Low-Earth orbit and geostationary remote sensing for inferring surface NO_2 exposure and public health impacts

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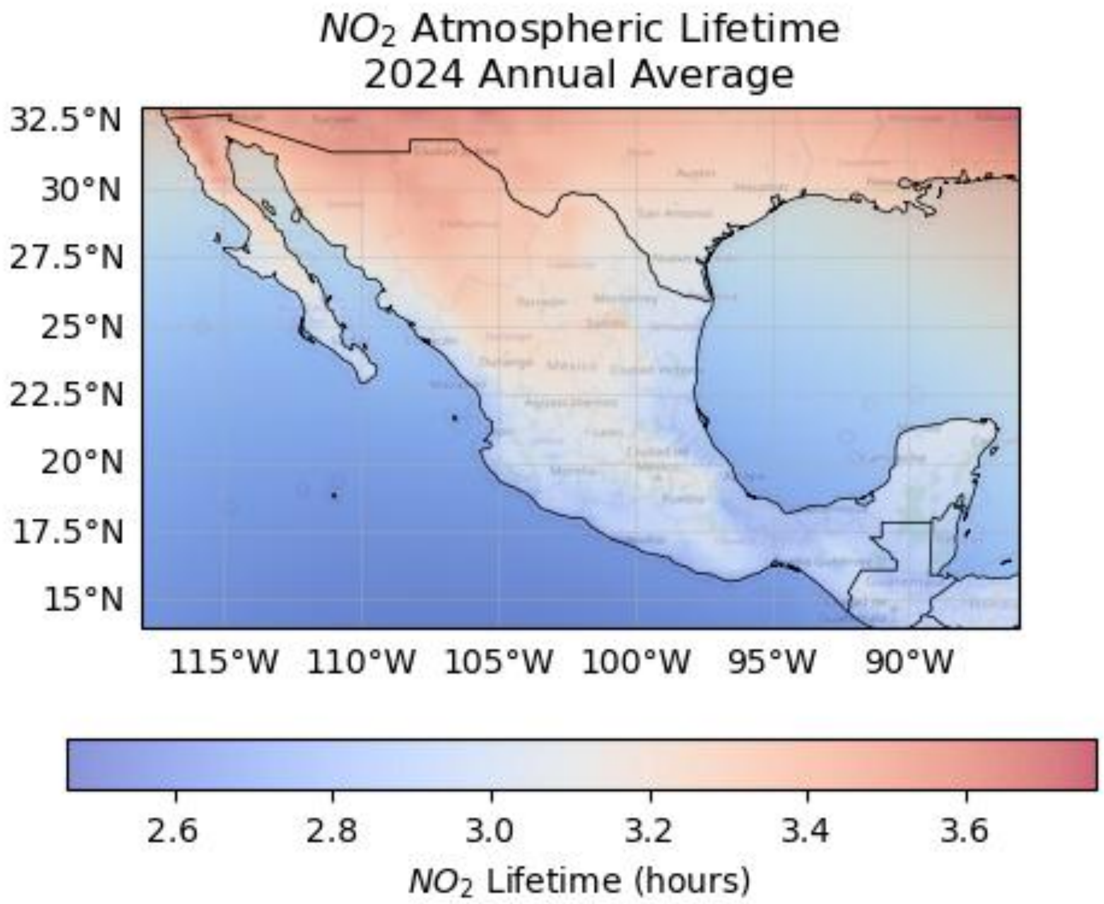
Motivation

- Nitrogen Dioxide (NO_2) linked to childhood asthma and premature death
- Short atmospheric lifetime means steep near-source gradients
- Once per day overpass of typical LEO satellites combined with sharp spatial gradients makes surface NO_2 difficult to model and validate

What can geostationary remote sensing reveal about NO_2 exposure and public health at the surface?



