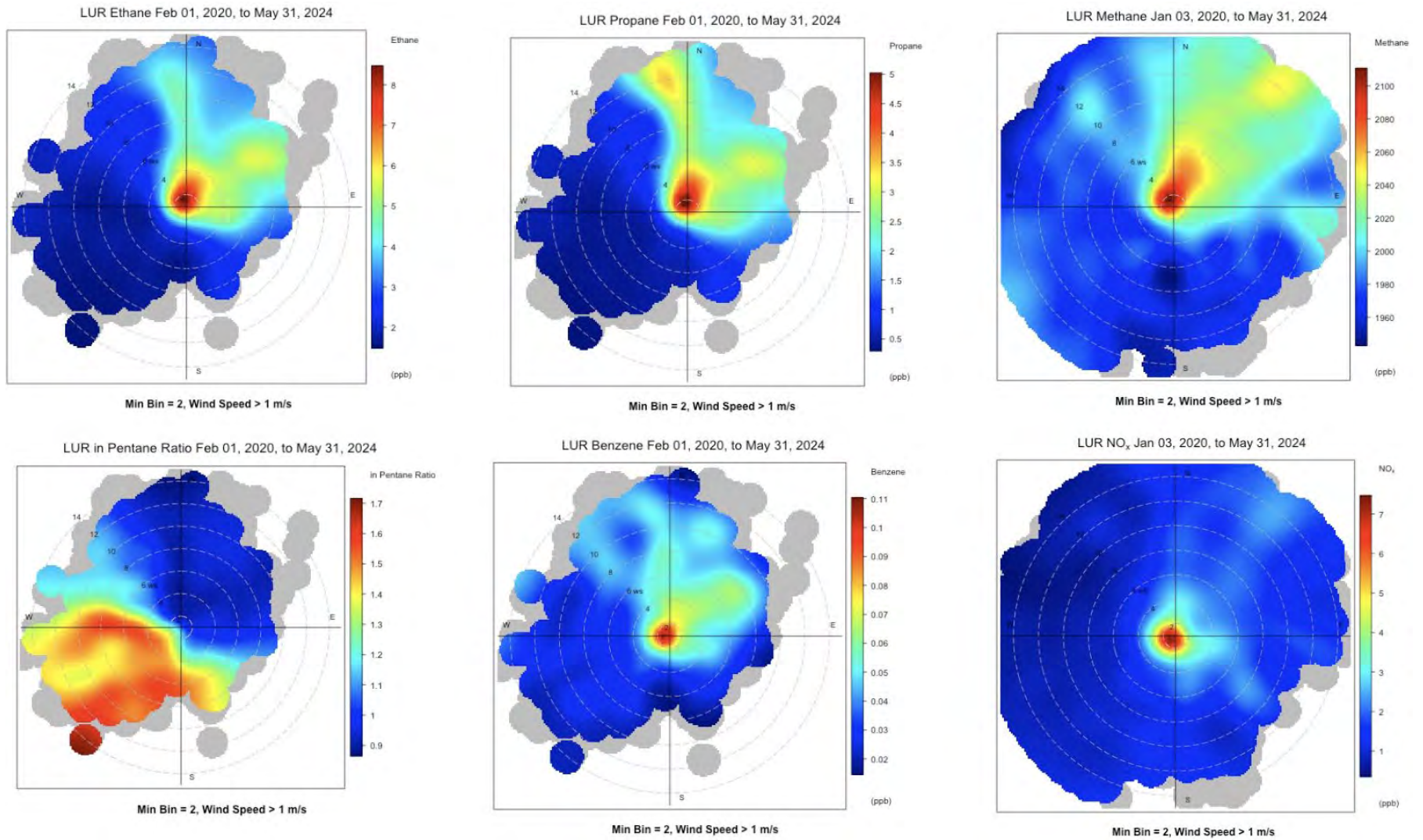


Figure C2-9c. Same as Figure C2-9a but for NO<sub>x</sub>.

Sector Analysis Plots: LUR Western: 190°–280°, O&G: 350°–90°



**Figure C2-10.** Well sites and their status near LUR. Yellow is currently producing when accessed (2024 July 15-17). Source: [https://cogccmap.state.co.us/cogcc\\_gis\\_online/](https://cogccmap.state.co.us/cogcc_gis_online/).



*Figure C2-11a. Bivariate polar plots, same as figure C2-8a, but for the LUR site.*

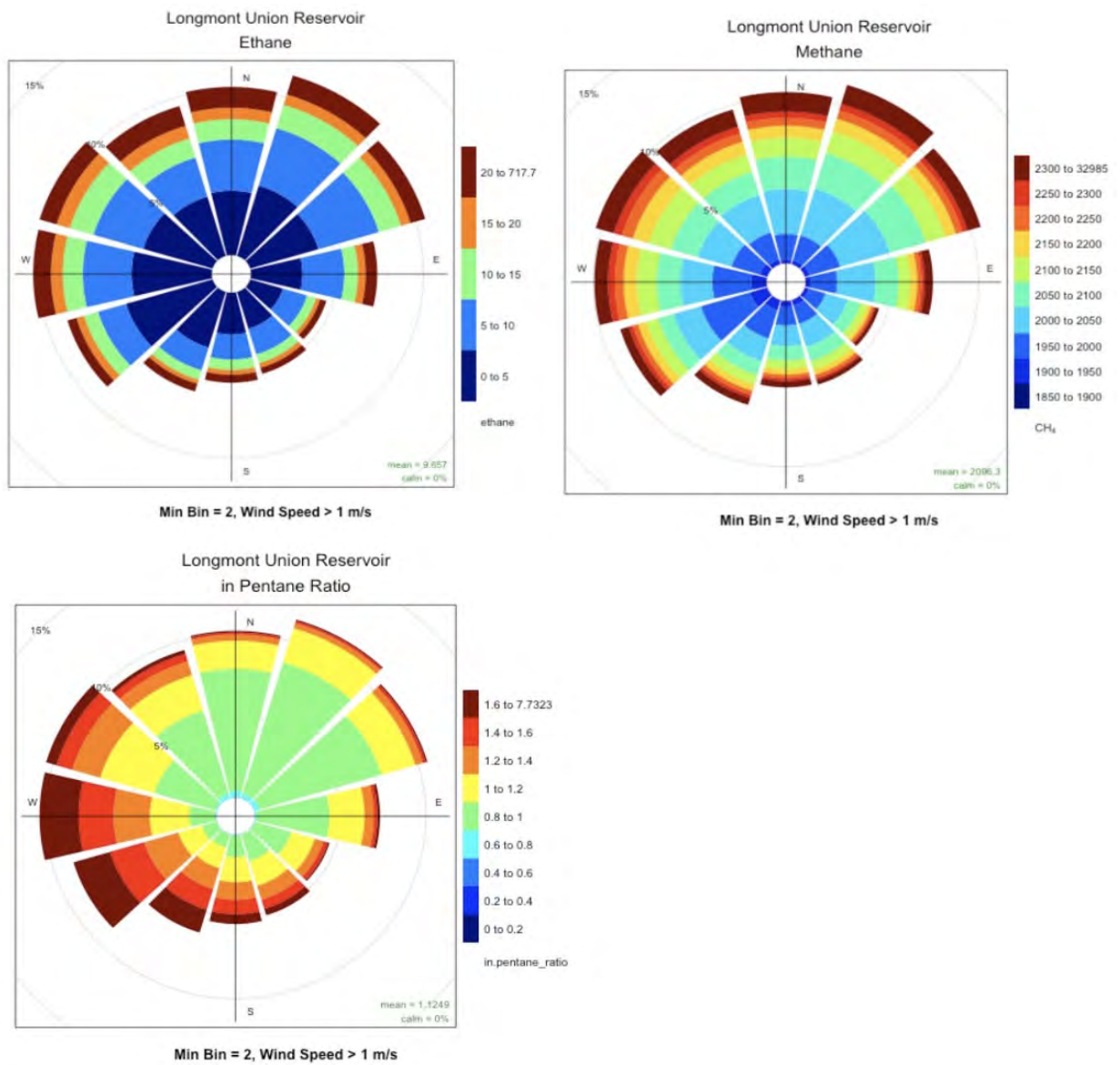
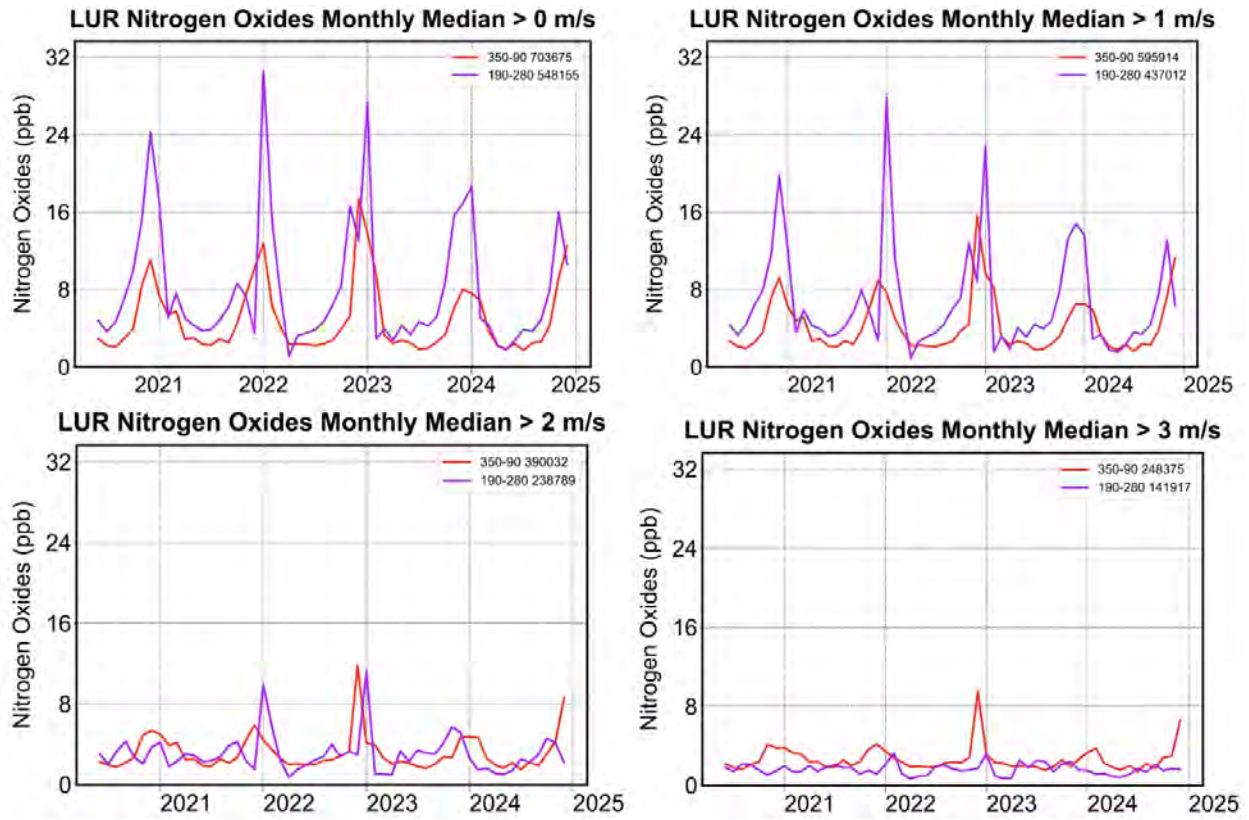
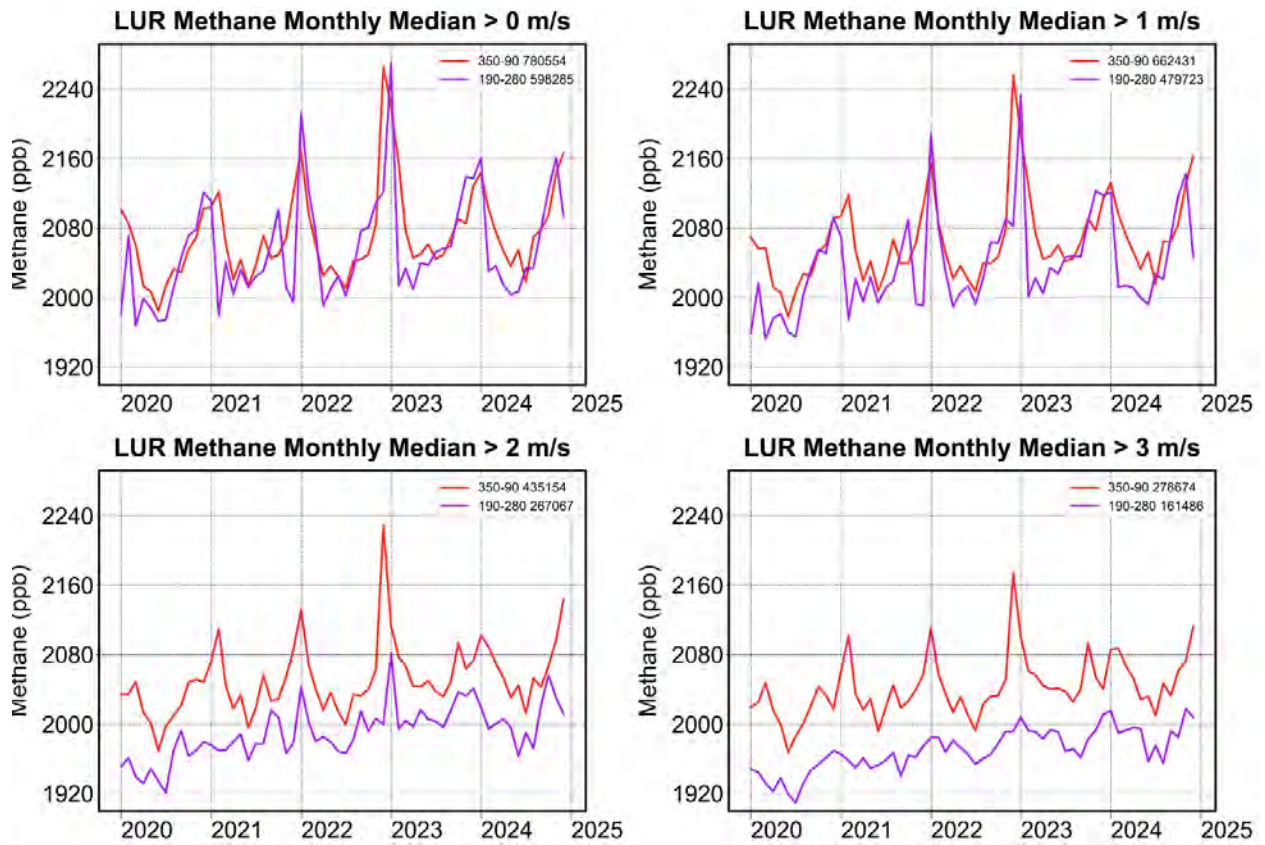


Figure C2-11b. Pollution roses, same as Figure C2-8b, but for the LUR site.

