VOC and Methane Emissions from U.S. Oil and Natural Gas Production

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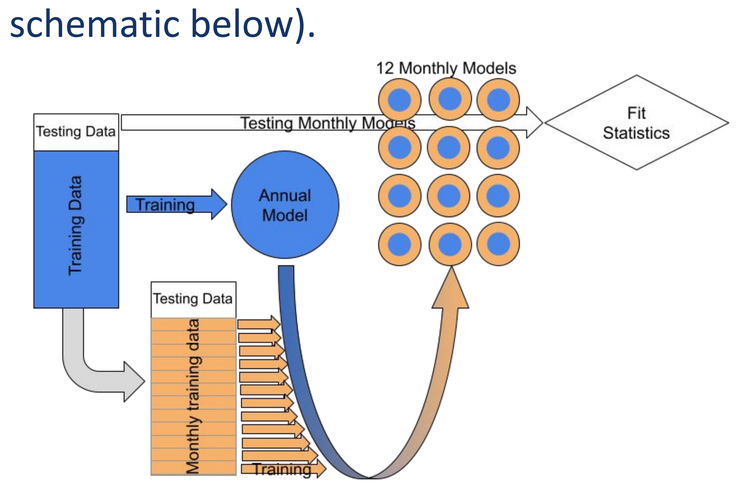
Background

- Oil and natural gas (O&G) production is associated with NOx, VOC and methane emissions.
- NOx and VOCs lead to ozone formation, affecting local and regional air quality. Methane is a potent greenhouse gas.
- These emissions are generally not well monitored. Satellite observations can help.

Instruments & Methods

- We study emissions from O&G production using satellite observations of NO_2, formaldehyde (HCHO) and methane (CH_4) from the TROPOspheric Monitoring Instrument (TROPOMI).
- TROPOMI provides daily global coverage at ~1:30pm local time, with a footprint of 3.5x5.5km^2 for NO2 and HCHO and 7x5.5 km^2 for CH_4.
- Divergence Technique: Horizontal gradients in background corrected satellite vertical columns, V_{corr}, multiplied with horizontal boundary layer wind fields, **u**, provide source location and strength of underlying emissions, E: $E = \mathbf{u} \cdot \nabla V_{corr}$
- Tensorflow machine learning (ML) deep transfer learning model framework was used to train an annualized model on 2018-2022 TROPOMI data, then retrained on monthly data subsets. Target data was GOSAT proxy retrieval measurements (see schematic below).



Formaldehyde and VOC Emissions (1)

TROPOMI observations and spatial correlation analysis show:

- Summer HCHO and NO2 Vertical Column Densities (VCDs) over the Permian basin, one of the largest O&G basins, are enhanced over areas with high production (Fig. 1a-c).
- A strong correlation between observed gases and production locations (Fig. 1d/e).
- A tighter spatial correlation of production with NO2 (Fig. 1f).