NO_2 lifetime to OH loss at TROPOMI overpass over Mexico from Nawaz et al. in Preparation

Low-Earth orbit and geostationary NO_2 observation

Instrument	Orbit	Temporal Fidelity	Spatial Coverage
TROPOMI	Low-Earth orbit	One daytime overpass (~13:30)	Near-global at 3.5 × 5.5 km^2
GEMS	Geostationary	Hourly, daylight	Asia at 3.5 × 8.0 km^2
TEMPO	Geostationary	Hourly, daylight	North America at 2.0 × 4.75 km^2
Sentinel 4	Geostationary	Hourly, daylight	Europe at 8.0 × 8.0 km^2

Focus of this presentation

Instrument	Orbit	Temporal Fidelity	Spatial Coverage
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***Caveat:* All TEMPO results in this presentation are using V3**

The problem: columns aloft vs surface exposure

Column NO_2 — what satellites measure (molec cm^{-2})

↓ *inference*

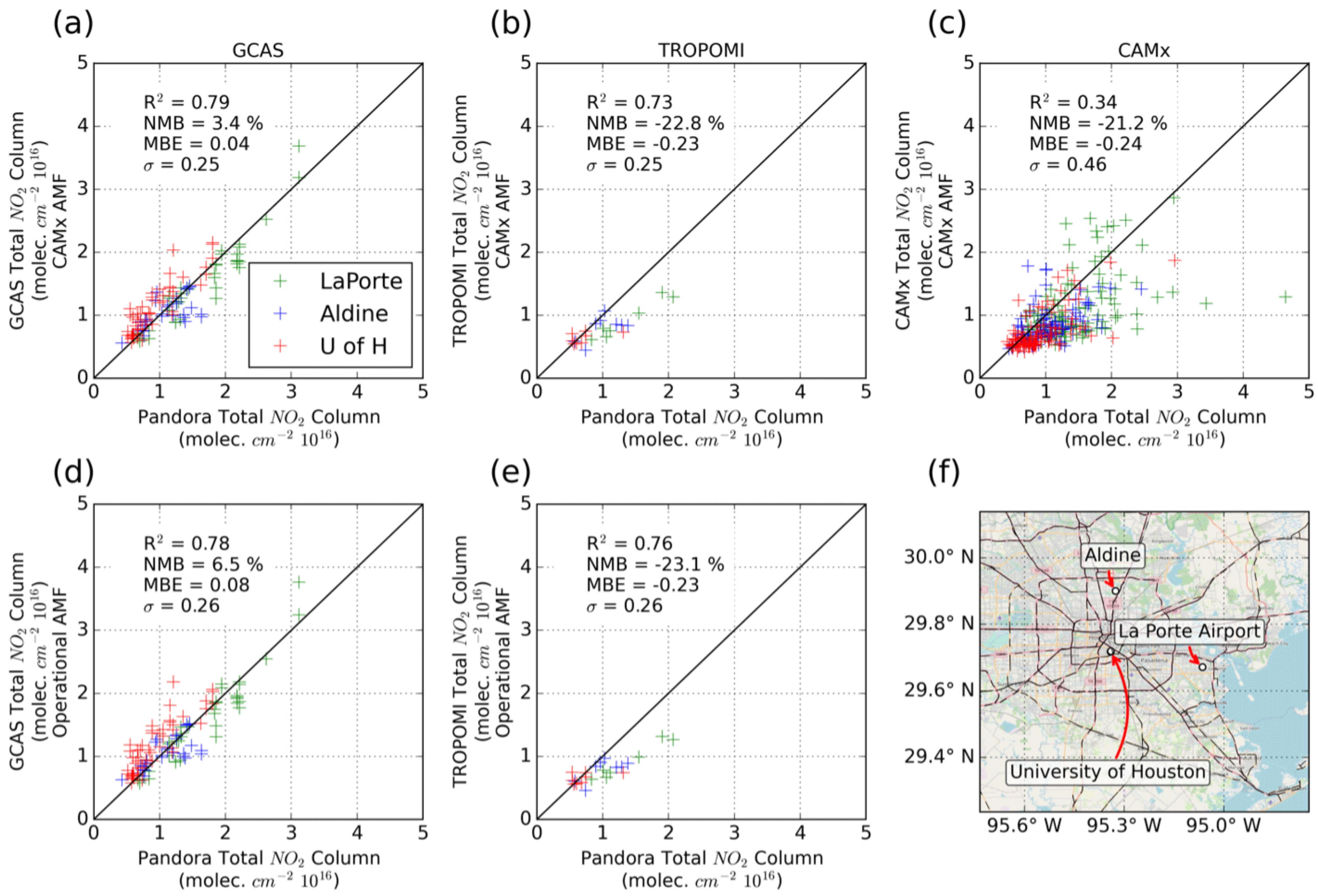
Surface NO_2 — what drives exposure (ppb)