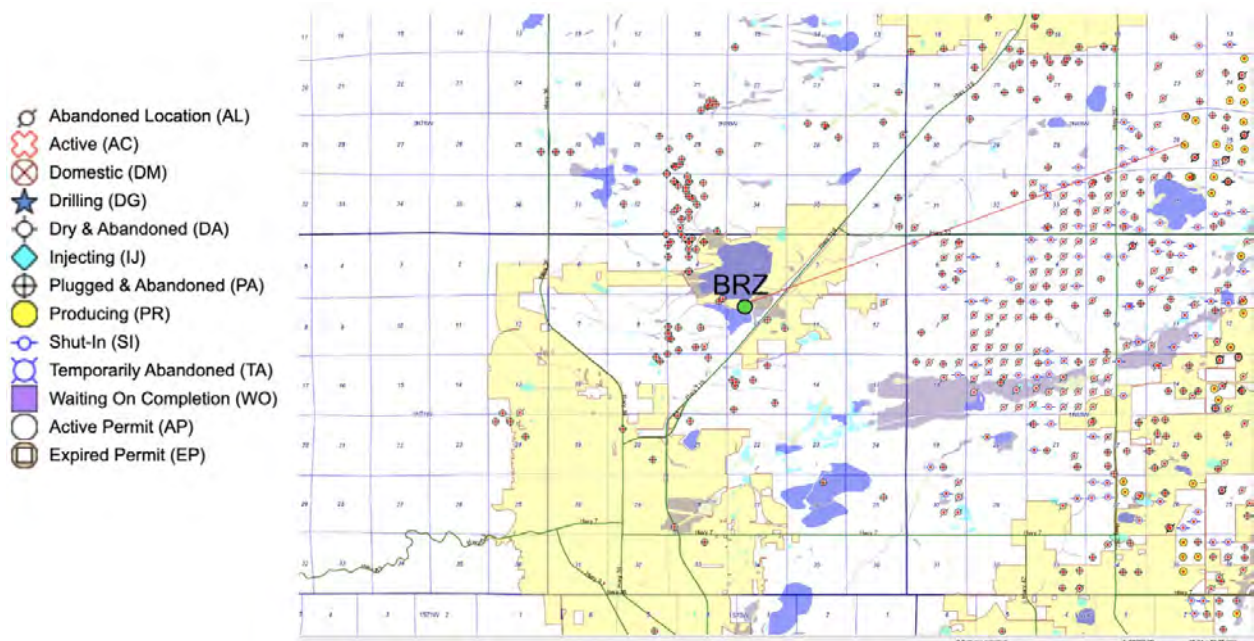


**Figure C2-12a.** Western vs. O&G sector comparison for monthly median NOx at the LUR site where locally measured winds exceeded different thresholds, including the number of observations available for each sector's bounds.



**Figure C2-12b.** Same as Figure C2-12a but for methane.

Sector Analysis Plots: BRZ Western: 200°–320, O&G: 350°–90°



*Figure C2-13. Same as Figure C2-10, but for BRZ. The red line indicates a 7.8-mile distance.*

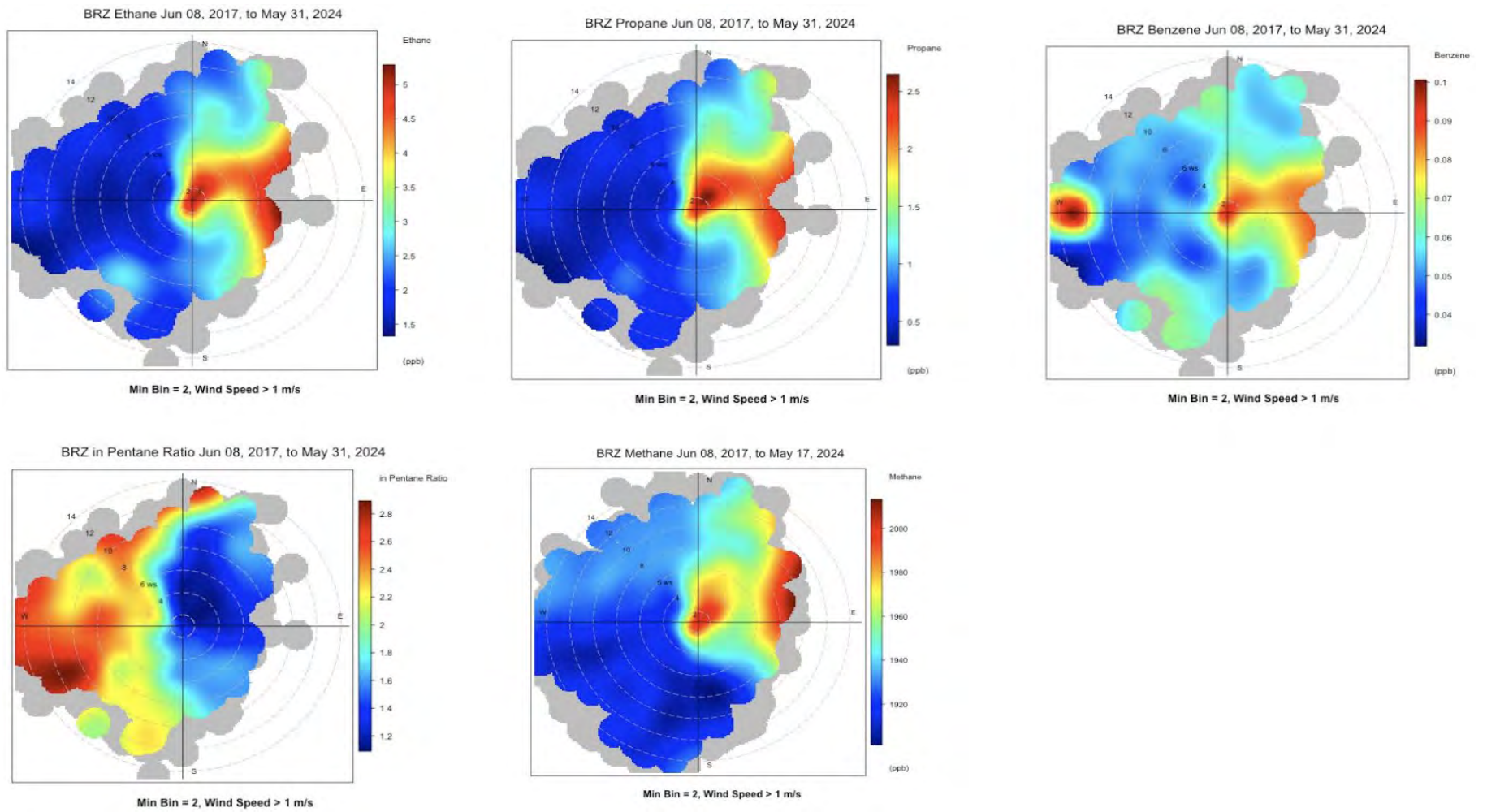


Figure C2-14a: Bivariate polar plots, same as Figure C2-8a but for the BRZ site.

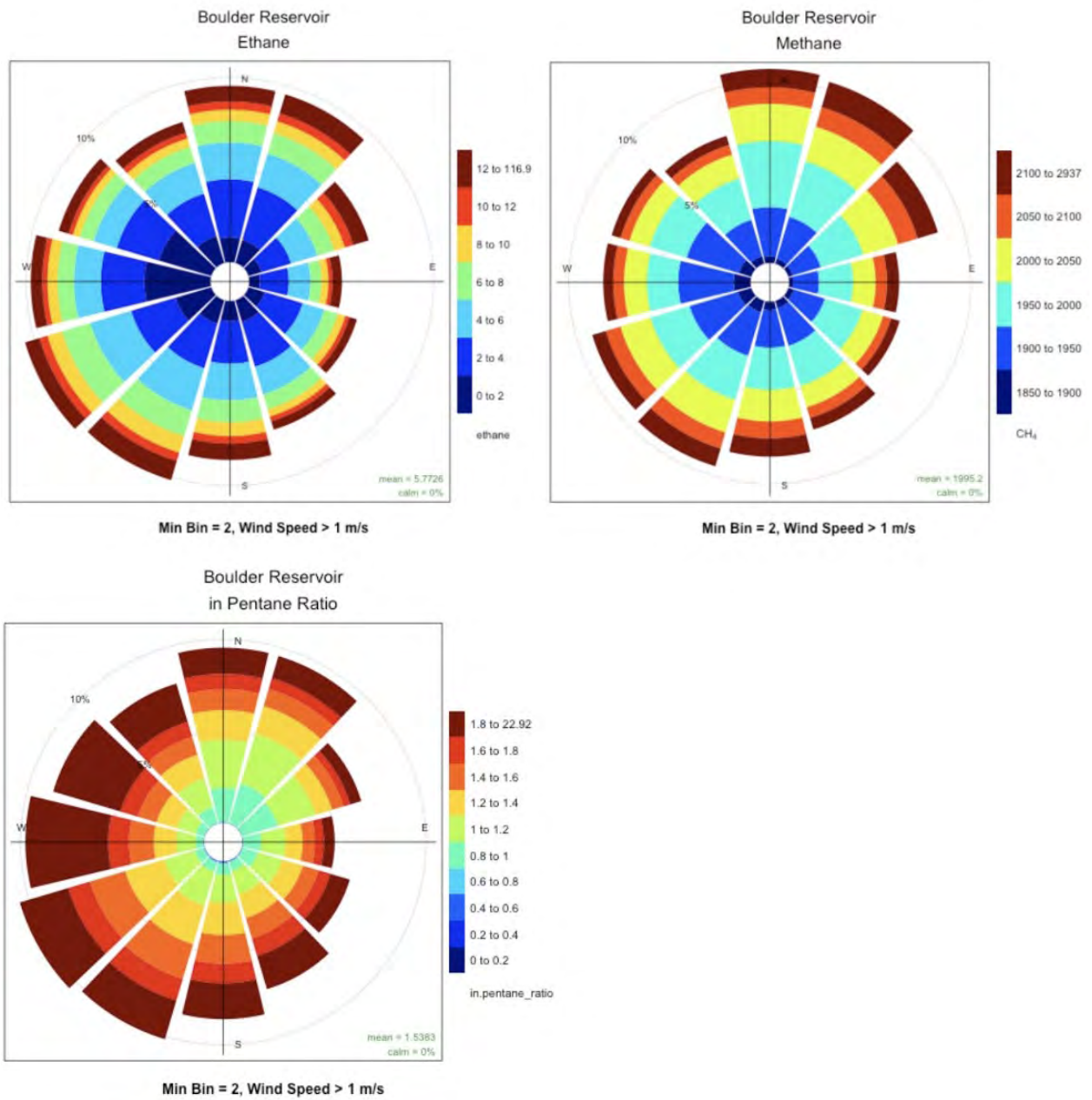
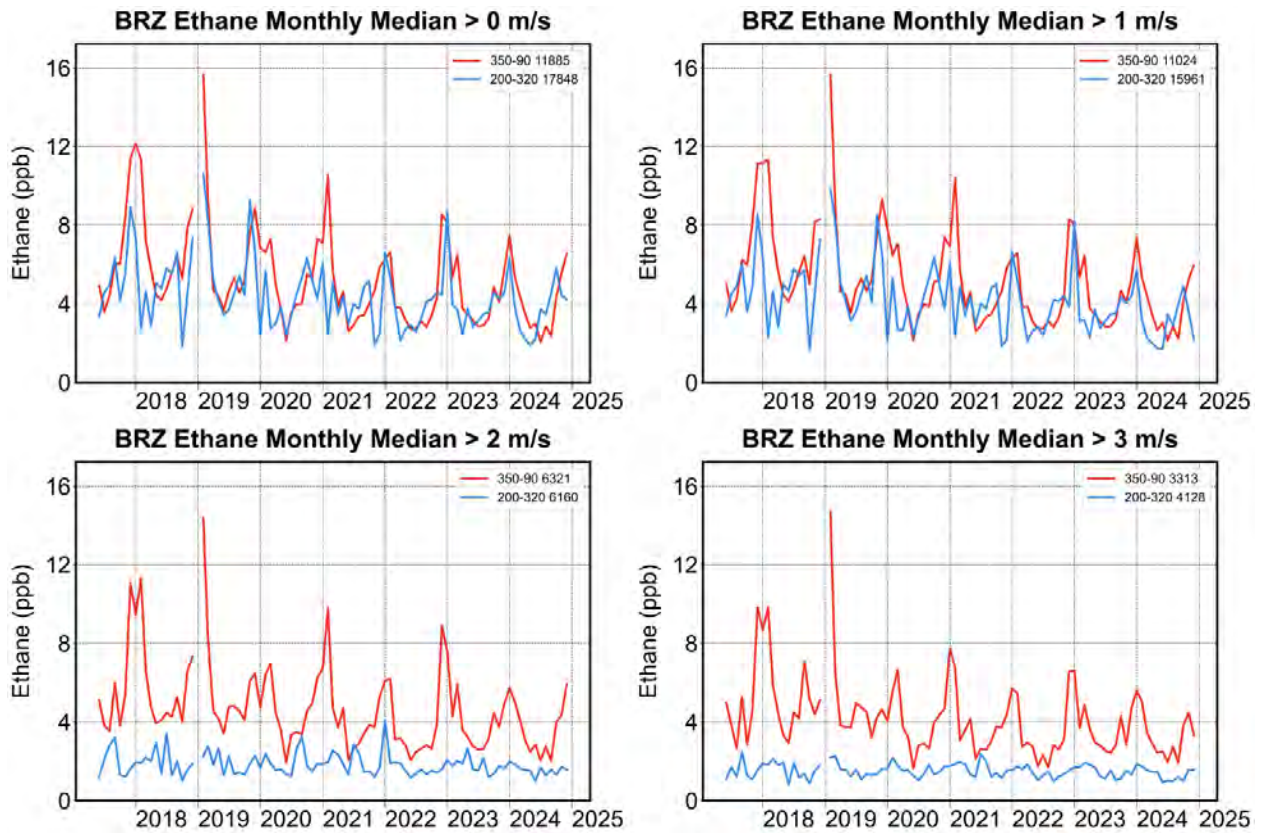


Figure C2-14b. Similar to the pollution rose Figure C2-11b, but using the BRZ site data.



**Figure C2-15a.** Western (“clean”) vs. O&G sector comparison for monthly median ethane at the BRZ site when locally measured winds exceeded different thresholds, including the number of observations available for each sector’s bounds.