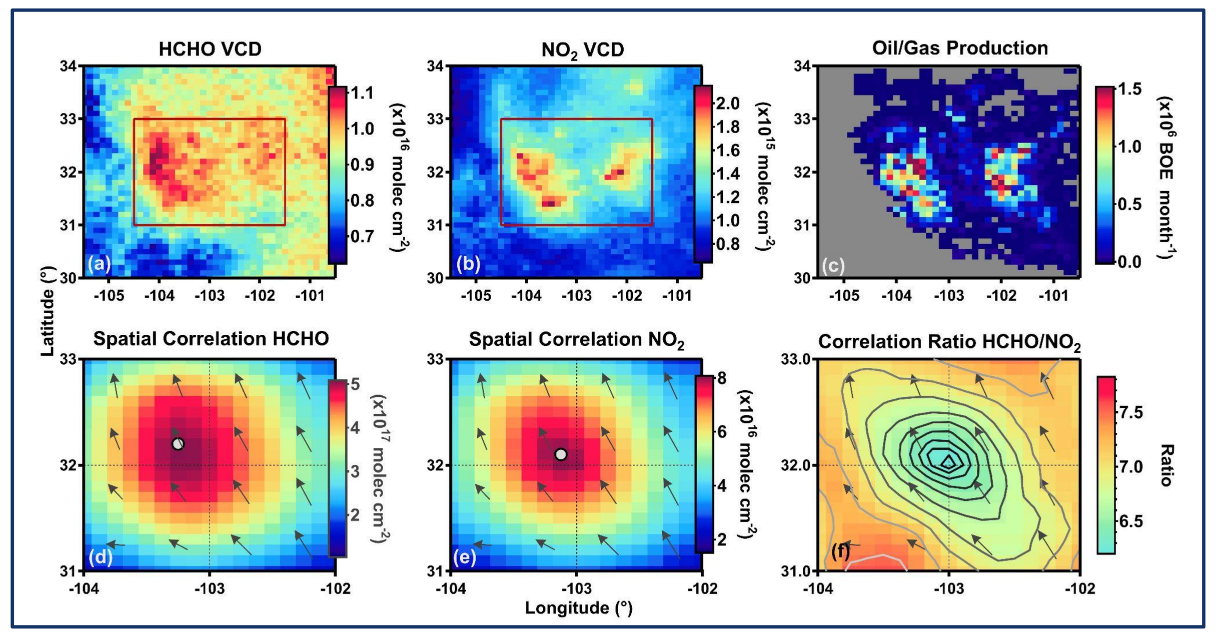


Figure 1: Top: 2018/19 summer (JJA) averages of a) HCHO and b) NO2 VCDs, and c) O&G production. Bottom: Results of spatial correlation analysis. White points mark correlation maxima; arrows indicate ECMWF wind vectors at 100 m above ground.

→ *Consistency with O&G NOx emissions and secondary HCHO formation from O&G VOCs.*

WRF-Chem sensitivity studies show:

- HCHO simulated with Fuel-based Oil and Gas (FOG) inventory NOx and VOC emissions are in good agreement with TROPOMI (Fig. 2a/b).
- O&G precursor VOCs lead to HCHO formation, as do other anthropogenic VOCS. The HCHO yield is highly sensitive to NOx (Fig. 2d/e).

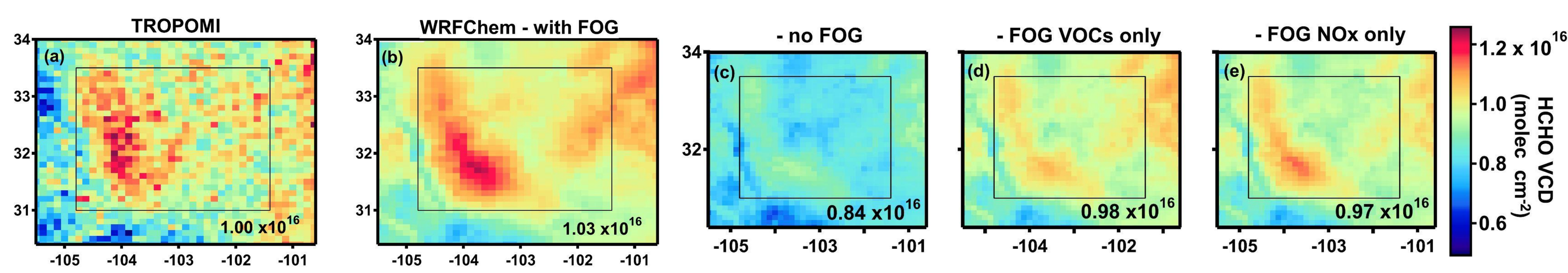


Figure 2: HCHO VCDs over the Permian basin for 10 July to 16 August, 2018, a) observed by TROPOMI, b)-d) simulated by WRF-Chem. Numbers denote average VCD for the area marked by a black box. Acknowledgements: WRF-Chem model data: Meng Li and Brian McDonald; FOG data: Colby Francoeur and Brian McDonald.