Two families of methods bridge the gap:

Statistical: land-use regression modelling, machine learning, kriging approaches, etc.

Deterministic: flux divergence, CTM downscaling, etc.

How does remote sensing compare to ground-based monitoring?



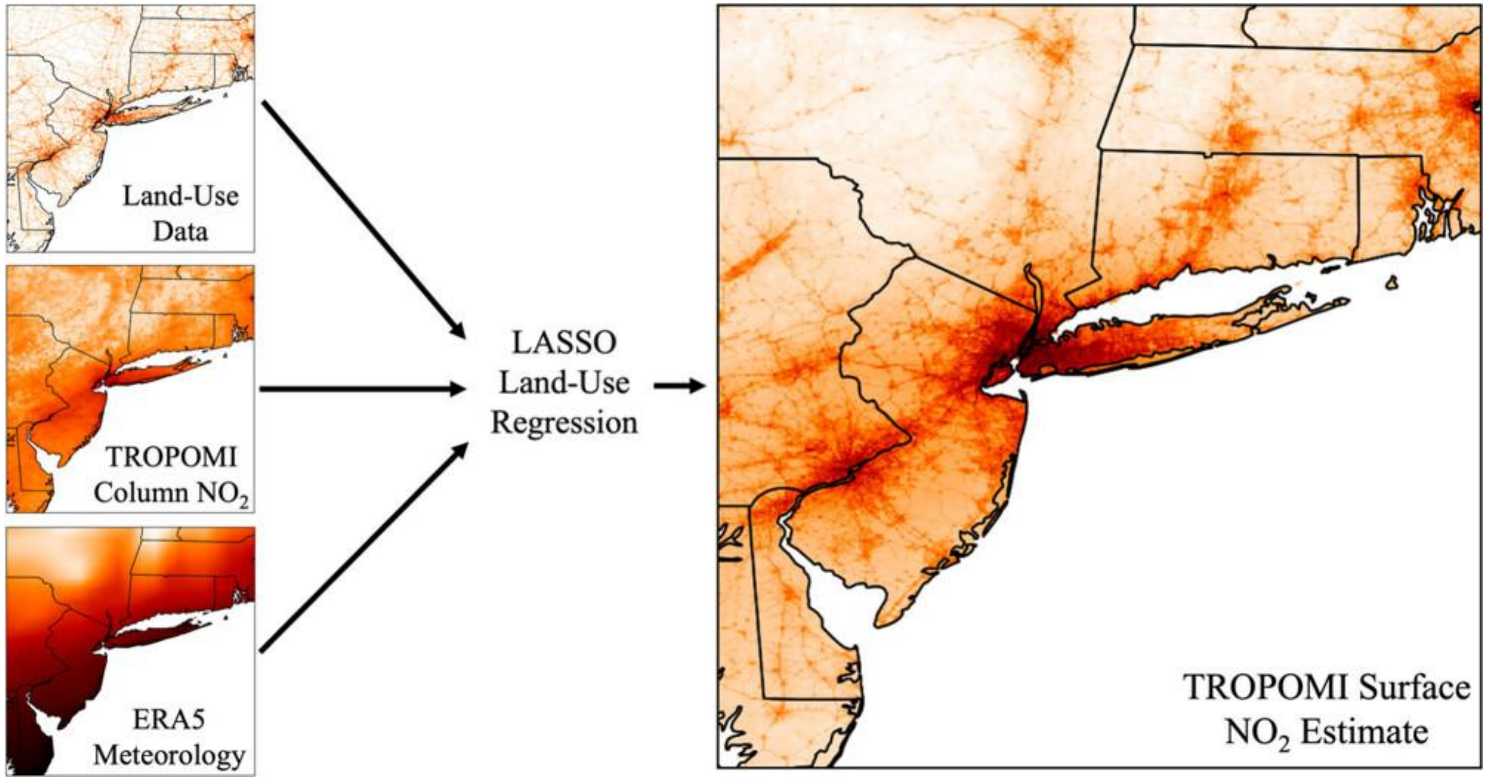
GCAS (airborne), TROPOMI (satellite) and WRF-CAMx (modelled) NO_2 columns over Houston 2021 during TRACER-AQ
Nawaz et al. 2024, ACP