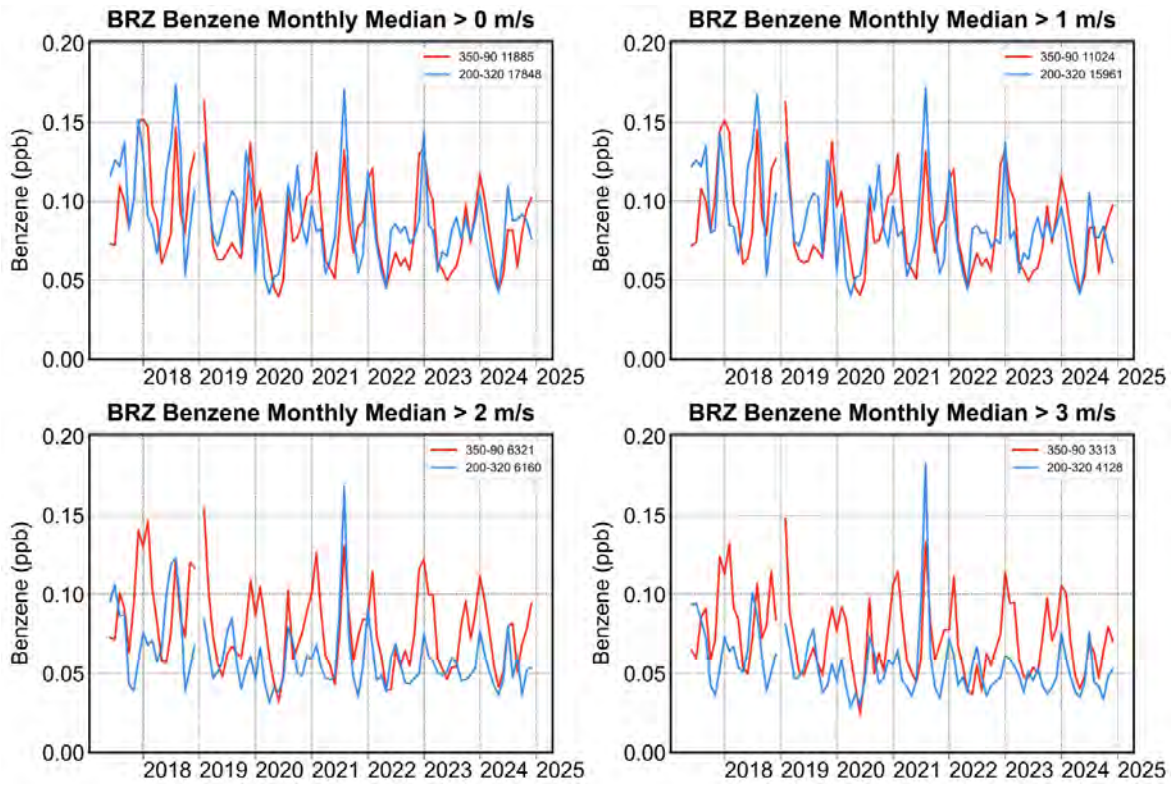


Figure C2-15b. Same as Figure C2-15a but for benzene.

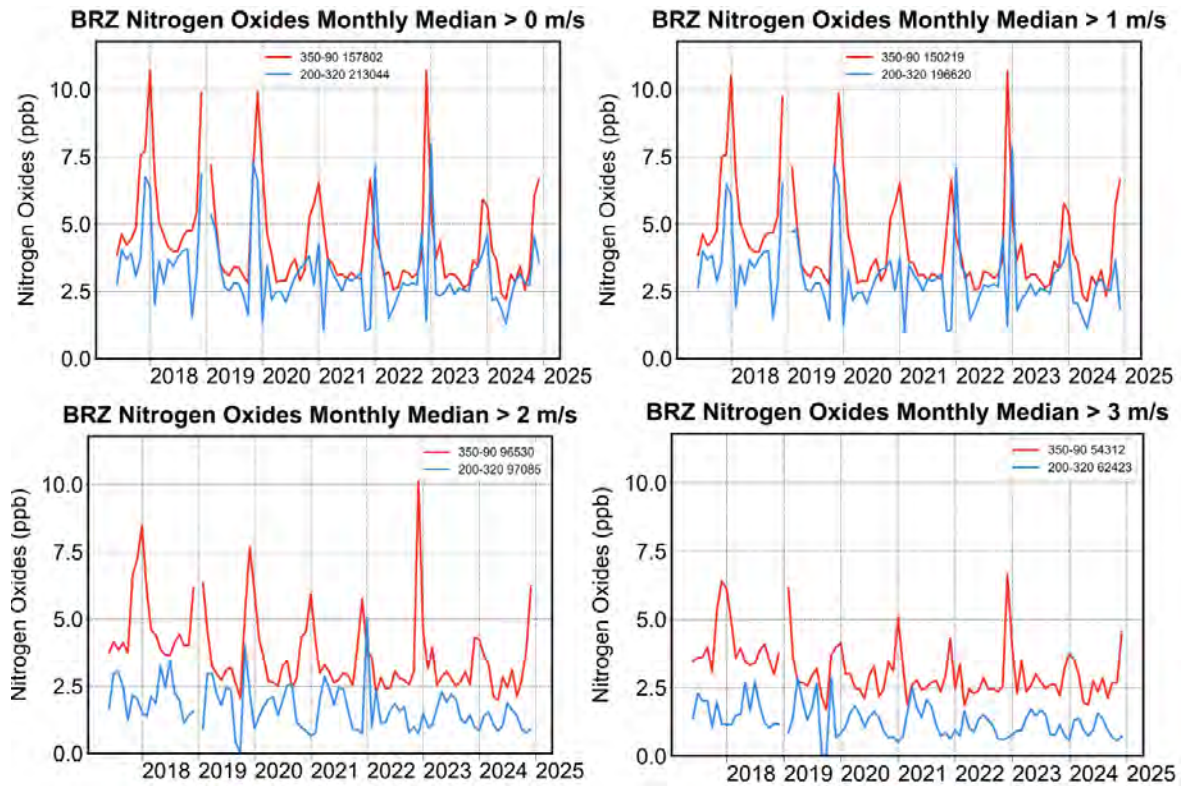


Figure C2-15c. Same as Figure C2-15a but for NO<sub>x</sub>.

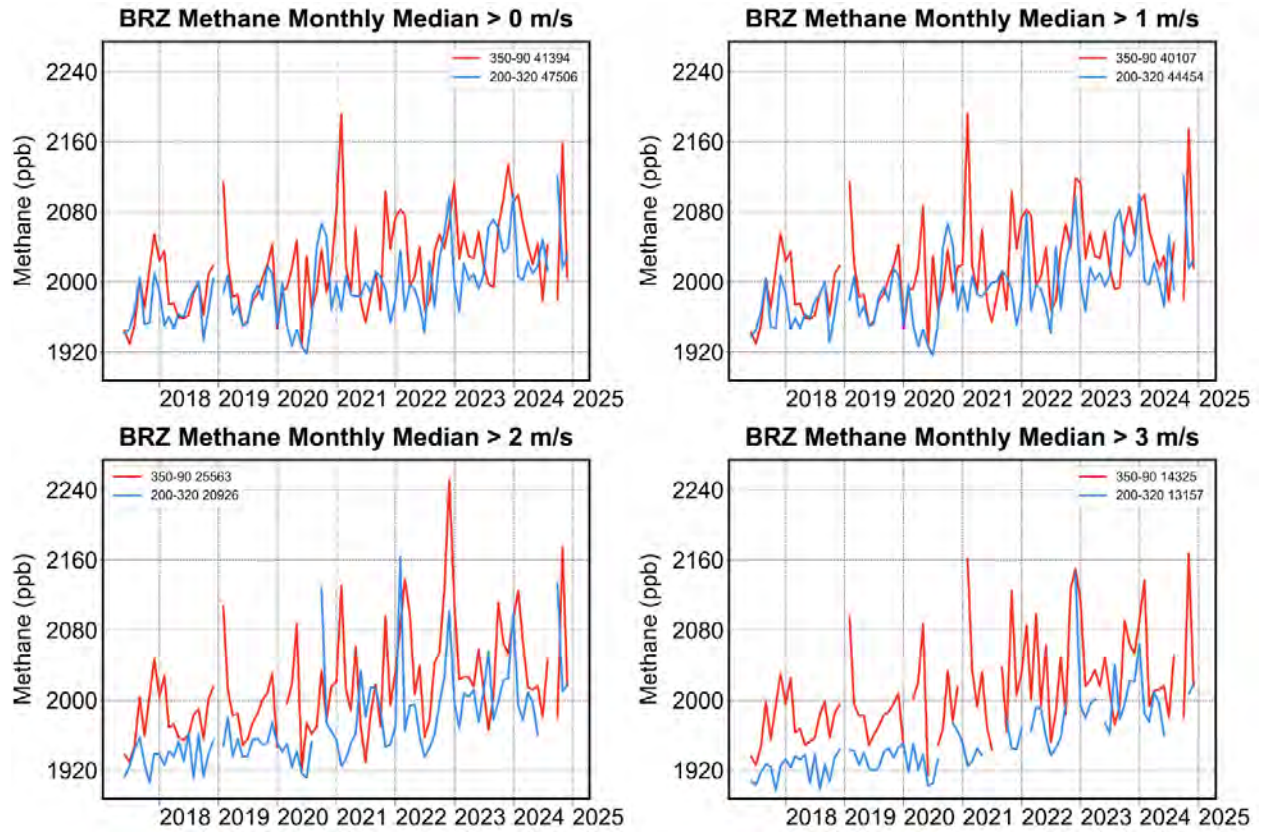


Figure C2-15d. Same as Figure C2-15a but for methane.

Sector Analysis Plots: ECC Western: 200°–290°, O&G: 350°–90°

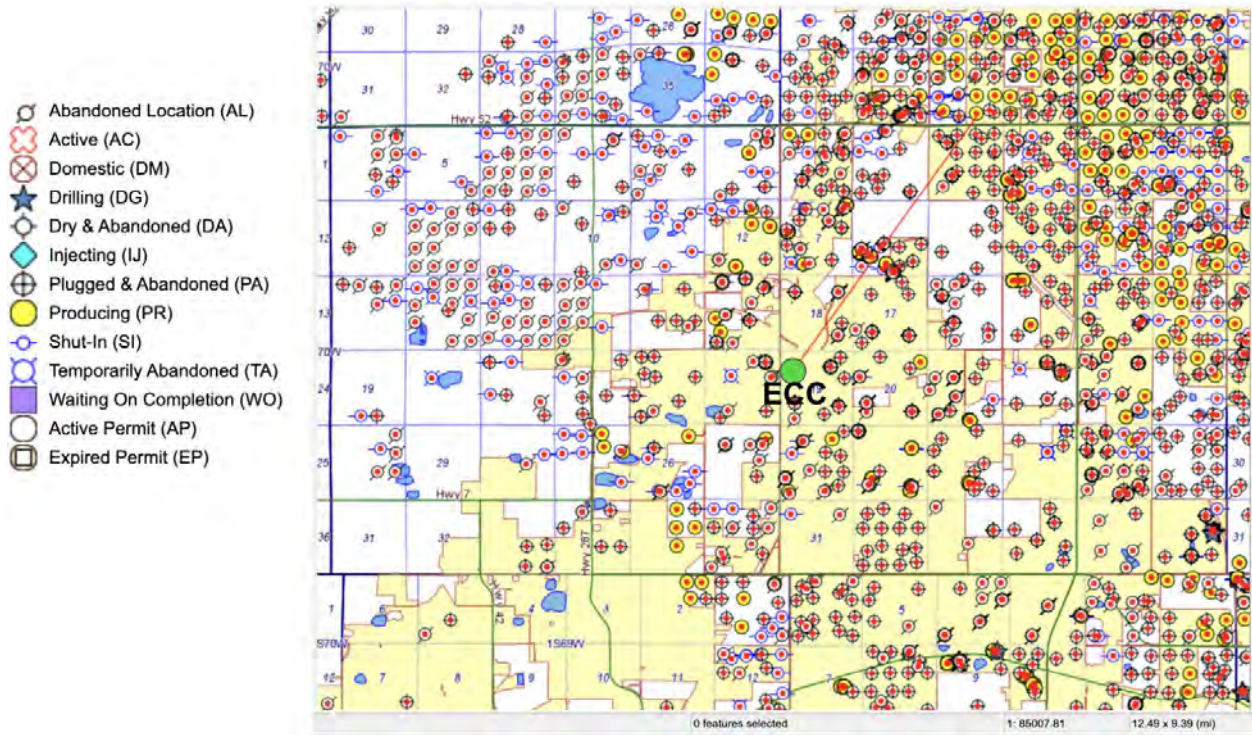
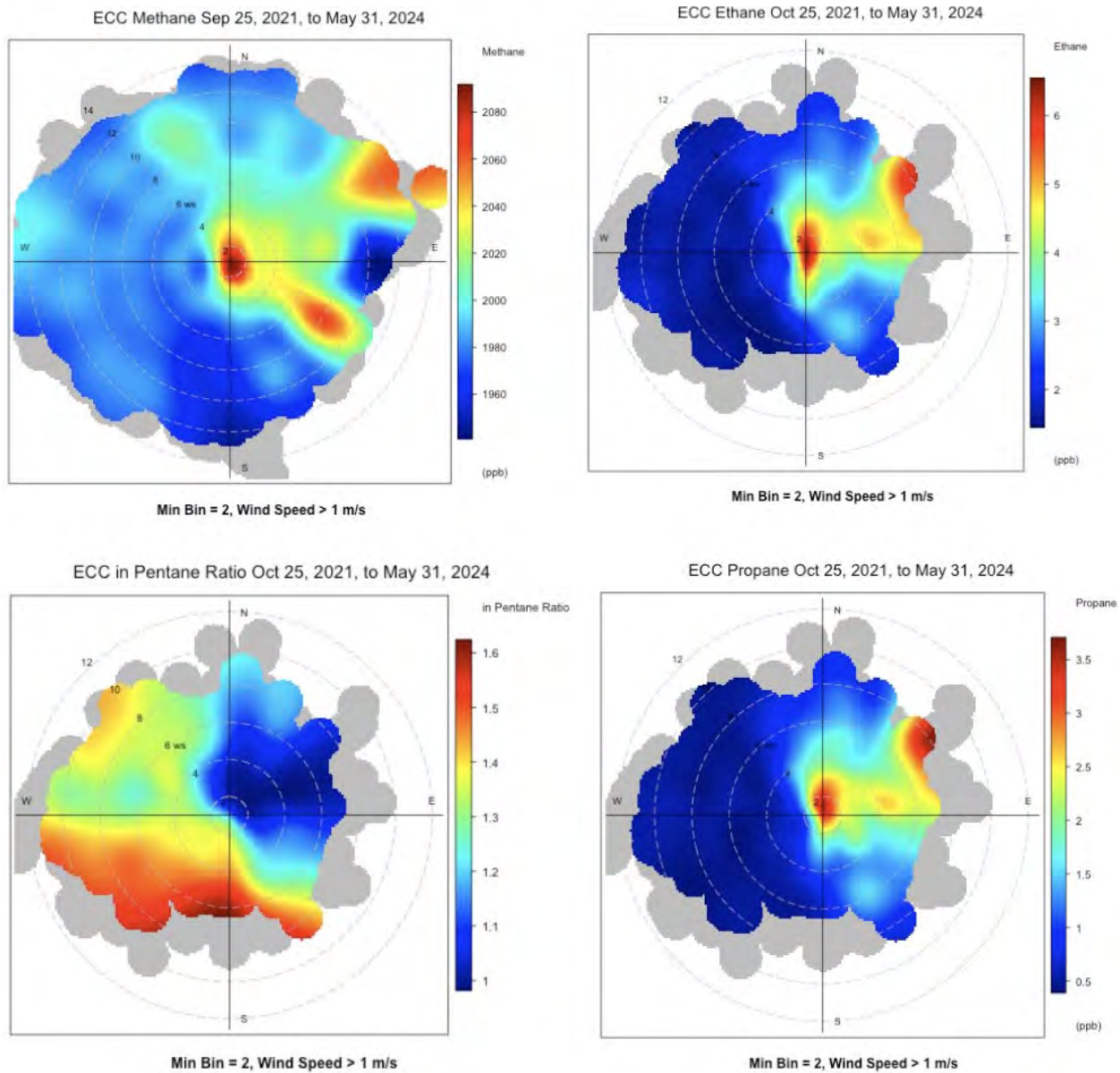


Figure C2-16. Same as Figure C2-10, but for ECC. The red line indicates a 4.2-mile distance.



