High-Resolution Urban Emission Mapping: Sensor-Driven CO_2 Inverse Modeling in Glasgow

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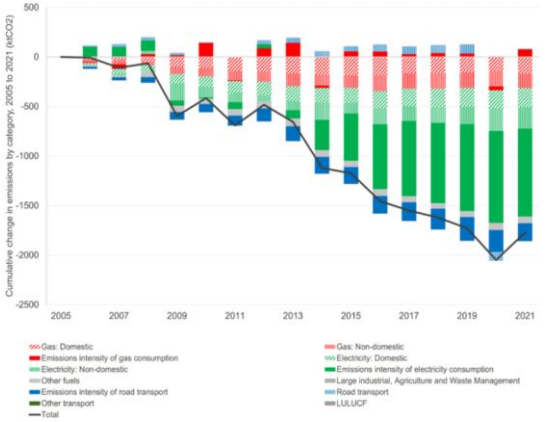
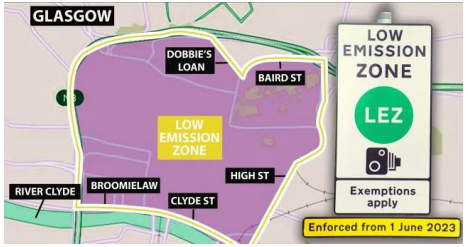
Background

- Urban CO_2 emissions account for approximately 70% of global anthropogenic CO_2 emissions.
- Emission estimates are complex due to lack of fine-grained data, hence need accurate emission estimations in city scale.
- Need for more observations to achieve targeted emission reduction strategies and updating existing emission inventories.
- Glasgow has set a Net Zero carbon target by **2030.**
- Almost 50% reduction in CO2 emissions in Glasgow city in last 20 years.





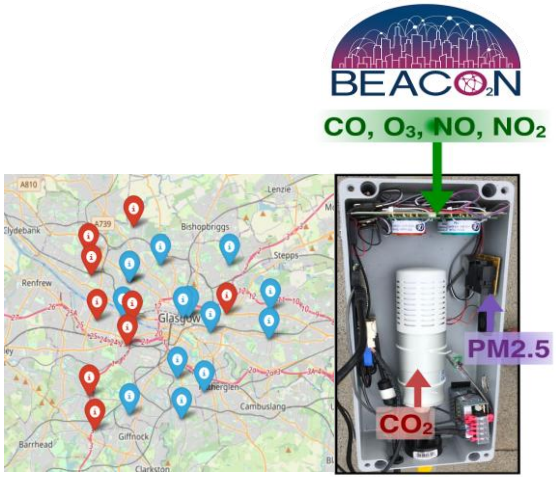
Transport, electricity, and buildings account for most of the reductions

Data and Methods

Berkley Environmental Air quality and CO_2 Network

*Part of the **Glasgow Environmental Monitoring of Indoor and Outdoor Air (GEMINOA)** Project*

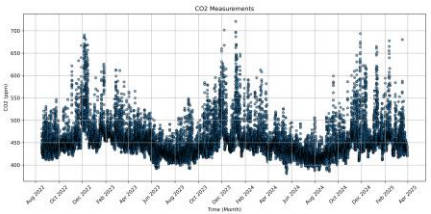
- Deployed CO_2 sensors in schools throughout Glasgow
- High-resolution, minute-by-minute CO_2 concentration data
- Spatial concentration footprints across the city

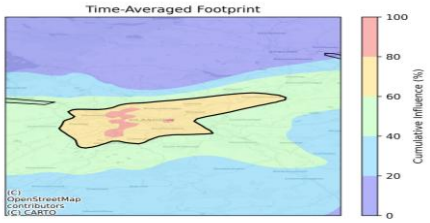


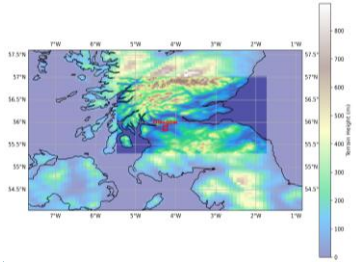
Vaisala CarboCap
GMP343 CO2 sensor

Data and Methods

Inverse modelling framework for Glasgow







$$J(x) = (x - x_a)^T B^{-1}(x - x_a) + (y - Hx)^T R^{-1}(y - Hx)$$

$$\frac{\partial J(x)}{\partial x} = 0$$

$$x = x_a + BH^T(R + HBH^T)^{-1}(y - Hx_a)$$

National Atmospheric Emissions Inventory

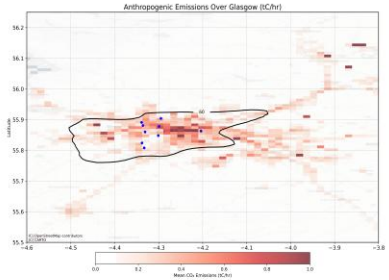
Lagrangian Transport model (STILT)