Pandora comparison:

- GCAS (airborne) R^2 = 0.79
- TROPOMI (satellite) R^2 = 0.73
- WRF-CAMx (modelled) R^2 = 0.34, biased low (NMB −21%)

WRF-CAMx agreement was worse at the surface implicating under-resolved local sources or vertical mixing too strong

Statistical approach I: land-use regression with TROPOMI



- Trained LUR on EPA AQS
- **Predictor variables:** oversampled TROPOMI, ERA5 meteorology and land use data (e.g., OSM road systems)
- Adjusted $R^2 = 0.72$ compared to legacy OMI LUR of $R^2 = 0.54$
- Mean bias 14.2% compared to OMI LUR: 49%
- Yields monthly and annual exposure surfaces for health and equity analysis

TROPOMI LUR applications for EJ and health

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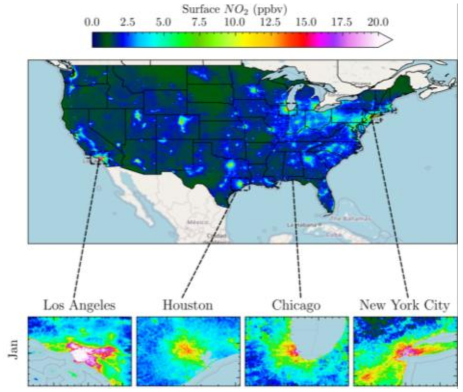
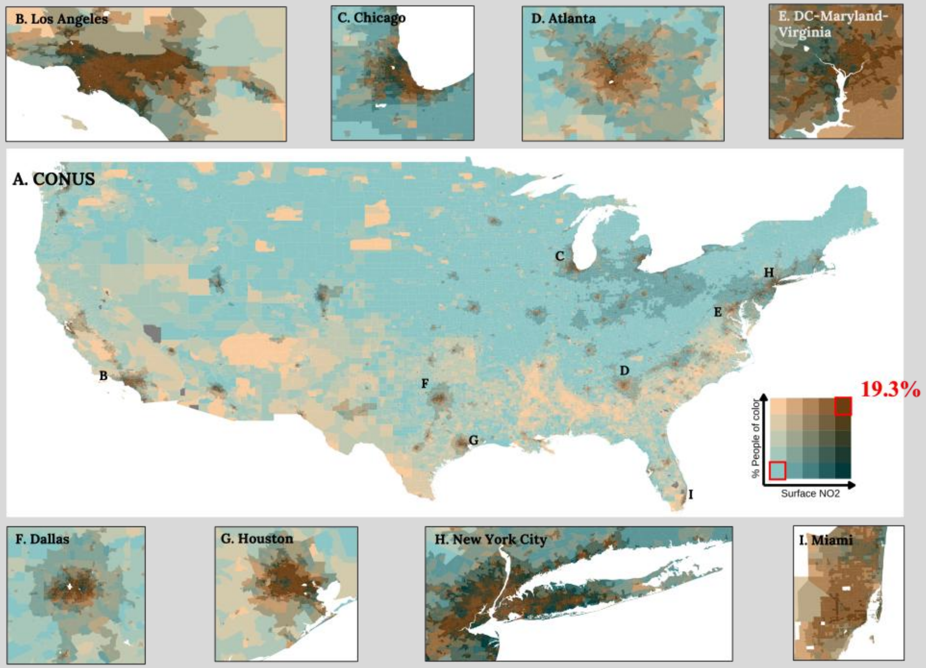
TROPOMI Satellite Data Reshape NO_2 Air Pollution Land-Use Regression Modeling Capabilities in the United States