*Figure C2-17a. Bivariate polar plots same as figure C2-8a, but for ECC.*

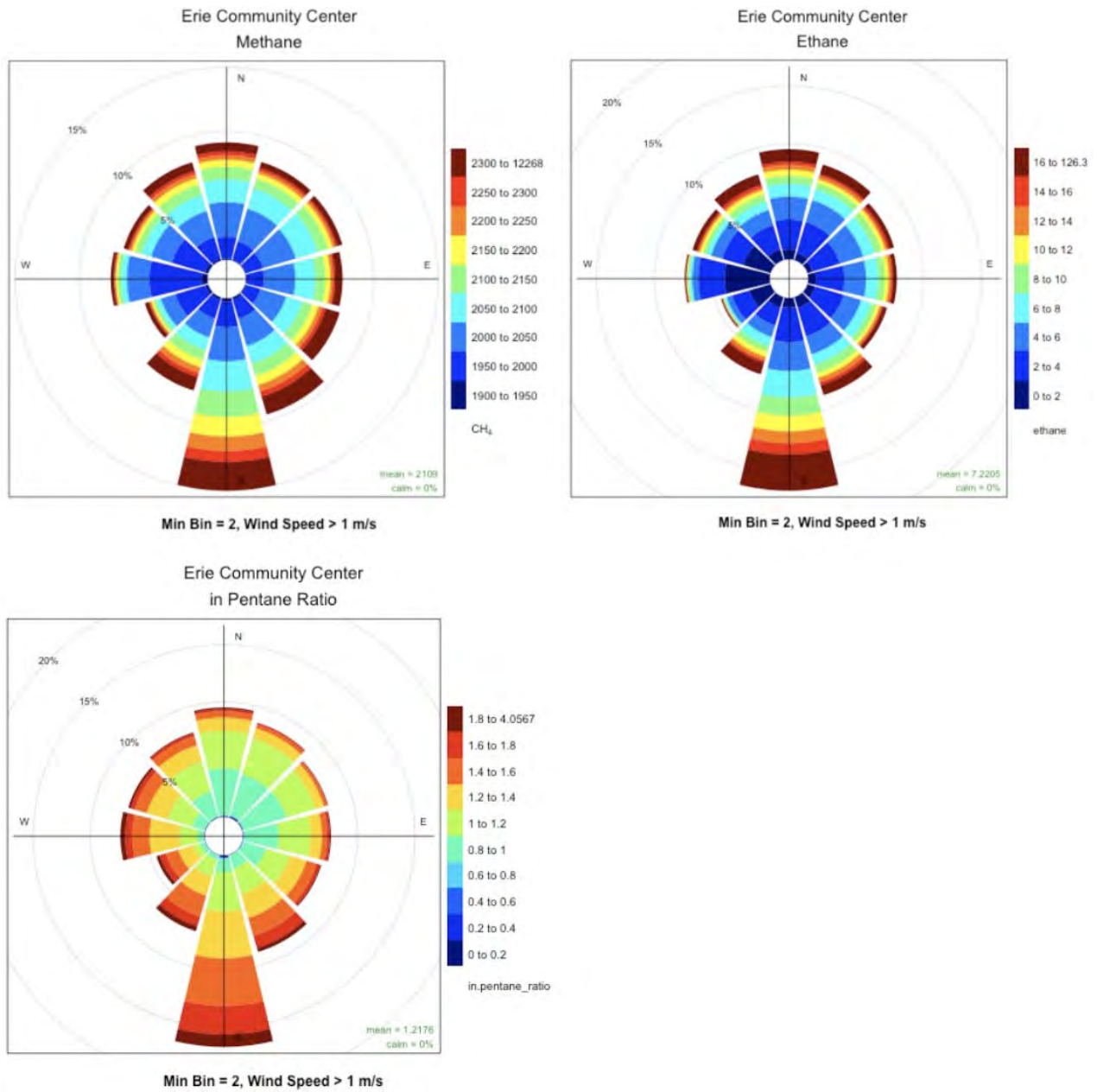
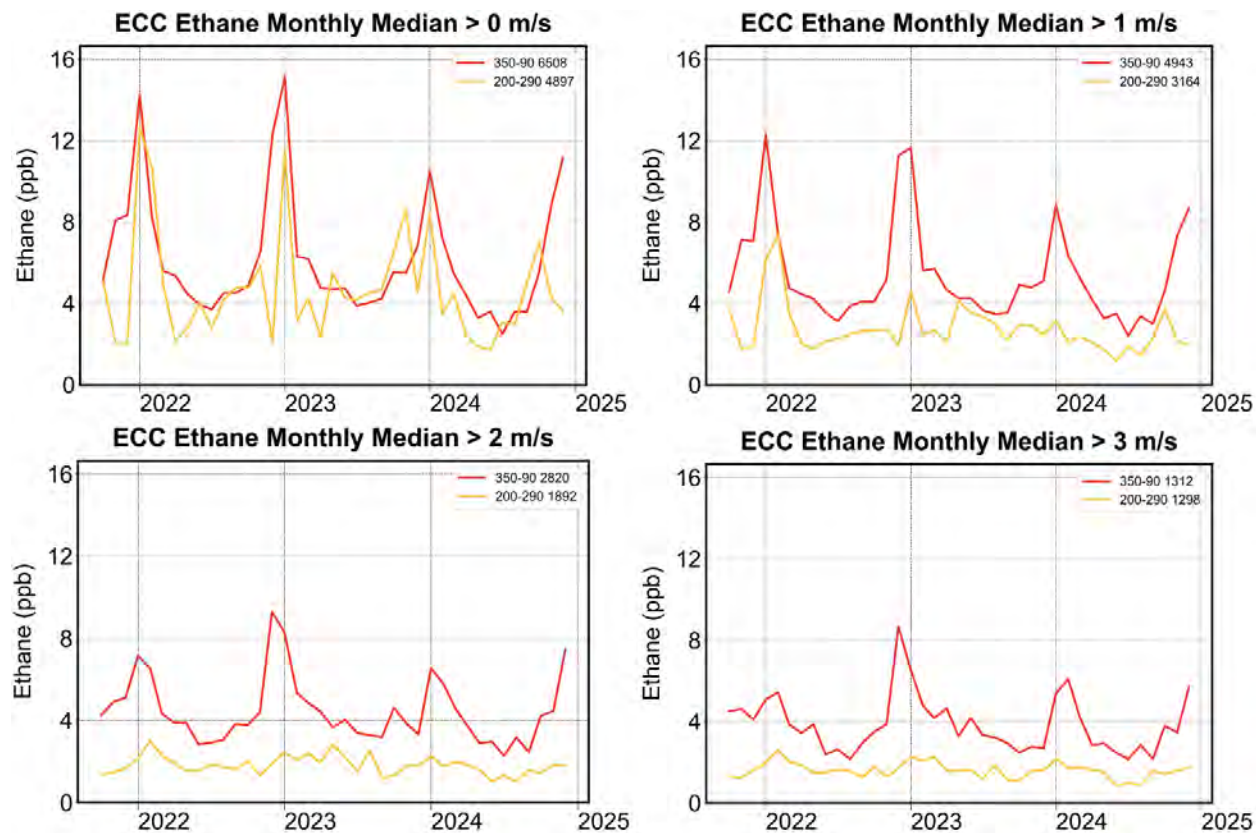
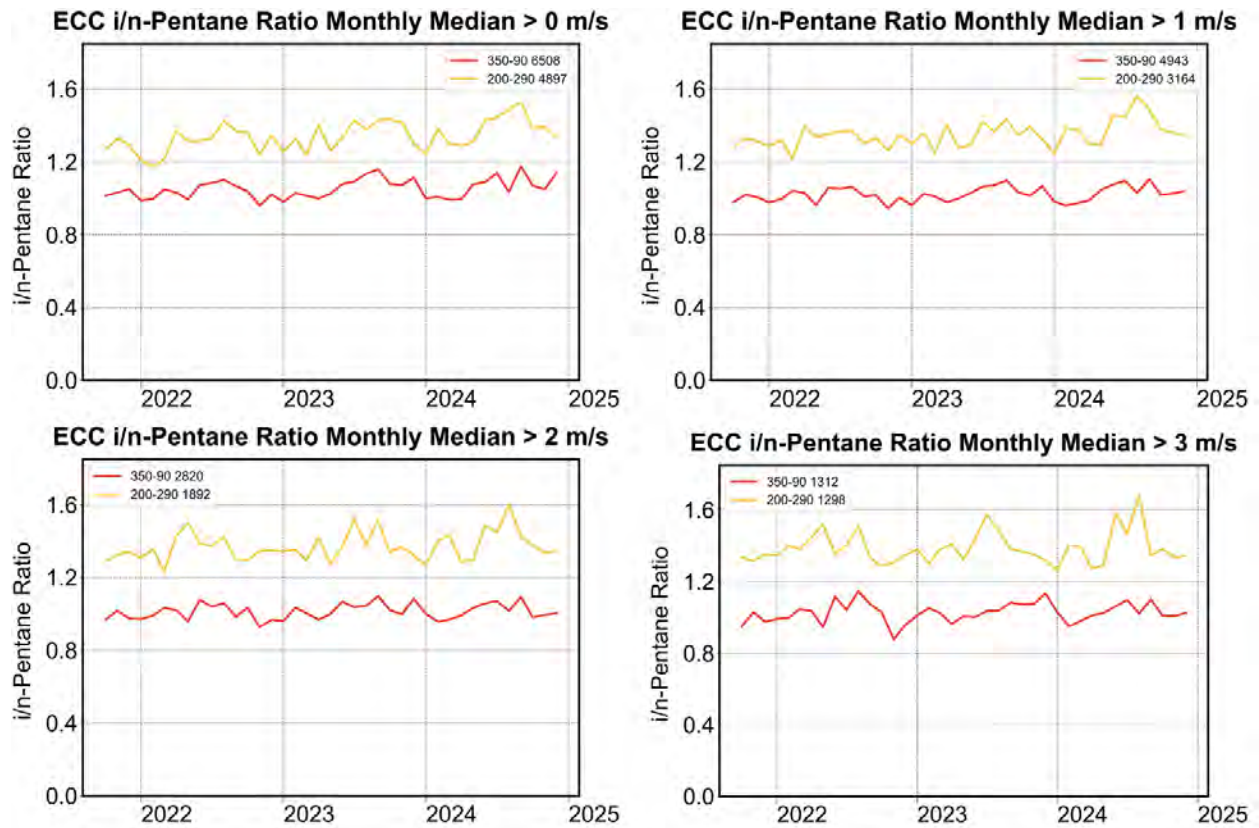


Figure C2-17b. Similar to the pollution rose Figure C2-11b, but using ECC data.



**Figure C2-18a.** Western (“clean”) vs. O&G sector comparison for monthly median ethane at the BRZ site when locally measured winds exceeded different thresholds, including the number of observations available for each sector’s bounds.



*Figure C2-18b. Same as Figure C2-18a, but for the i/n-pentane ratio.*

Sector Analysis Plots: BNP Western: 170°–270°, O&G: 300°–60°

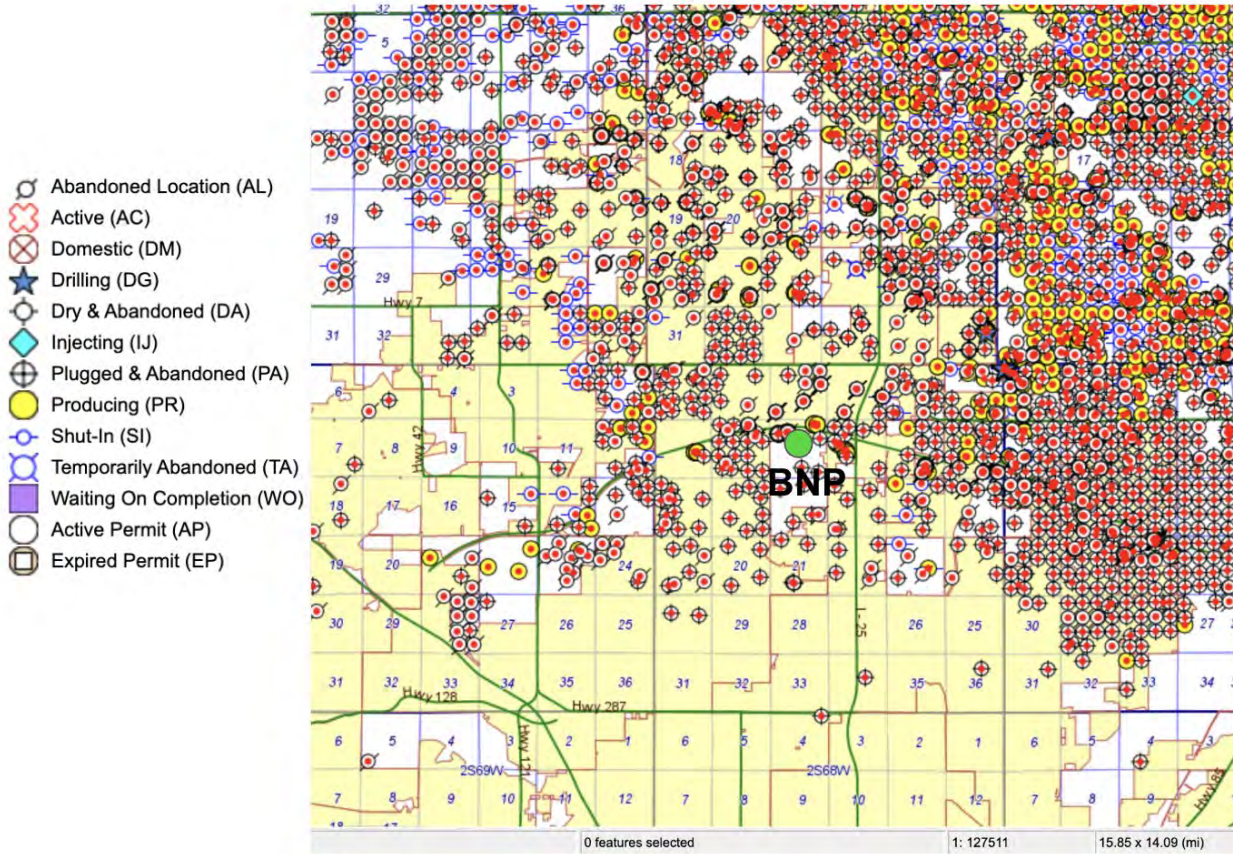


Figure C2-19. Same as Figure C2-10, but for BNP.