→ *O&G VOC and NOx emissions are equally important to VOC oxidation chemistry.*

Analysis of aircraft in-situ data shows:

- Observed HCHO correlates well with PAN - here a tracer for VOC oxidation - and only sporadically, in fresh emission plumes, with NOx - here a tracer for primary O&G emissions (Fig. 3).
- Multi-variate fitting of NOx and PAN to HCHO provides primary and secondary HCHO fractions.
- The NOx fit factor can be used to scale FOG NOx emissions to estimate primary HCHO emissions from O&G production (Fig. 4).

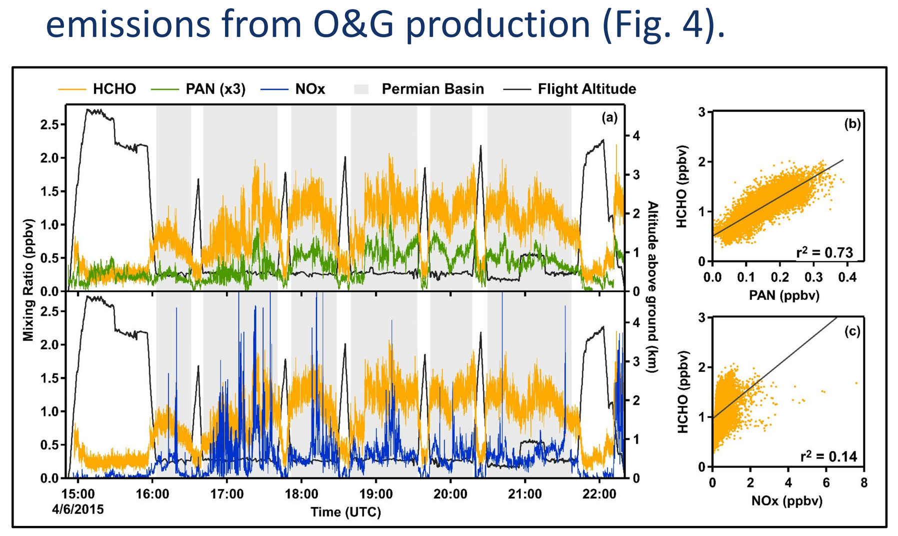


Figure 3: Flight data example from the Shale Oil and Natural Gas Nexus (SONGNEX) campaign, conducted March/April 2015 on the NOAA WP-3D. Acknowledgements: HCHO data: Thomas Hanisco, Frank Keutsch, Jason St. Clair, Glenn Wolfe; PAN data: James Roberts, Patrick Veres; NOx data: Steven Brown, Robert Wild.

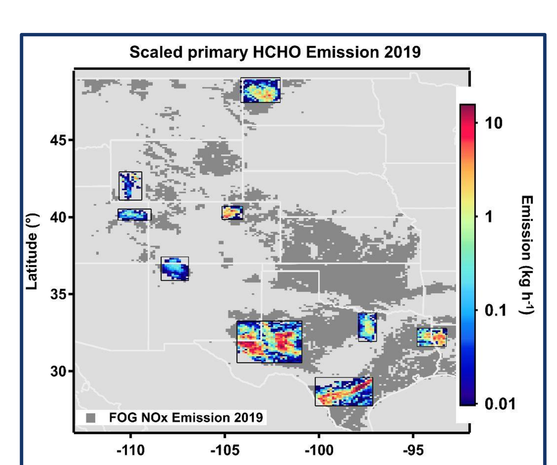


Figure 4: Estimate of O&G primary HCHO emissions for SONGNEX sampled basins. Acknowledgements: FOG data: Colby Francoeur and Brian McDonald.