M. Omar Nawaz*, Daniel L. Goldberg, Gaige H. Kerr, and Susan C. Anenberg





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Census-level NO_2 environmental injustices

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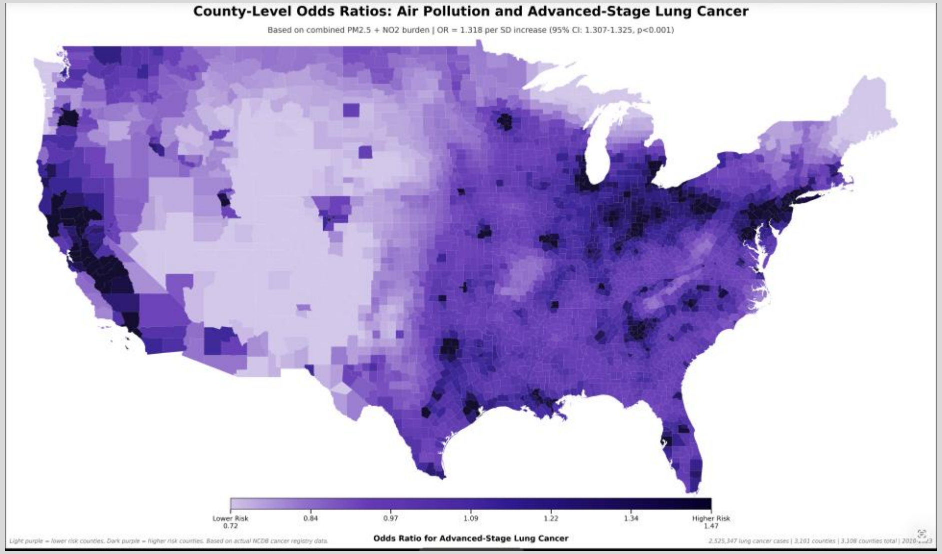
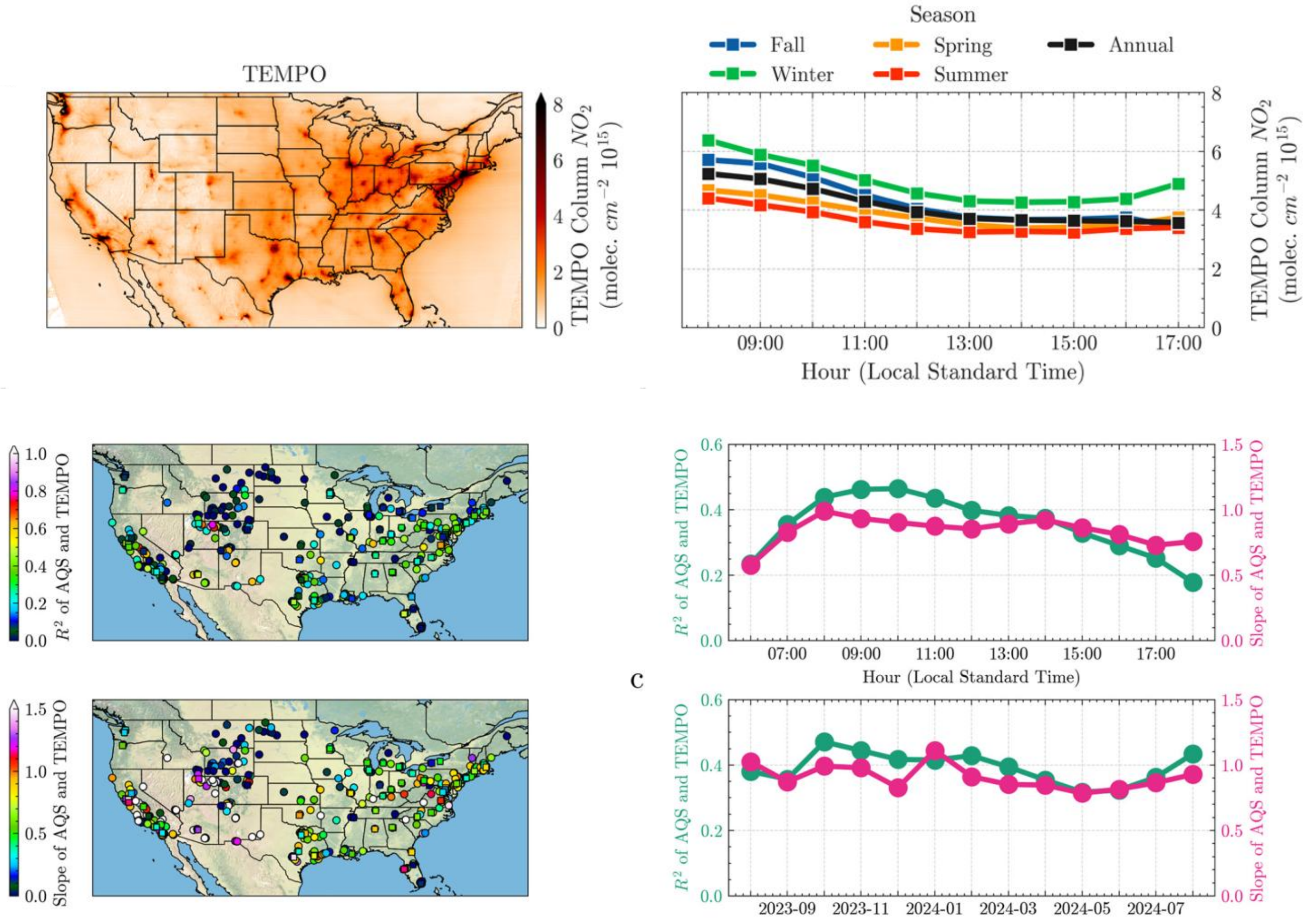
Associating NO_2 exposure with advanced stage lung cancer