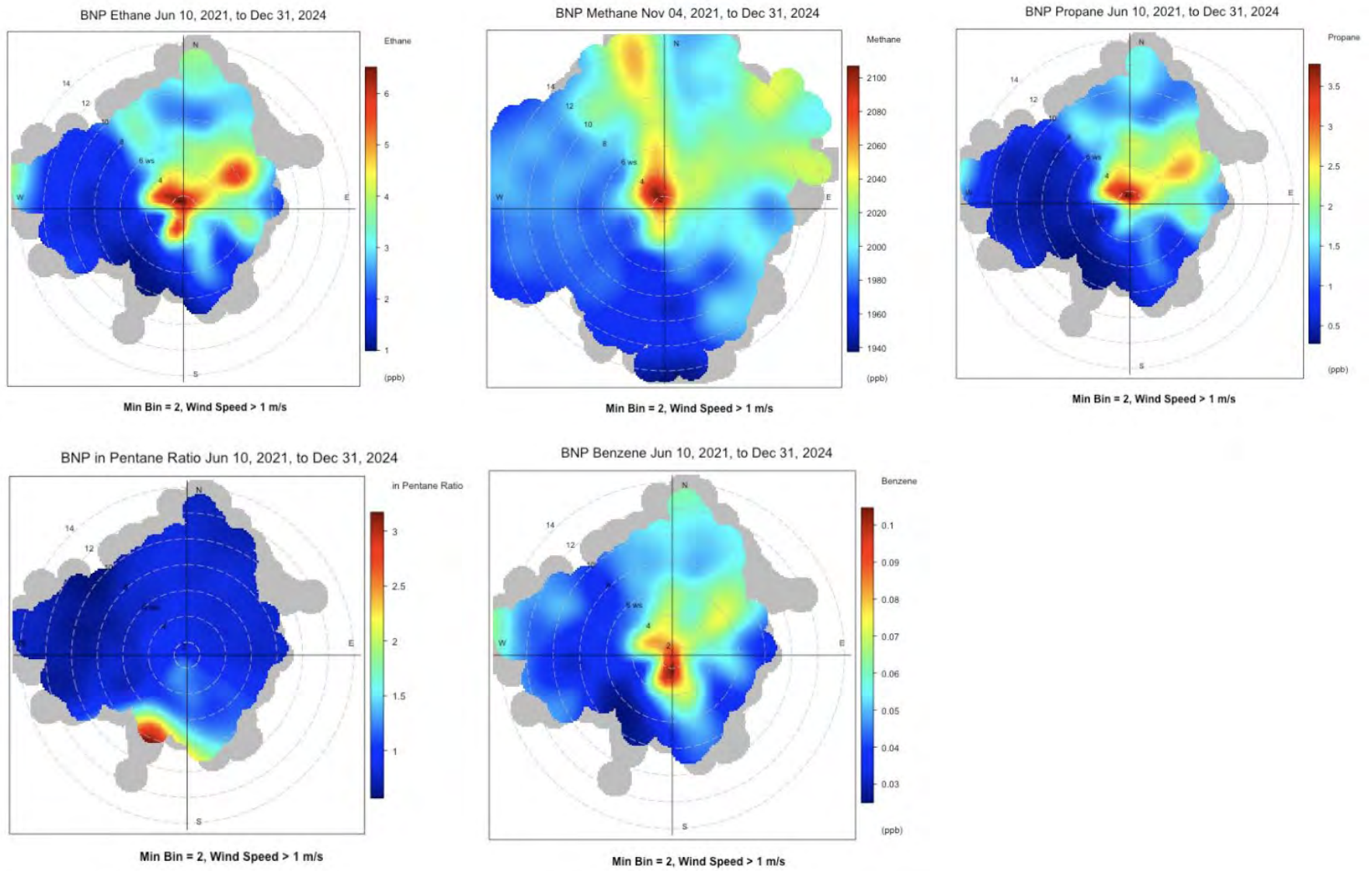


Figure C2-20a. Bivariate polar plots same as figure C2-8a, but for BNP.

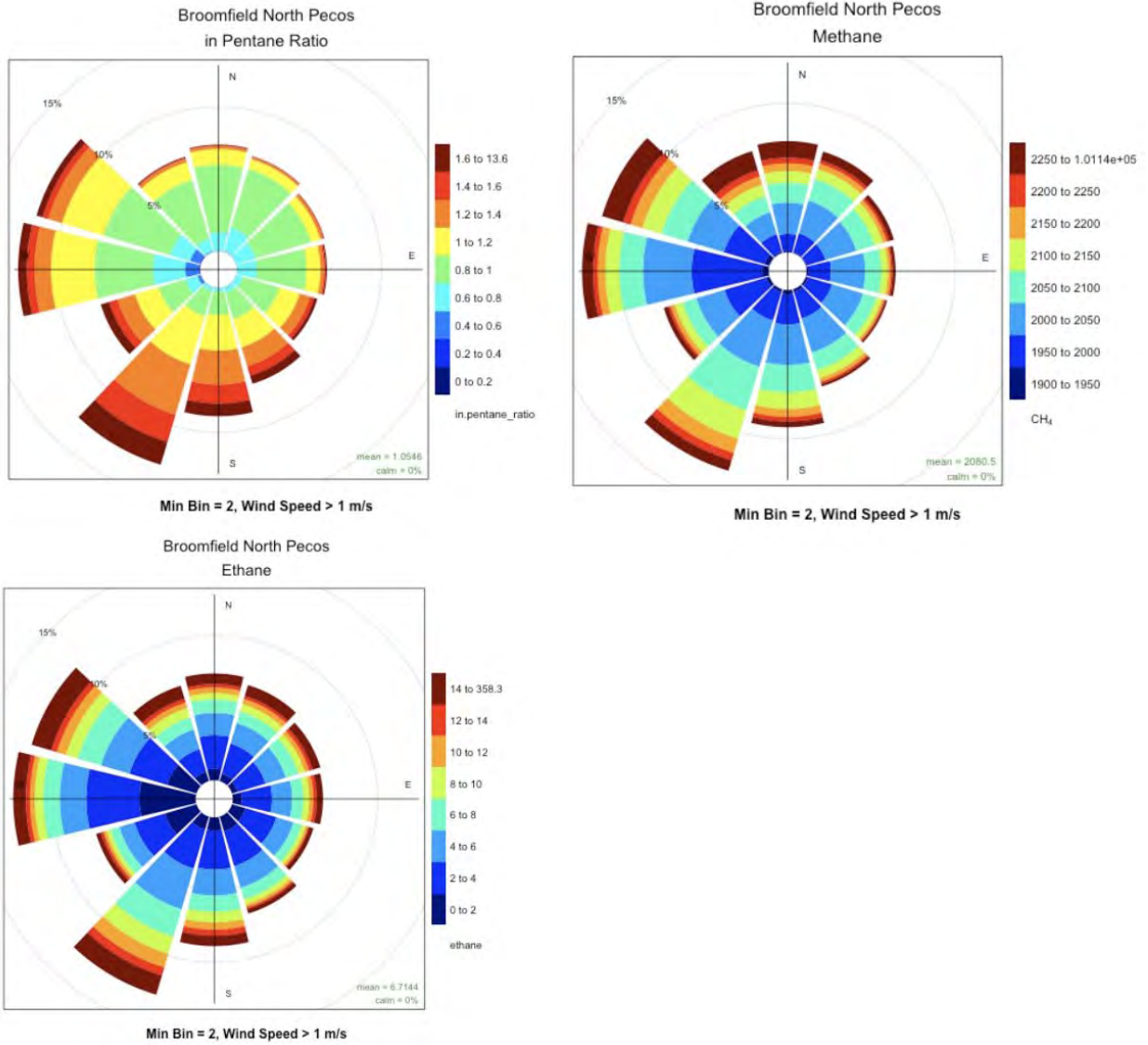
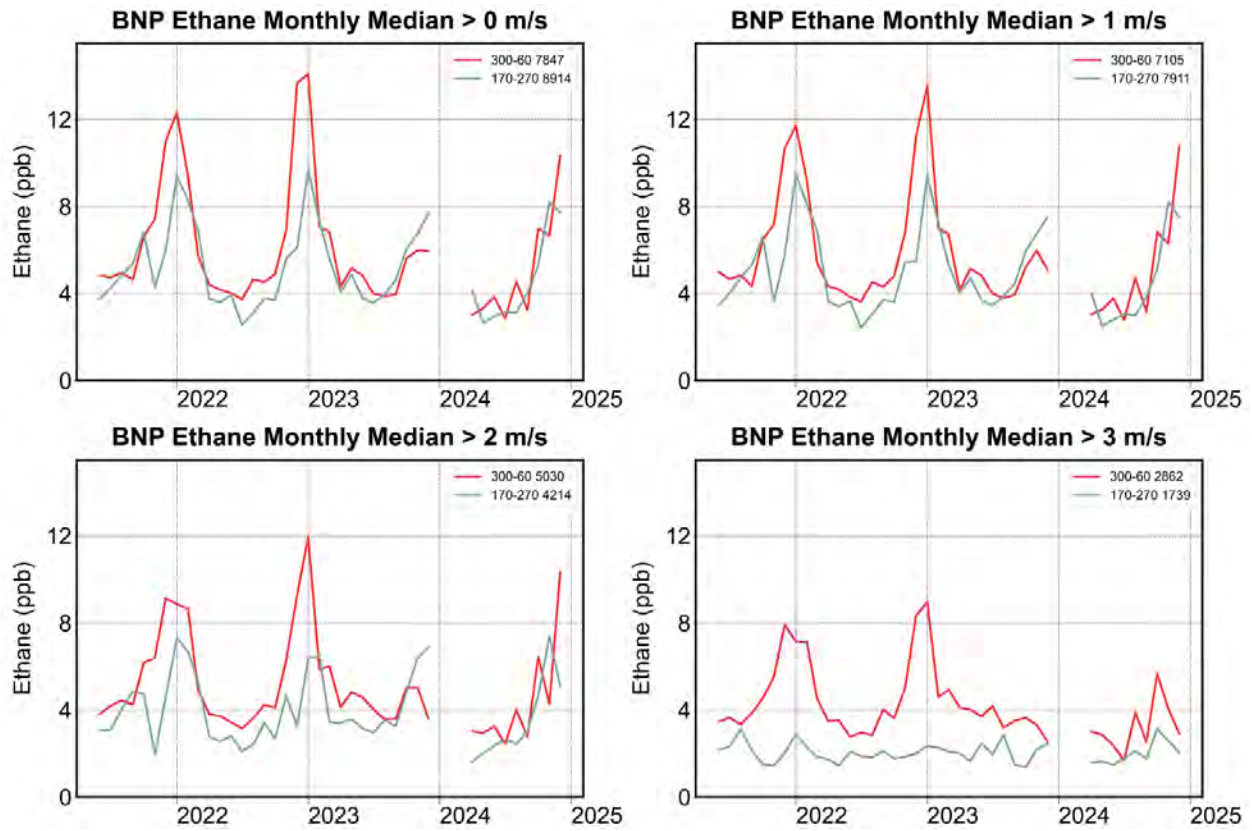


Figure C2-20b. Similar to the pollution rose Figure C2-11b, but using BNP data.



**Figure C2-21a.** Western (“clean”) vs. O&G sector comparison for monthly median ethane at the BNP when locally measured winds exceed different thresholds, including the number of observations available for each sector’s bounds.