→ *About 96% of observed HCHO during March/April is the product of VOC oxidation.*

→ *Total primary O&G HCHO emissions are between 6-1500 kg/h per basin.*

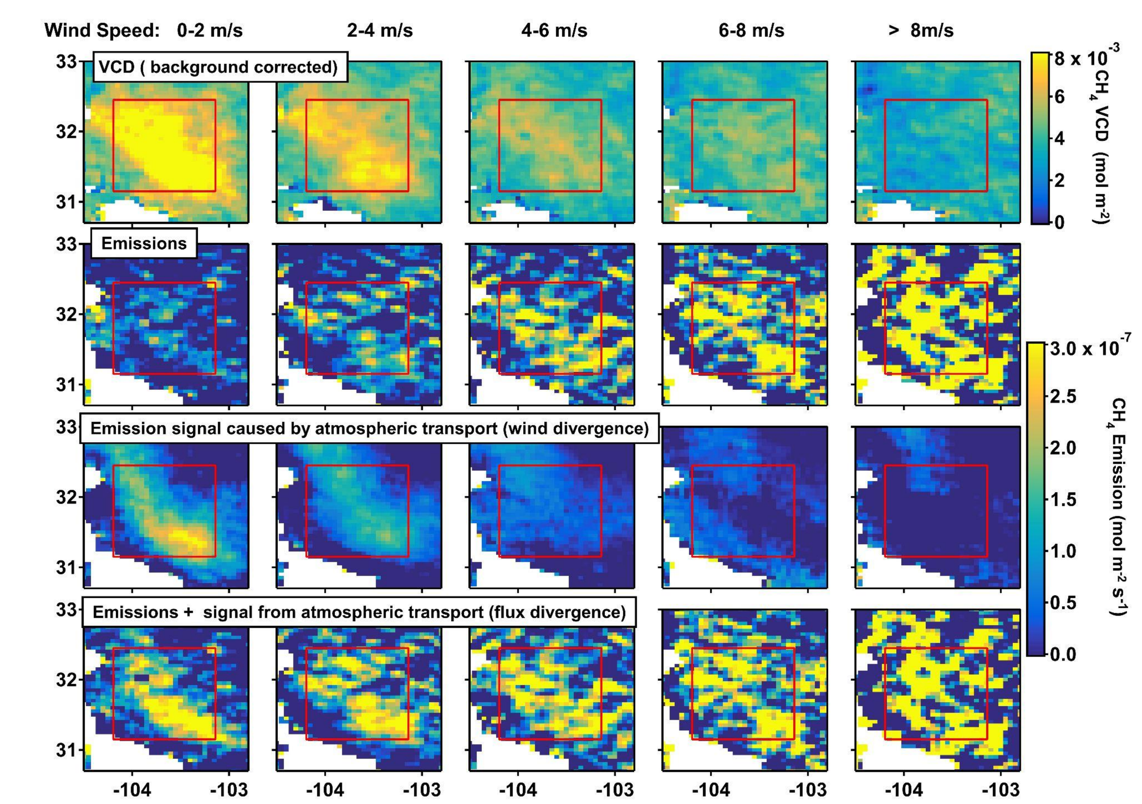
Methane Emissions in the Denver-Julesburg basin - a feasibility study

Study questions:

- Can we derive methane emissions for the Denver-Julesburg basin using TROPOMI CH_4 observations and the divergence technique?
- How are derived emissions impacted by the known ground-albedo bias in TROPOMI CH_4 VCDs and can we correct for that?
- Can we separate O&G emission from other methane sources by their seasonal signal?

Sensitivity study on deriving methane emissions for the Permian basin (strong signals/high data coverage) shows:

- Derived Emissions depend on boundary layer wind speeds (Fig. 4), which should not happen in theory.
- At low wind speeds, methane pools around sources, creating a constant offset not picked up by the divergence calculations.
- Flux Divergence results are less wind speed dependent and might account for offsets, but cause bias in source locations (Figs. 4 and 5).