High-resolution met data(3km) –WRF model

BEACO$_2$N hourly data
Prior emission/flux data
Background CO$_2$

Inverse modelling set up

Jena CarboScope
Data-based estimates of carbon cycle variability



Posterior Estimates

B - Prior error covariance matrix
H - STILT footprints
R - model-data mismatch error covariance matrix
x - State vector posterior
x_a - Prior estimate
y - observation

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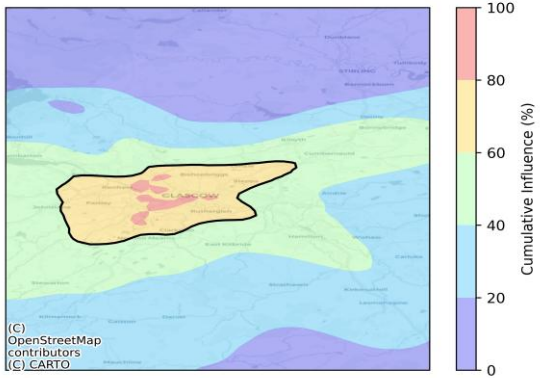
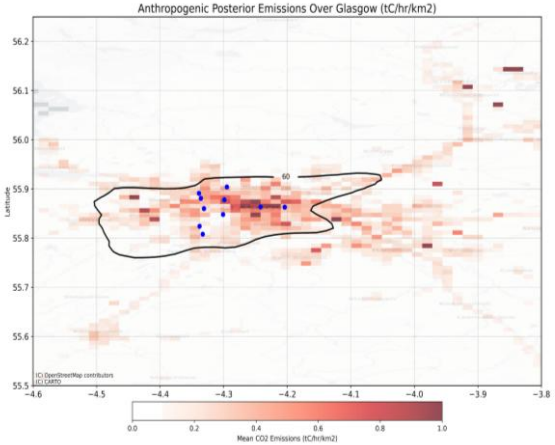
Adjusted emission map for Glasgow