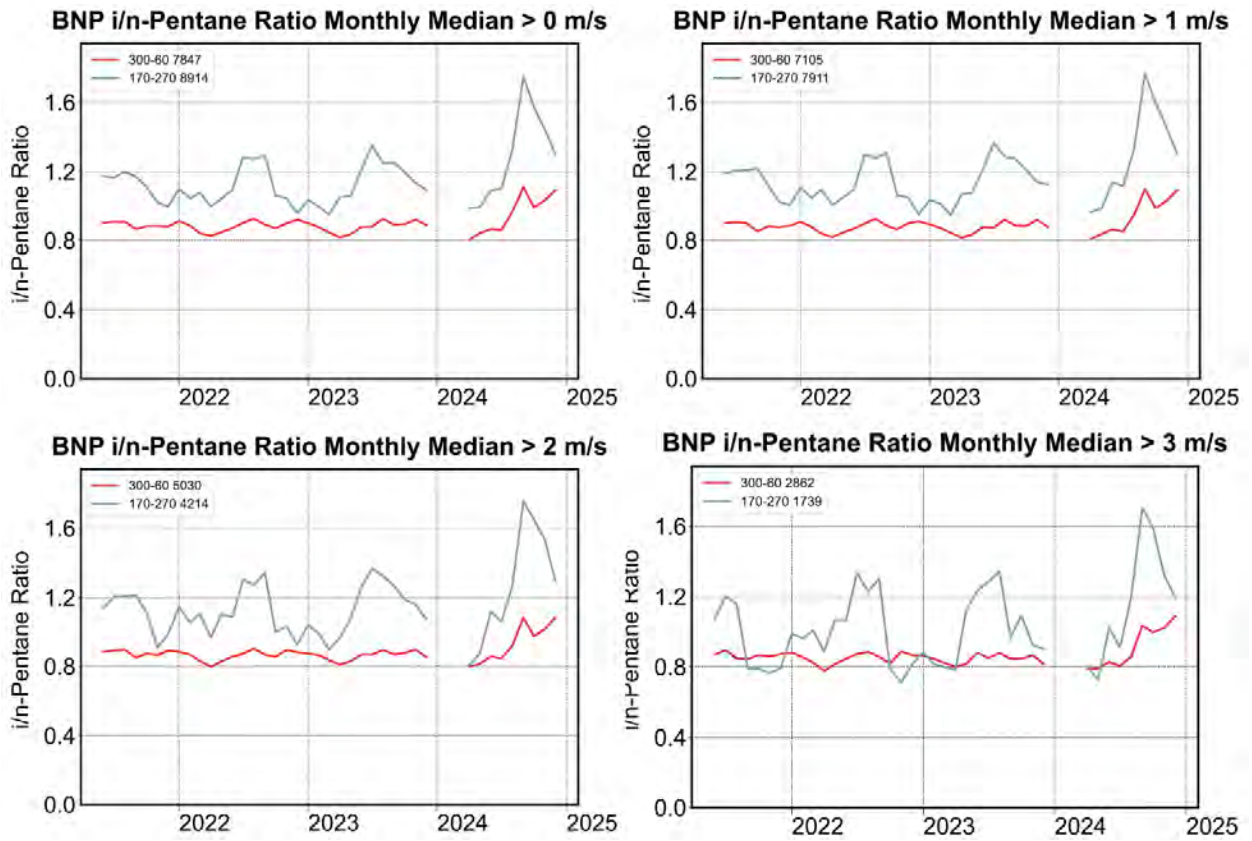
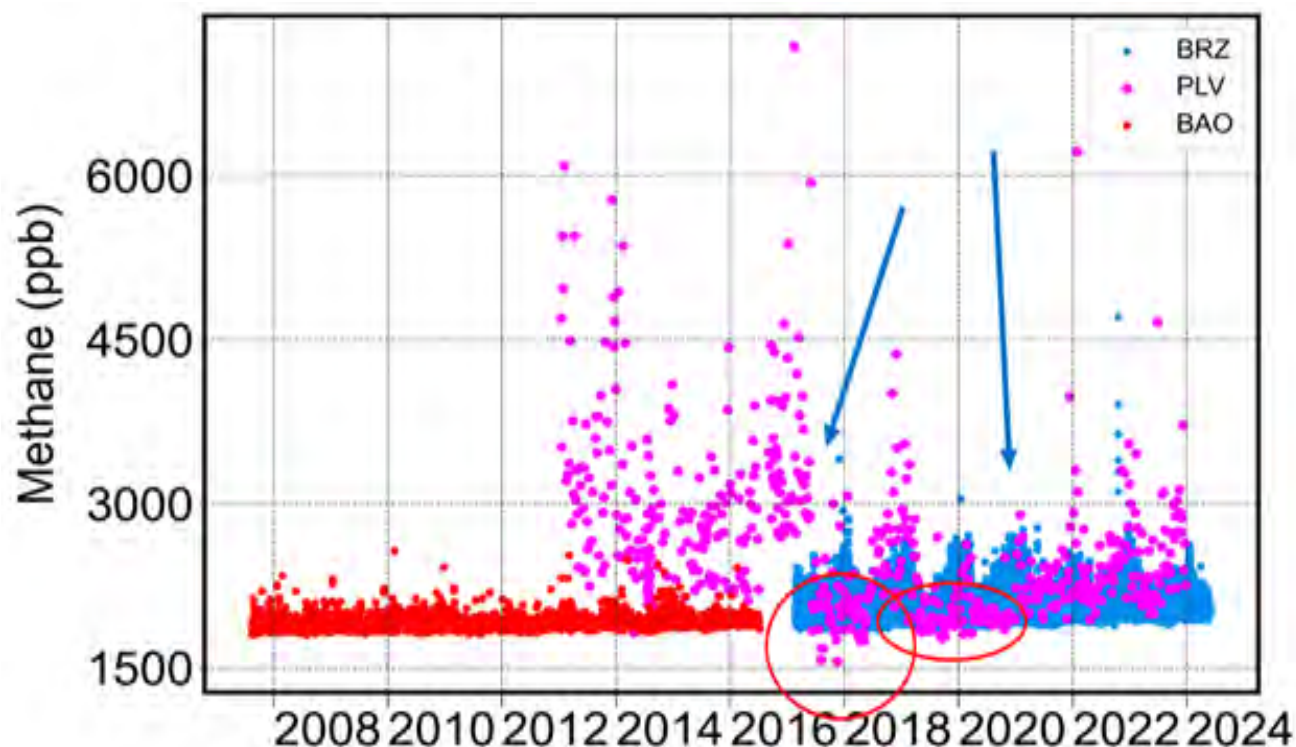


Figure C2-21b. Same as Figure C2-20a but for the i/n-pentane ratio.

## Platteville Site Data Evaluation

The state-operated site in Platteville (PVCO) displayed highly variable methane and NMHC data. Methane and ethane data from the CDPHE's air monitoring program at Platteville (PVCO) were plotted as time series alongside selected data from other monitoring programs. The PVCO methane record, along with concurrent data from BRZ and BAO, is shown in **Figure C2-22**. The PVCO methane data (shown in pink) exhibit significantly higher variability, frequently exceeding 3 ppm — unlike BAO and BRZ observations, which mostly remain below that threshold.



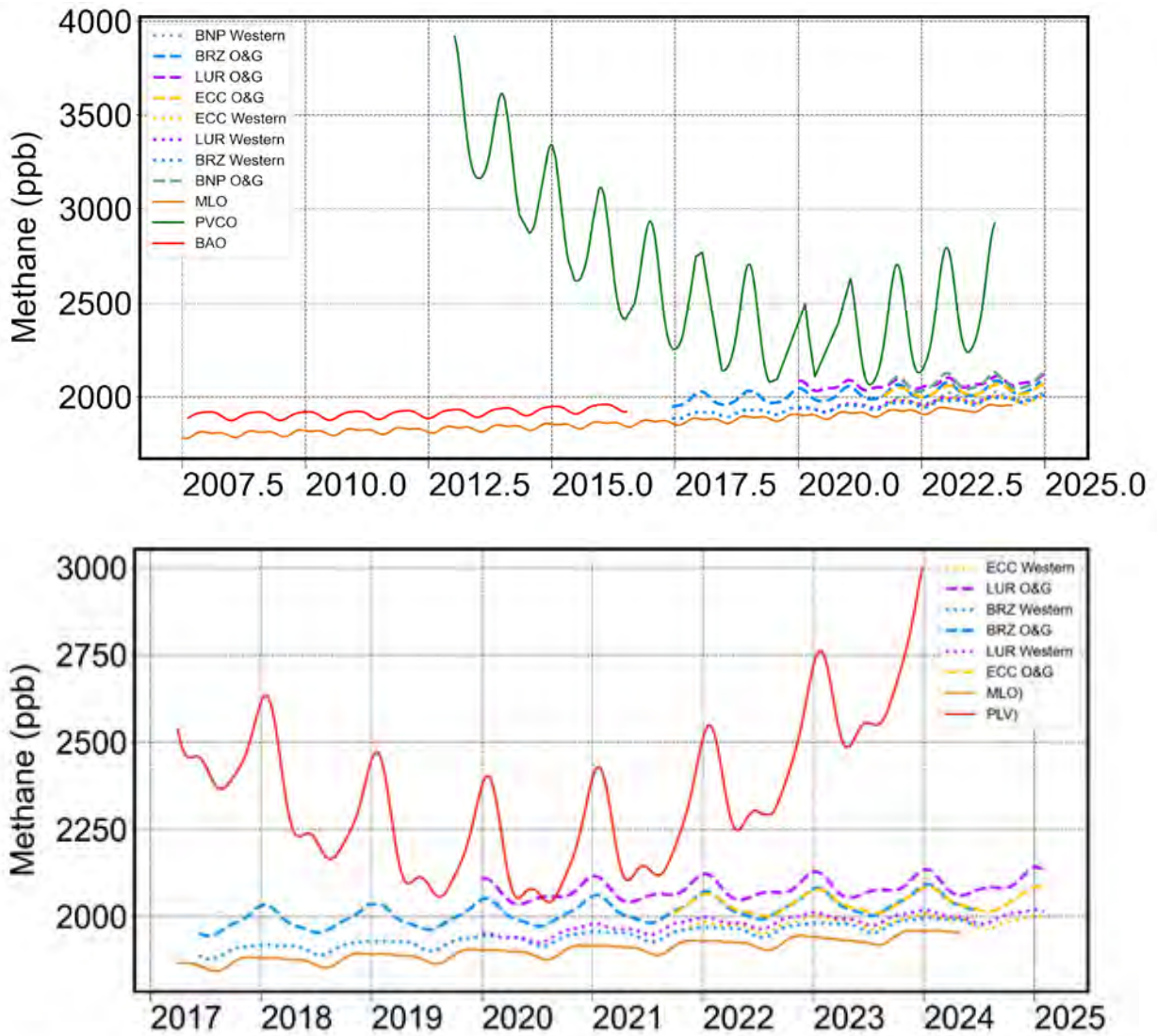
**Figure C2-22.** Record of atmospheric methane monitoring data from the Boulder Reservoir (BRZ), the Boulder Atmospheric Observatory (BAO), and the Platteville Chemical Observatory (PVCO). Step changes in the data record are indicated by the blue arrows, and unexpectedly low recordings by the red circles.

Two specific features strongly suggest issues with data quality:

1. **Step Changes in the Record:** There are abrupt shifts in the PVCO methane data — specifically, a sharp drop in 2016 and a noticeable increase in early 2021. Such step changes are unusual and have not been observed in other datasets. This suggests a possible change in the analytical protocol, likely involving alterations to the calibration standards used for methane measurements.
2. **Unrealistically Low Methane Values:** Several recorded methane concentrations are far below expected levels for ambient atmospheric conditions (Fig. C2-22). Given methane's ~10-year atmospheric lifetime and relatively uniform global background, such extreme deviations are implausible. For instance, values approaching 1500 ppb were reported, roughly 450 ppb below even the cleanest expected background levels. This ~20% discrepancy cannot be explained by

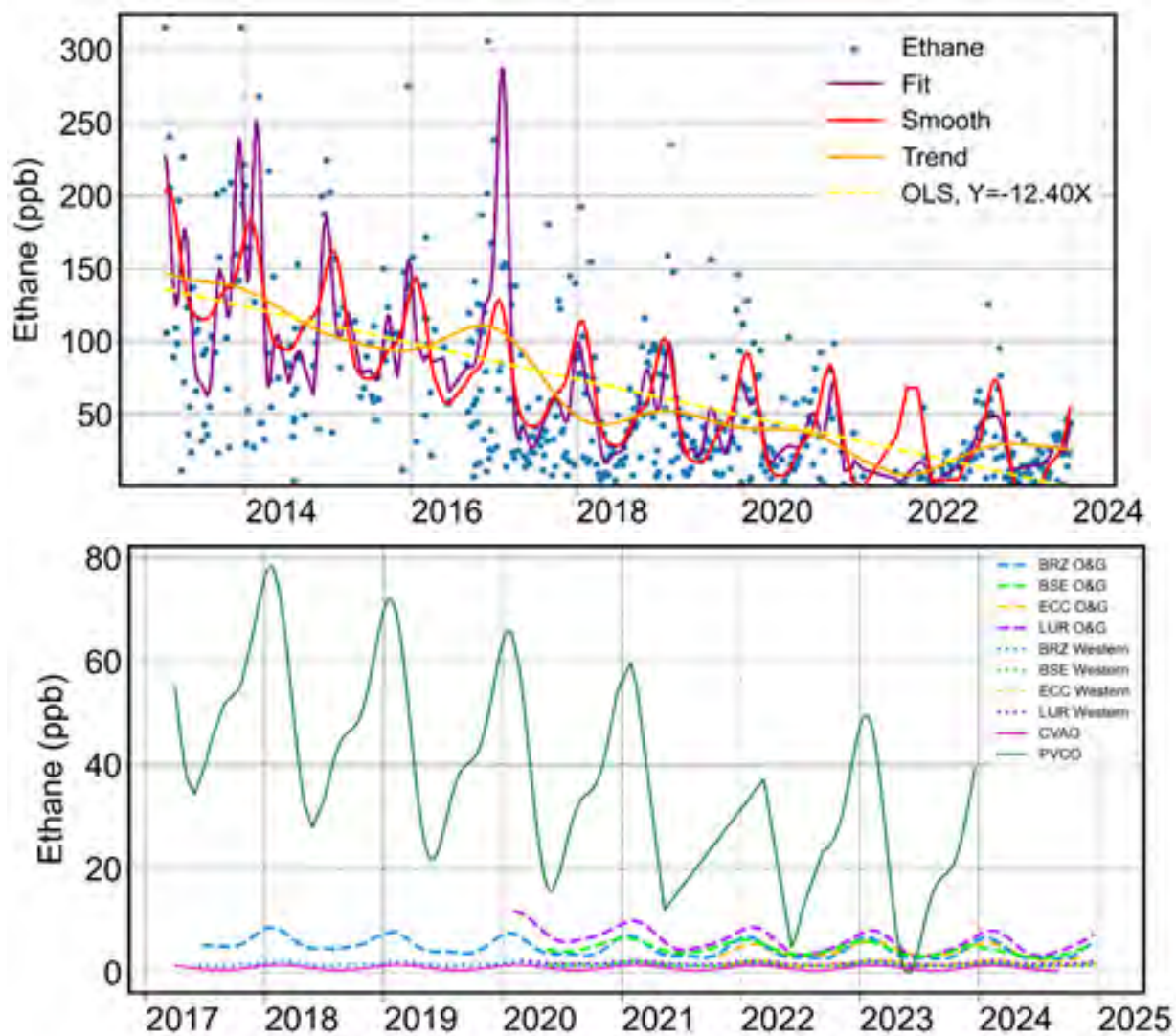
standard measurement uncertainty, as even older, offline GC-FID techniques typically have relative uncertainties well below 5%.

When subjected to trend analysis, the PVCO methane data deviated substantially from other monitoring datasets (Figure C2-23). While the seasonal cycle aligns in timing, the methane mole fractions are much higher, showing a steep decline before 2020 followed by an increase afterward. Additionally, the seasonal amplitude is about 10 times greater than in other datasets, and the post-2020 increase does not match trends observed at all other stations.



**Figure C2-23.** Smooth trend line output from the NOAA FFT trend tool comparing the PVCO data with five other monitoring records, including the Mauna Loa Observatory atmospheric northern hemisphere background (upper panel). The lower panel shows the last 8 years of data at higher resolution.

Similar anomalies were evident in the PVCO ethane data (**Figure C2-24**), which display higher variability, greater total mole fractions, and a more pronounced downward trend than data from comparison sites. In the case of ethane, evaluating data quality is more challenging due to its shorter atmospheric lifetime (on the order of months), which results in a (global) background that is 2000 to 4000 times lower than that of methane. Nonetheless, trend analysis revealed that the PVCO ethane slope is an order of magnitude greater than those observed at other oil and gas sector monitoring sites. Regression analysis shows that PVCO's error margins are up to two orders of magnitude larger than those from other stations.