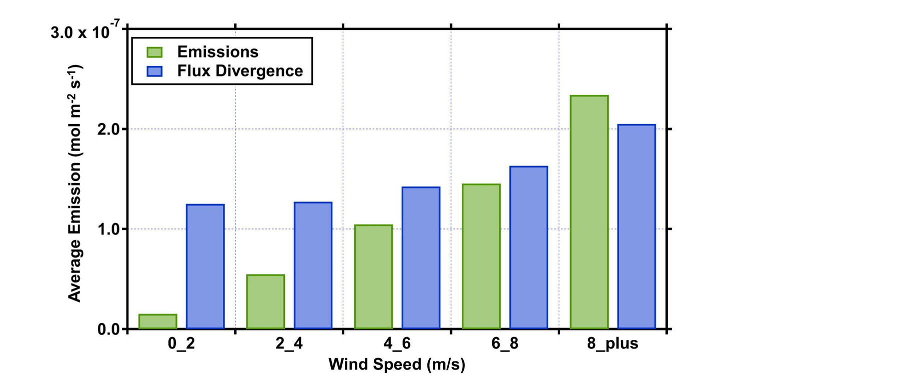


Figure 4 (left) and 5 (top): Results of sensitivity study on deriving methane emissions from 2018-2022 CH_4 VCDs over the Permian basin, separated by boundary layer wind speed bins.

→ *The long lifetime of methane (~9 years) creates biases in emissions derived with the divergence technique when the boundary layer is not efficiently vented.*

Development of seasonal methane albedo correction is motivated by:

- CH_4 columns correlate with surface albedo in the operational retrieval. Existing corrections are built on annual or longer timescales.
- Deconvoluting seasonal from non-seasonal oil & gas methane emissions could help build more accurate inventories.

Application of seasonal methane albedo correction:

- Is based on trained machine learning (ML) model with TROPOMI and GOSAT data
- Provides best correction of seasonal albedo bias compared to other correction methods (Fig. 6).

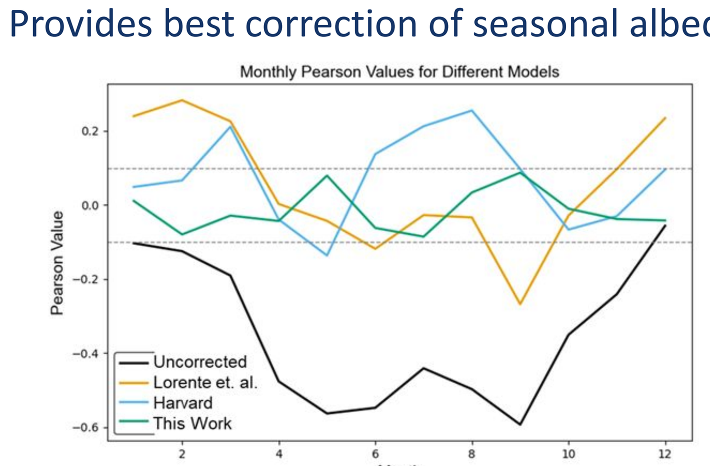


Figure 6: Pearson value compares (GOSAT XCH_4 / TROPOMI XCH_4) and surface albedo SWIR data. -0.1 < Pearson values < 0.1 are considered "no correlation" and are the ideal goal.