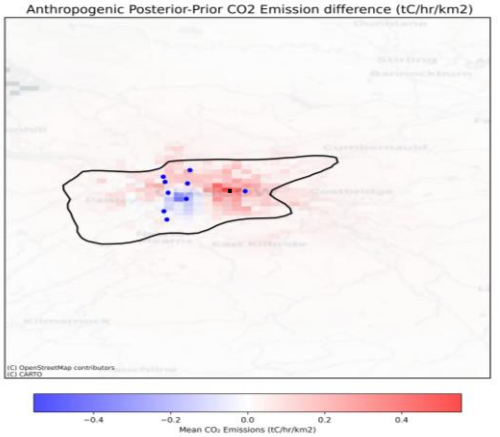
Sensitivity to Receptor sites



Mean Anthropogenic Emissions

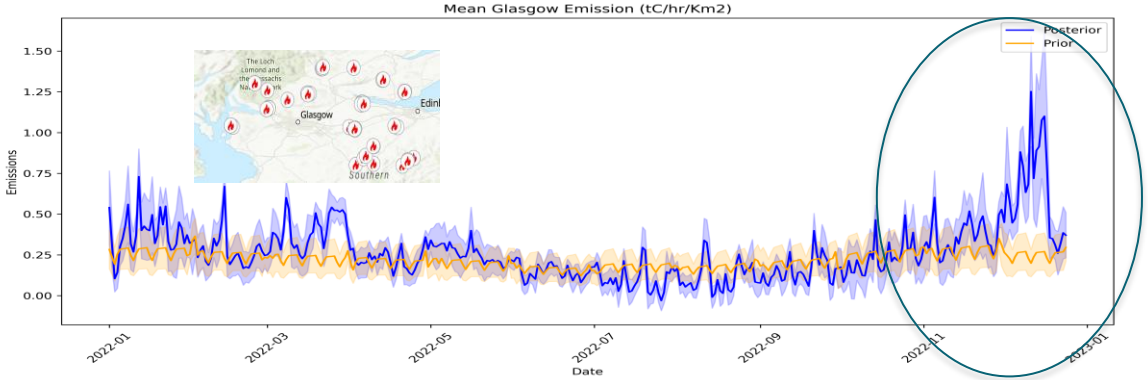


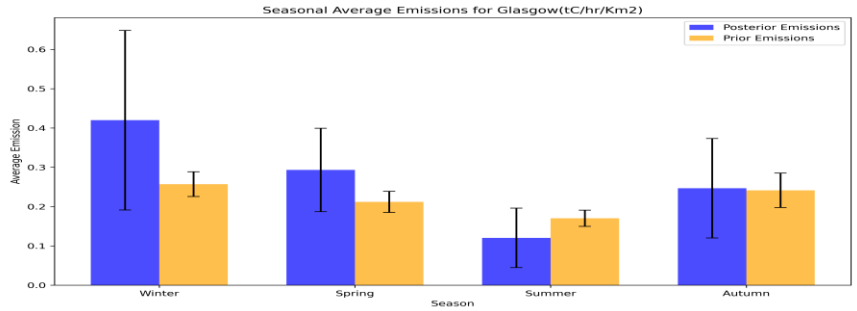
Difference between Posterior and Prior CO2 emissions



- The city center shows the largest discrepancies between prior and posterior emissions.
- The posterior estimate reflects a **23% increase** in CO_2 emissions compared to the prior.
- This corresponds to an additional **475 $ktCO_2e$** beyond what is reported by local bottom-up activity data in 2022

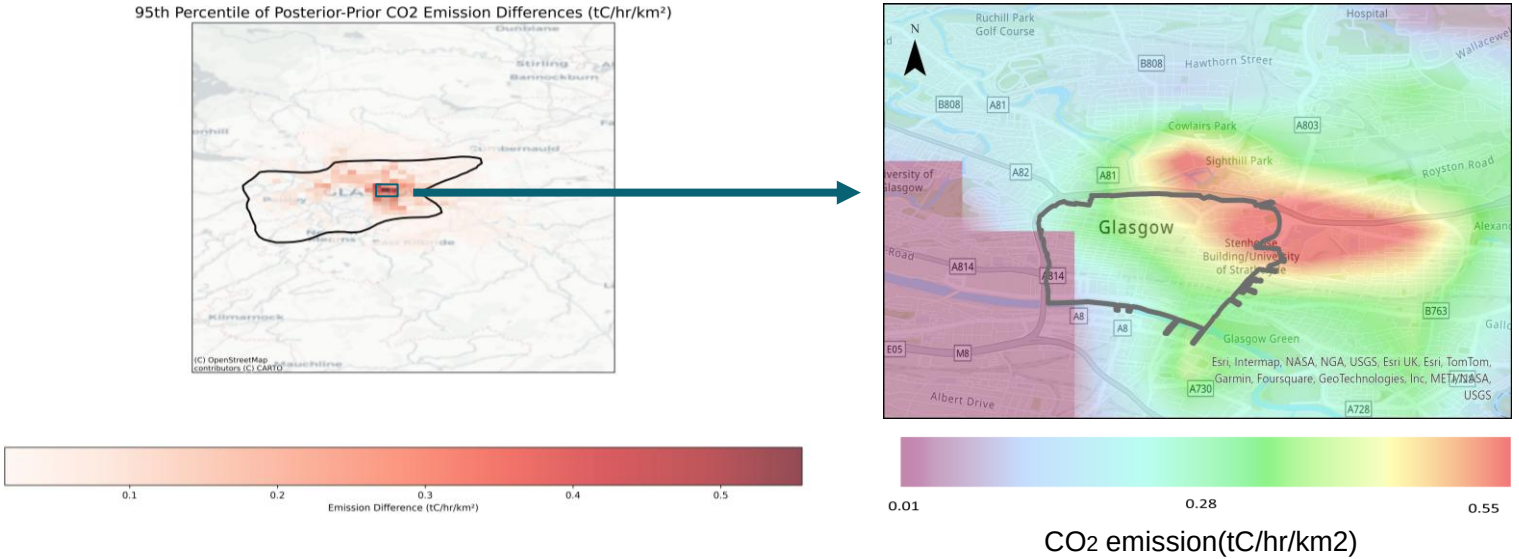
Posterior Emission estimates Glasgow(2022)





- **Winter**: ~ 70% increase emissions largely contributed by heating
- **Spring**: ~30% increase from fire emissions and urban sources.
- **Summer**: ~29% lower emissions
- **Autumn**: ~9% increase, relatively stable emissions.
- Highlights strong **seasonal impact** on CO_2 patterns.