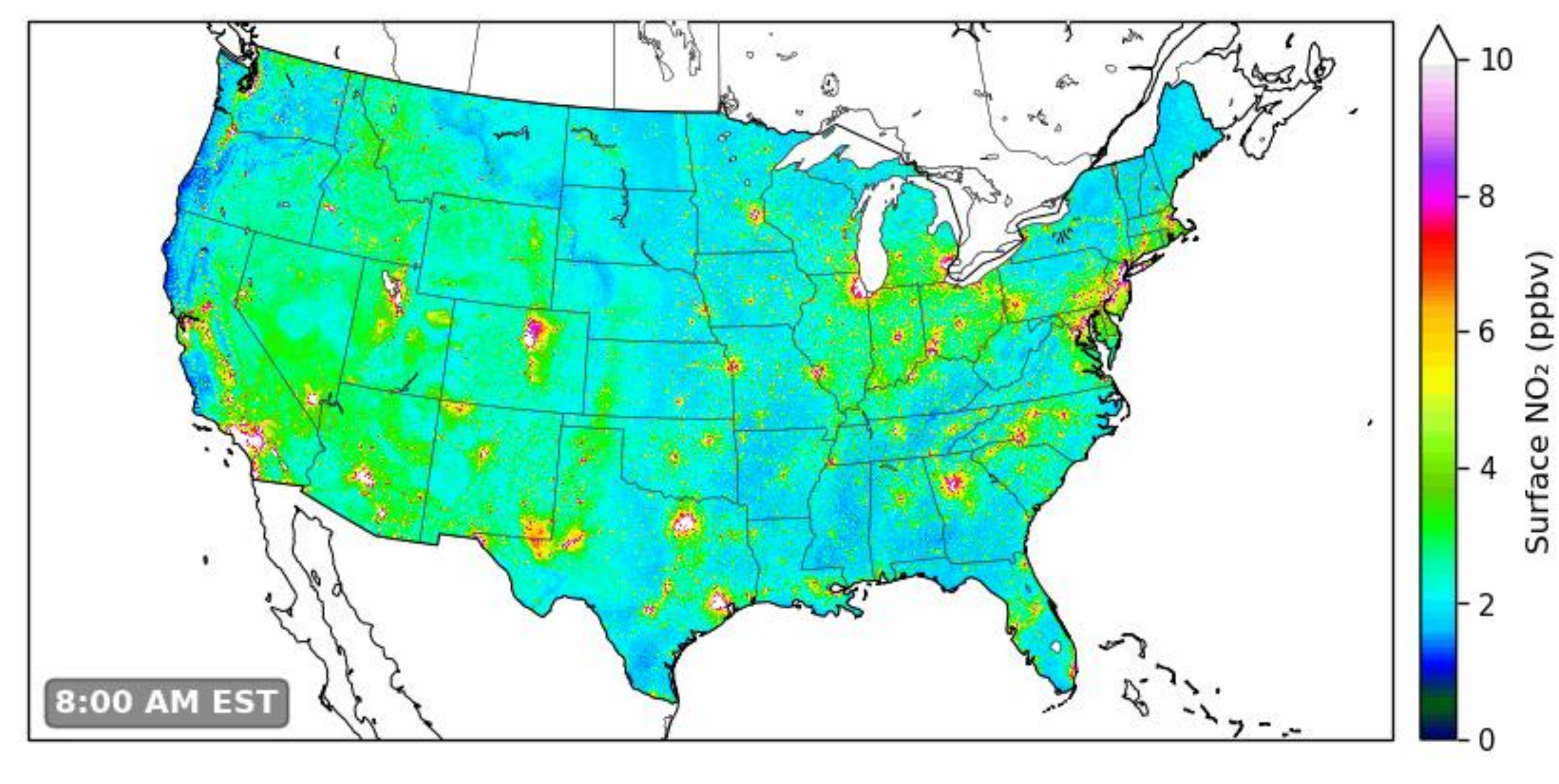
Resolving the NO_2 diurnal cycle with TEMPO