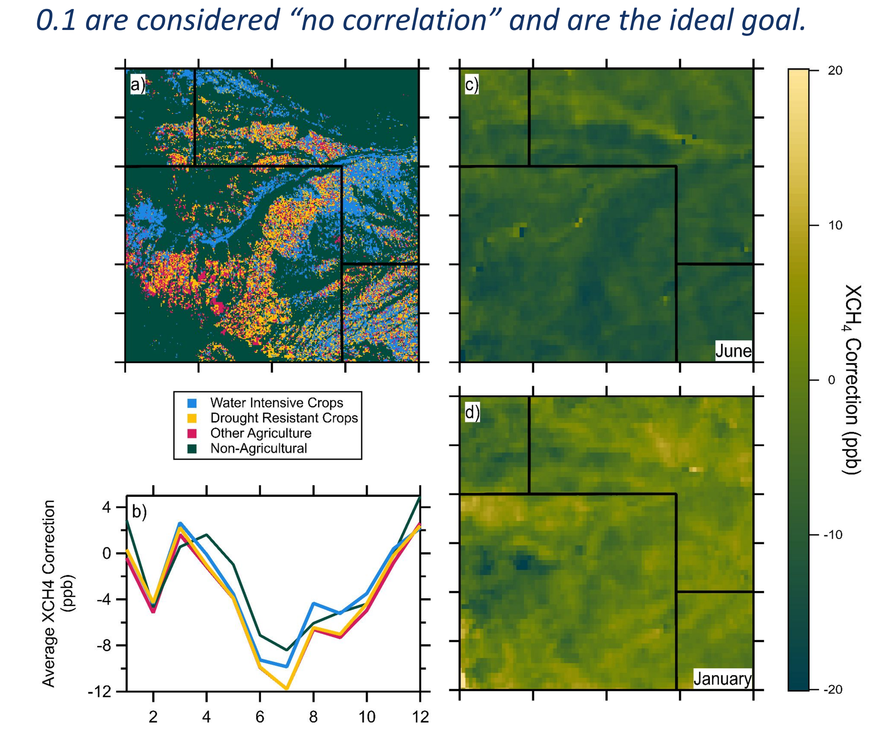


Figure 7: Agricultural land-use a) is reflected in albedo corrected CH_4 columns for summer c) and winter d). The magnitude of correction, b), has a clear seasonal cycle and is dependent on crop type.

Analysis of albedo corrected methane columns finds:

- Albedo corrected methane data shows dependence on underlying land-use structures, where different kinds of agriculture (water intensive crops: corn, sugarbeets, etc. drought resistant crops: winter wheat, dry beans, etc) tend to require different correction values (Fig 7a/c/d).
- Average correction values over each land-use type are distinctly different and show seasonality across the entire year, with larger corrections needed in the summer and smaller corrections needed in the winter (Fig. 7b).

Effect of seasonal albedo correction on derived emissions is:

- Preliminary! The Denver-Julesburg basin is a small area with comparatively low data statistics, which can lead to artefacts in retrieved emissions. Furthermore, winds and data statistics vary by season as well.
- Significant. Retrieved emissions are generally lower (Fig. 8) and more in line with other top-down estimates.

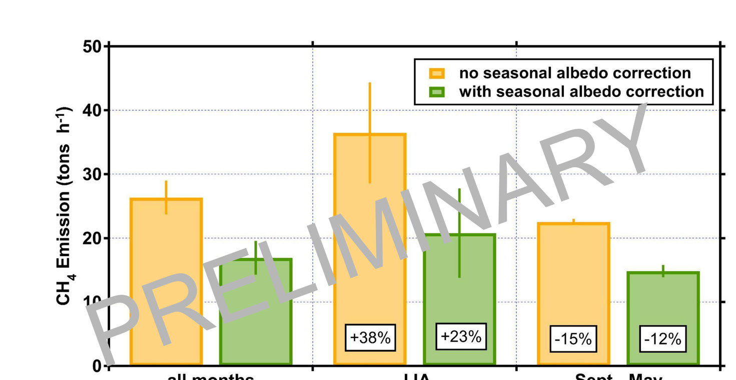


Figure 8: Effects of seasonal albedo correction on CH_4 emission retrieval from the Denver-Julesburg basin.

→ *CH_4 columns contain a significant seasonal albedo bias that is successfully addressed with our new, seasonal bias correction.*

References

(1) Barbara Dix, Meng Li, Esther Roosenbrand, Colby Francoeur, Steven S. Brown, Jessica B. Gilman, Thomas F. Hanisco, Frank Keutsch, Abigail Koss, Brian M. Lerner, Jeff Peischl, James M. Roberts, Thomas B. Ryerson, Jason M. St. Clair, Patrick R. Veres, Carsten Warneke, Robert J. Wild, Glenn M. Wolfe, Bin Yuan, J. Pepijn Veefkind, Pieternel F. Levelt, Brian C. McDonald, and Joost de Gouw: **Sources of Formaldehyde in U.S. Oil and Gas Production Regions**, ACS Earth and Space Chemistry (2023).

Acknowledgements

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