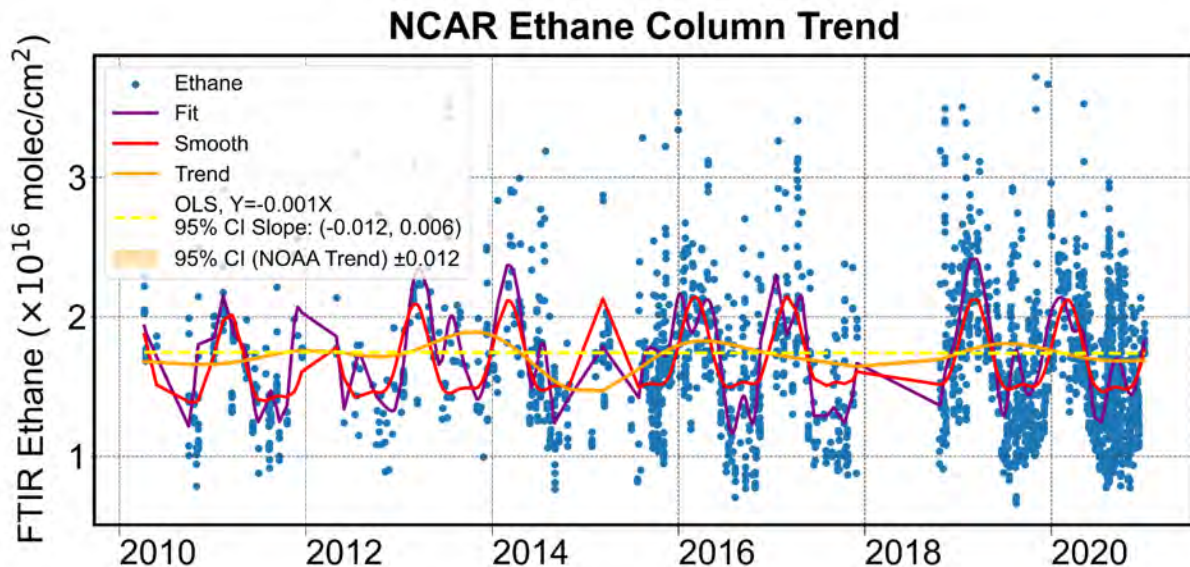


**Figure C2-24.** PVCO ethane data record with trend analyses fit (top panel), and comparison of the smooth fit output with the other NCFR sites (bottom panel).

- **Sampling Method:** PVCO relies on canister sampling, whereas other programs use in situ, real-time measurements.
- **Sampling Frequency:** PVCO collects samples every sixth day, resulting in about 60 samples per year, compared with approximately 8,500 samples annually at other NCFR sites.
- **Sampling Duration:** Each PVCO sample represents only a 3-hour collection window, whereas similar programs (e.g., in Texas) use 24-hour sampling intervals for such samples. Such long-duration sampling hinders filtering by wind direction or air mass transport.
- **Sampling Time and Location:** PVCO samples are collected between 6 and 9 a.m. local time at a low-lying location near the Platte River, surrounded by higher terrain. This geography can cause the pooling of local emissions in the nighttime surface layer, especially during strong inversions, which the sampling likely reflects.

In summary, the PVCO site sampling program collects far fewer samples and uses both longer and temporally biased sampling intervals, which limits the ability to apply additional quality controls such as air transport filtering. As a result, the data more likely reflect hyper-local emissions coming from a limited surrounding area and may not be representative of regional air quality. These concerns about the state’s methane monitoring program have been raised multiple times in the past. Our evaluation indicates that these issues remain unresolved.

### Individual Trend Plots: Ethane



**Figure C2-25.** NCAR FTIR ethane total vertical column data, NOAA trend tool output. Original data (blue) with NOAA tool outputs fit (purple), smooth (red), trend (orange), trend bounds (orange shading), and an OLS regression line fit (dashed yellow) to the trend.

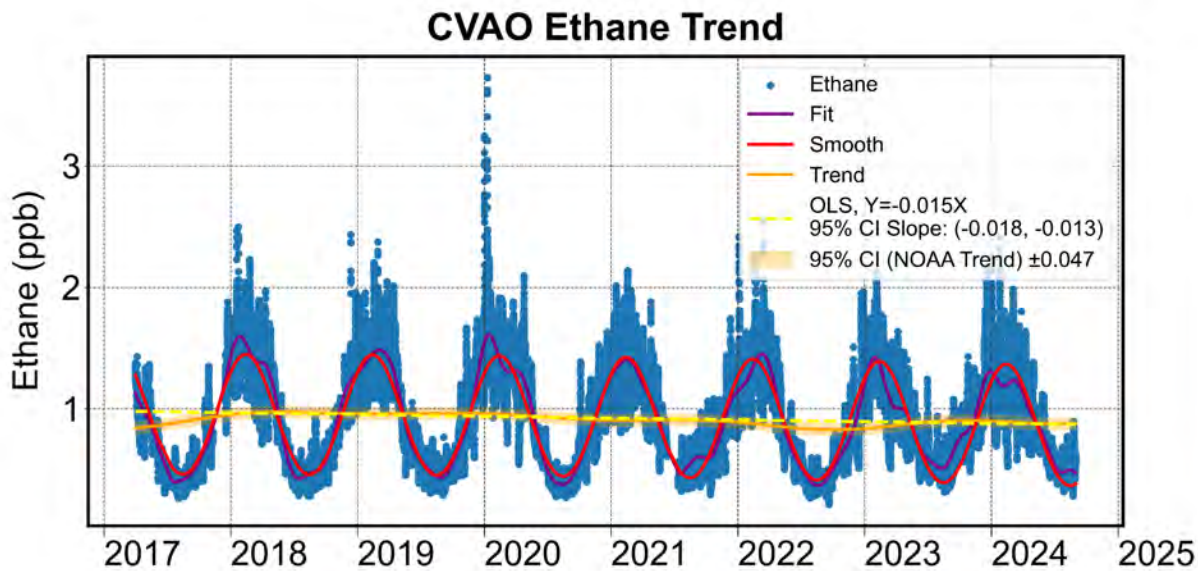


Figure C2-26. Same as C2-24 but for in-situ ethane in parts per billion for CVAO.

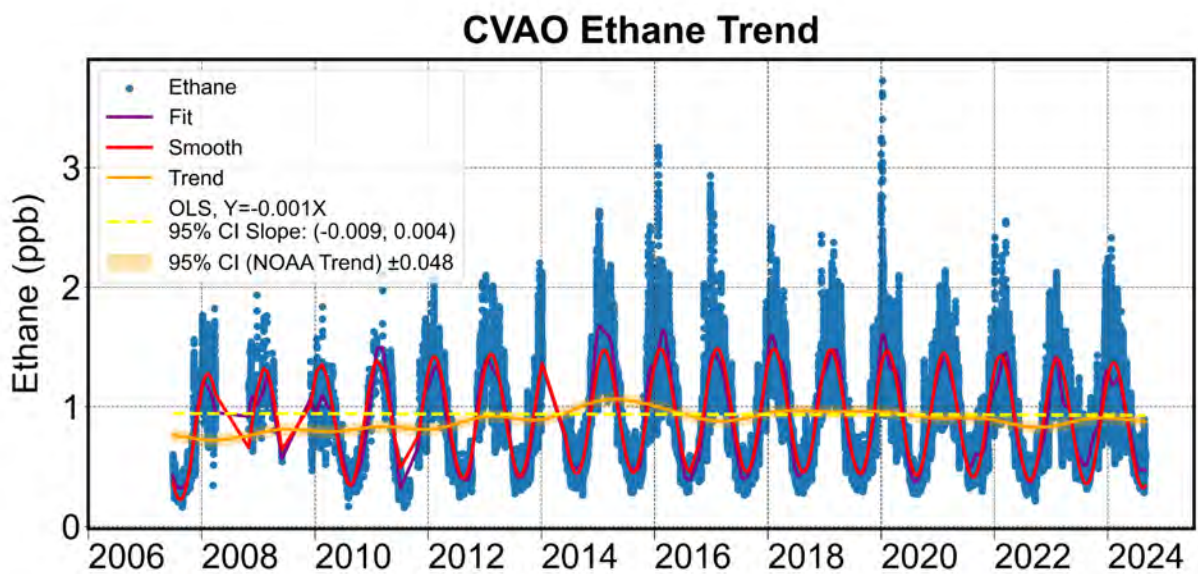


Figure C2-27. Same as C2-25 but with CVAO data starting in July 2007.

Individual Trend Plots: Methane

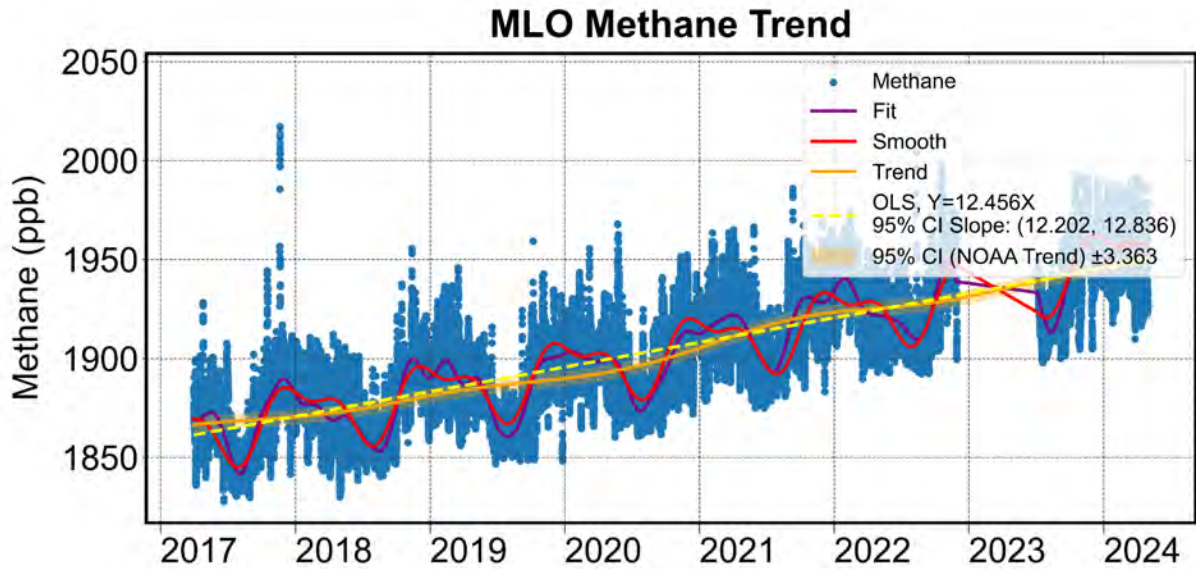


Figure C2-28. Same as C2-26 but for MLO methane with data beginning in April 2017.

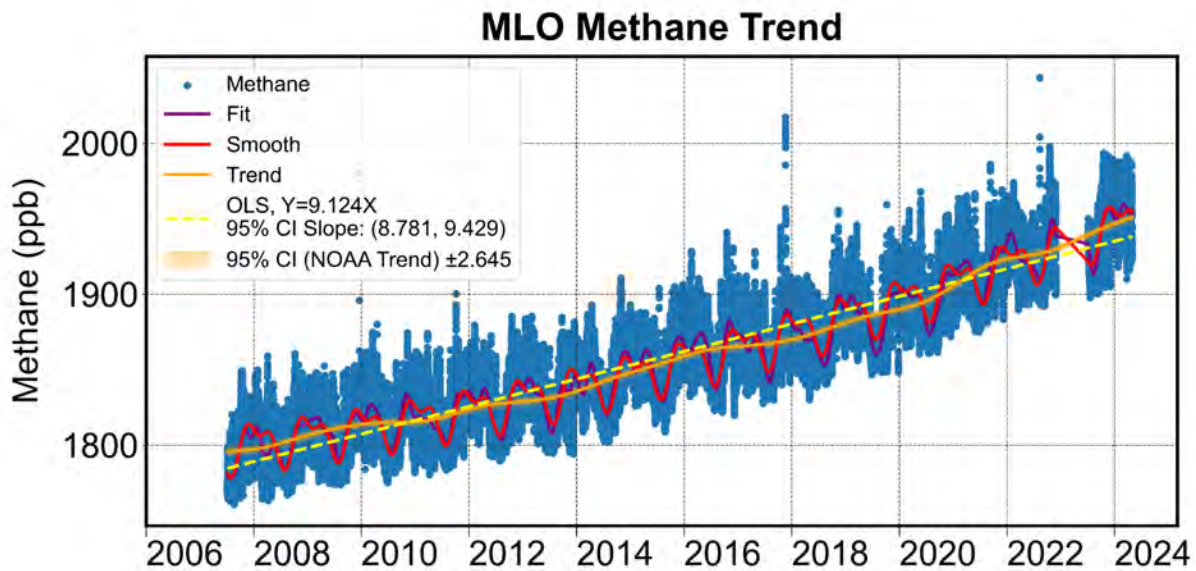
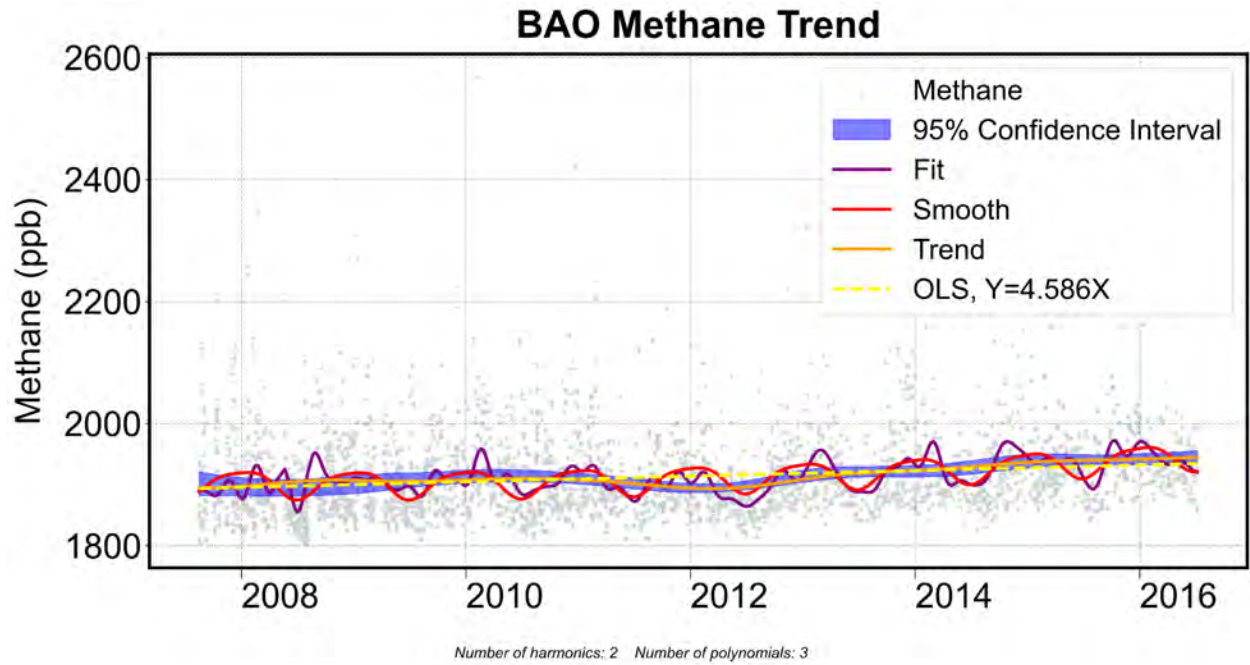
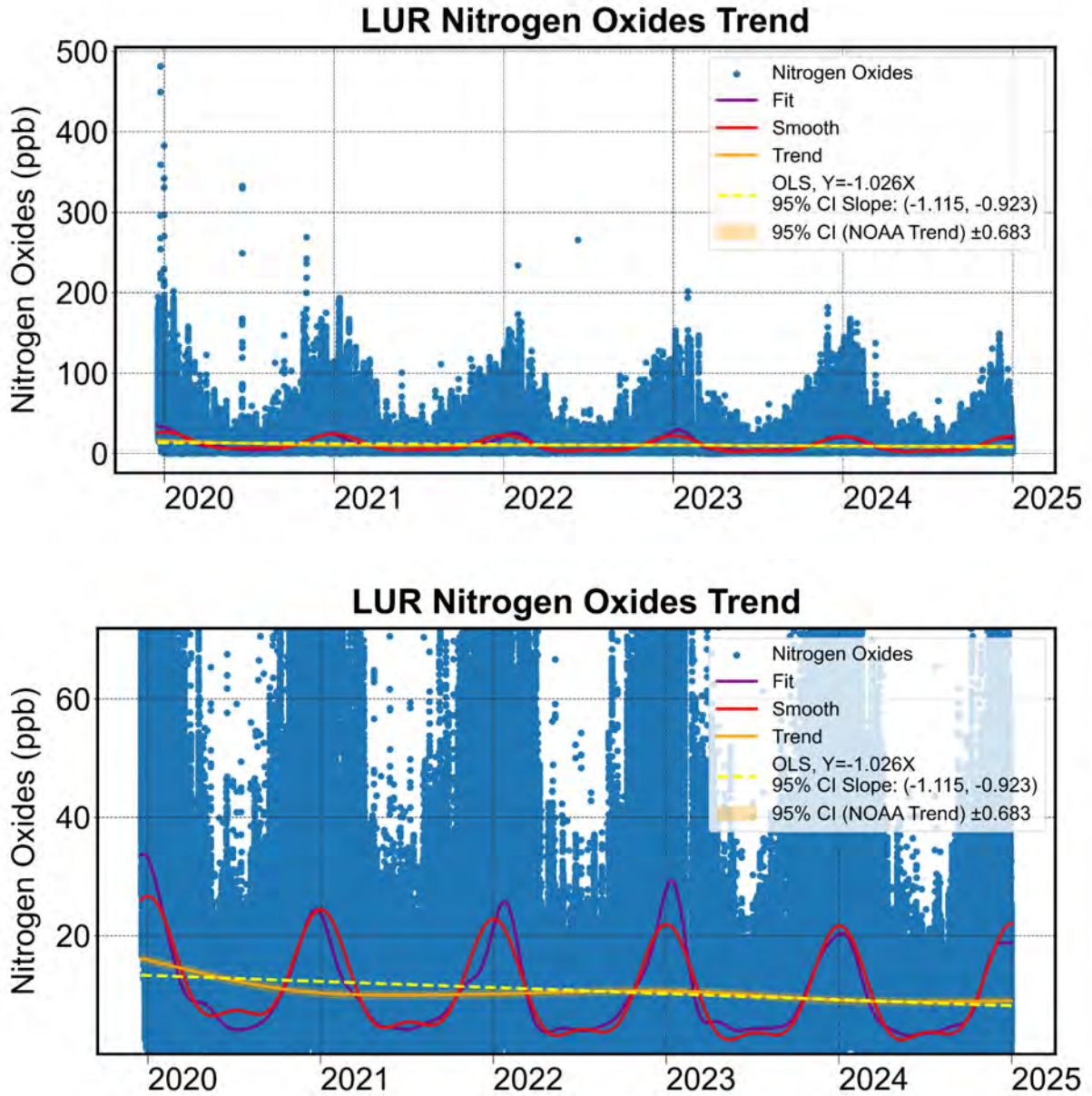