Nawaz et al. 2025, JGR Atmospheres

- Hourly "annual-average" correlation of R^2=0.61 of TEMPO compared to EPA AQS monitors (not near road)
- At TROPOMI overpass time: TEMPO SCDs (R^2=0.72), TEMPO VCDs (R^2=0.66), TROPOMI (R^2=0.65)
- Strong diurnal dependence on correlation

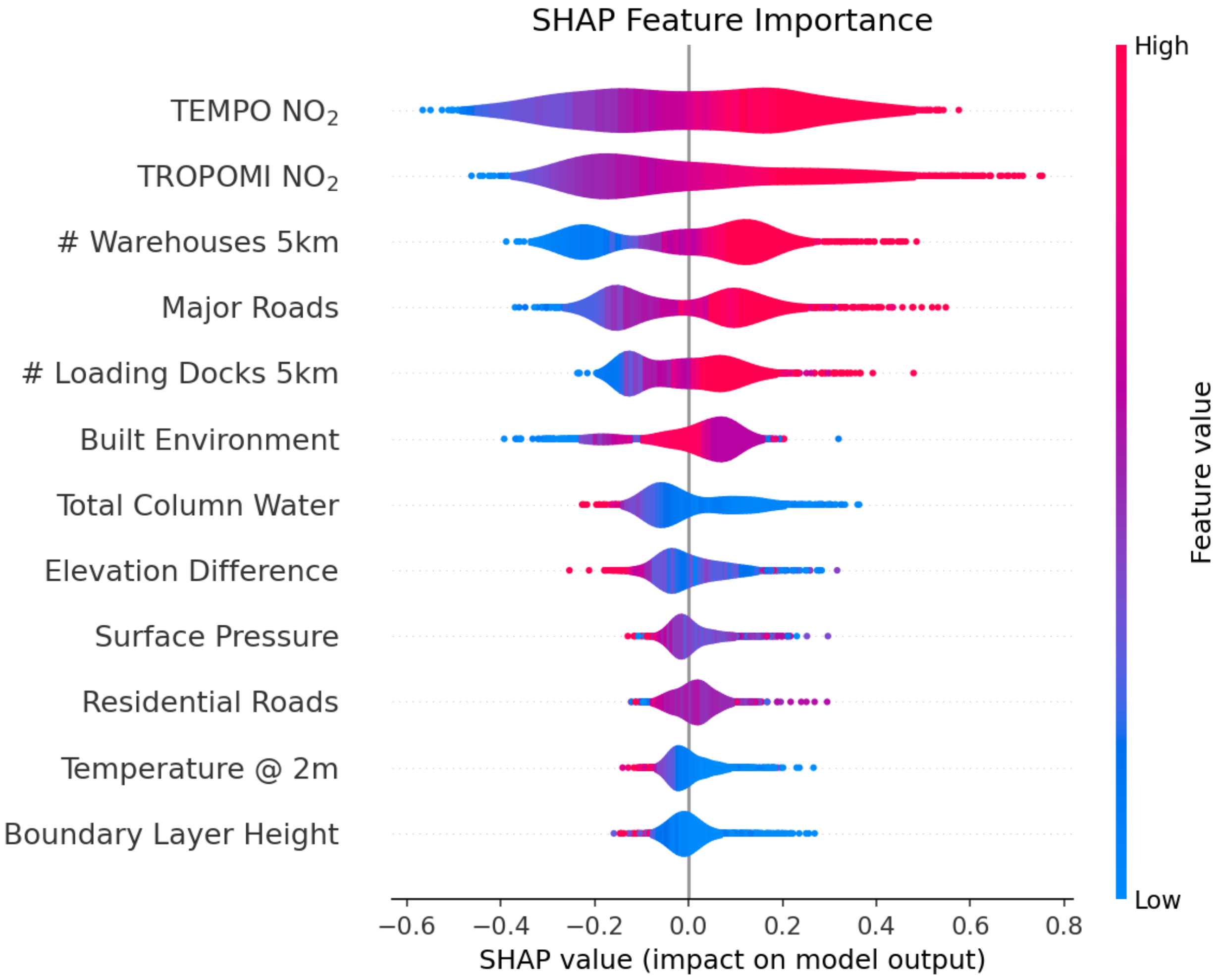
Inferring hourly surface NO_2 with Machine Learning & TEMPO



- Gradient-boosting random forest regression
- **Predictor variables:** TEMPO, TROPOMI, land use data, and meteorology
- Improvement over LUR: 10-fold CV R^2=0.93 normalised mean bias +5.5%

From Chen et al. in Preparation

Which predictors drive the estimate?



- SHAP analysis approach is used to compute the marginal contributions of predictor variables to the prediction
- TEMPO column NO_2 is the leading predictor followed by TROPOMI and then land-use information
- Meteorological variables have a smaller effect

Conclusions and future directions

Conclusions

- Finer space/time remote sensing improves our ability to infer surface NO_2 and exposure
- Satellite columns allow us to diagnose chemical-transport-model biases
- A growing NO_2 health-burden literature supports stricter, more equitable air-quality policy

Future directions

- Flux divergence approaches using geostationary columns for time-resolved NO_x emissions
- Hourly air pollution exposure assessments with wide spatial coverage
- Geostationary observations are needed for the Global South, how do we deal with data sparsity?

If you would like to collaborate on any of these, please reach out: nawazm3@cardiff.ac.uk

Thank you

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