Figure C2-29. Same as C2-25 but for MLO methane with data beginning in July 2007.

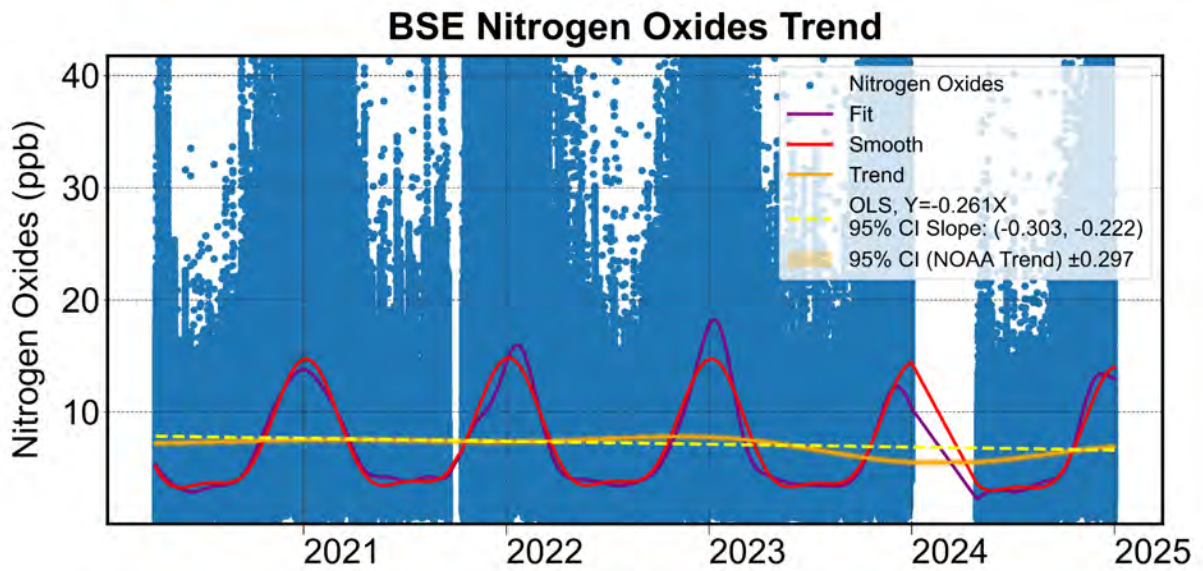
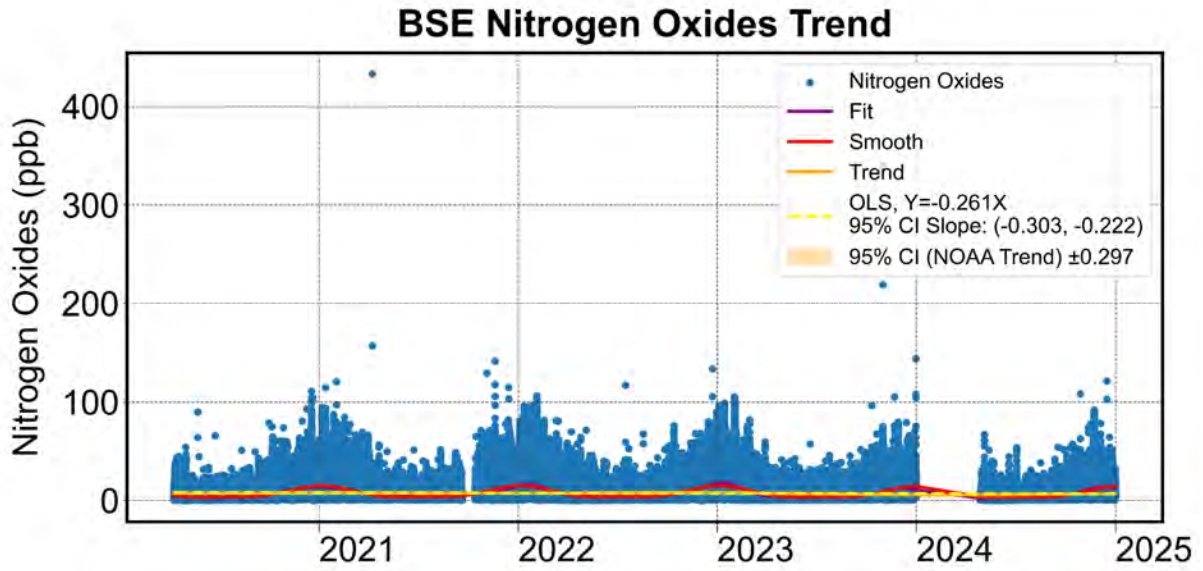


**Figure C2-30.** Same as C2-25 but for BAO methane with data beginning in August 2007 (start of sampling period).

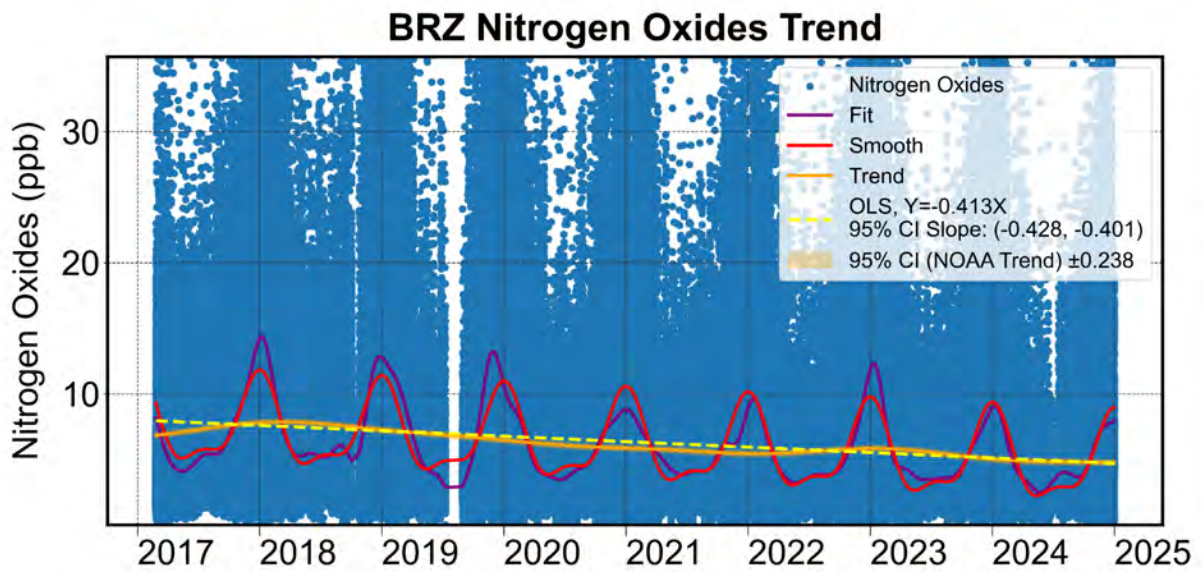
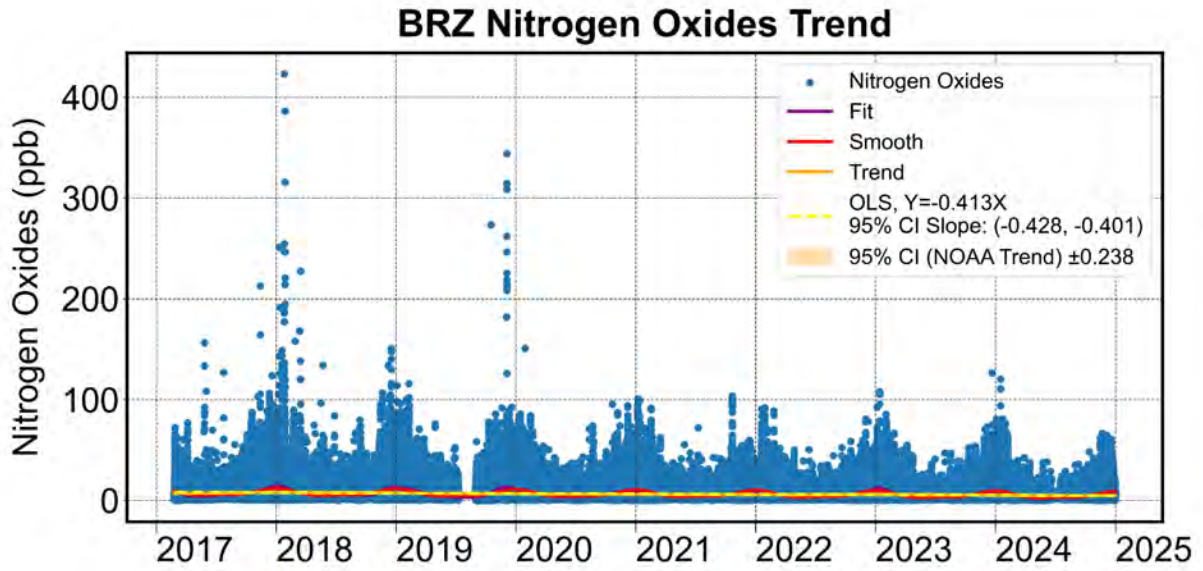
Individual Trend Plots: NO<sub>x</sub>



**Figure C2-31.** Same as C2-25 but for LUR NO<sub>x</sub>. The top plot includes the full data scale on the y-axis; the bottom plot's y-axis is restricted to zoom in on trend behaviors.



**Figure C2-32.** Same as C2-25 but for BSE  $\text{NO}_x$ . The top plot includes the full data scale on the y-axis; the bottom plot's y-axis is restricted to zoom in on trend behaviors.



**Figure C2-33.** Same as C2-25 but for BRZ  $\text{NO}_x$ . The top plot includes the full data scale on the y-axis; the bottom plot's y-axis is restricted to zoom in on trend behaviors.

## Additional Multisite Trend Analysis

**Table C2-1.** Comparison of the propane analysis slope and confidence interval calculation in parts per billion. 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 reported by the NOAA trend output.

Site	Sector	Linear Slope (ppb/yr)	Slope Confidence Interval	
			Lower	Upper
BRZ	O&G	-0.16	-0.23	-0.10
LUR	O&G	-0.75	-1.04	-0.23
BSE	O&G	-0.46	-0.55	-0.39
BNP	O&G	-0.39	-0.64	0.17
ECC	O&G	0.04	-0.12	0.32
BRZ	Western	-0.02	-0.04	-0.01
LUR	Western	-0.01	-0.03	0.01
BSE	Western	-0.04	-0.06	0.01
BNP	Western	-0.16	-0.26	-0.08
ECC	Western	-0.01	-0.04	0.03
CVAO	None	-0.01	-0.01	-0.01