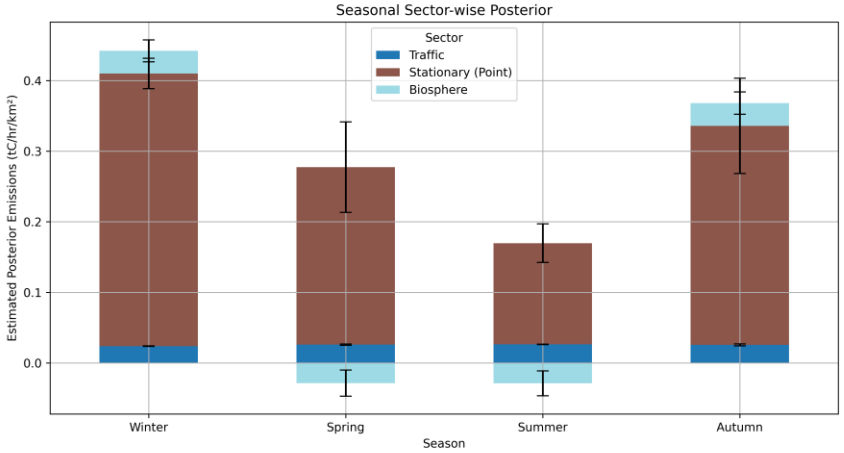
Emission Hotspots in the city

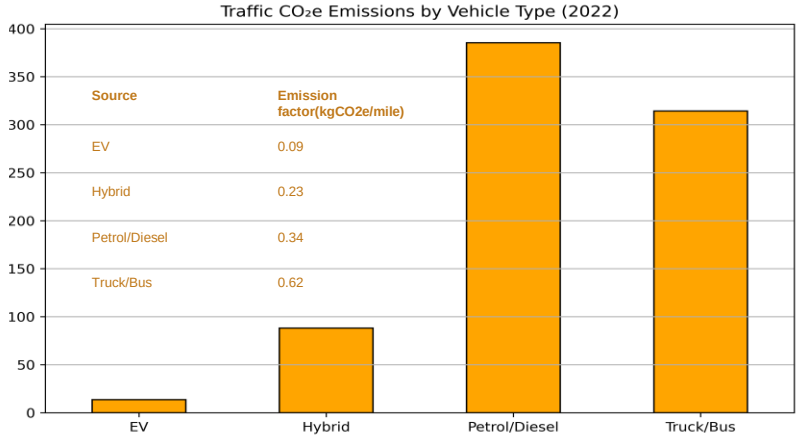


Major roads and dense buildings in Glasgow city Centre combine to create a CO_2 emission hotspot

Sectoral Emissions

In 2022, Cars & Taxis - 1.667 billion miles (76.7% of total VMT)
Other Vehicles (Buses, Trucks, Vans etc.) -507 million miles (23.3% of total VMT)





Traffic emissions remain relatively constant in primary analysis, while point sources exhibit notable seasonal fluctuations

- **Bottom-up Estimate (Inventory-based): ~ 774 $ktCO_2e$**
- **Top-down Estimate (Inverse Modeling):~ 802 $ktCO_2e$**

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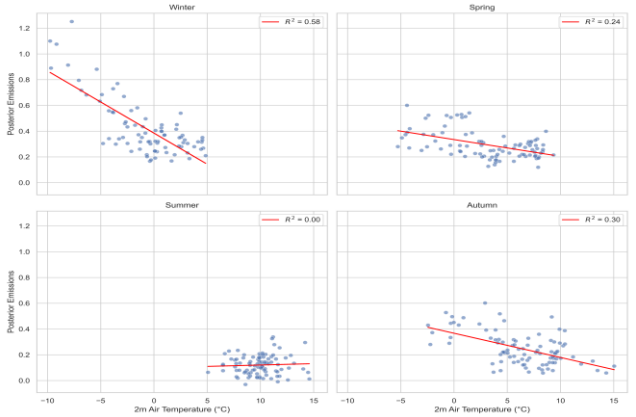
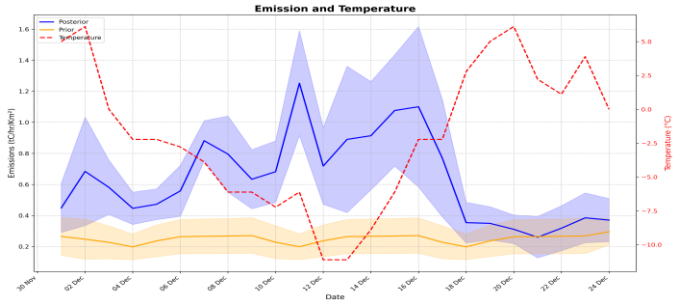
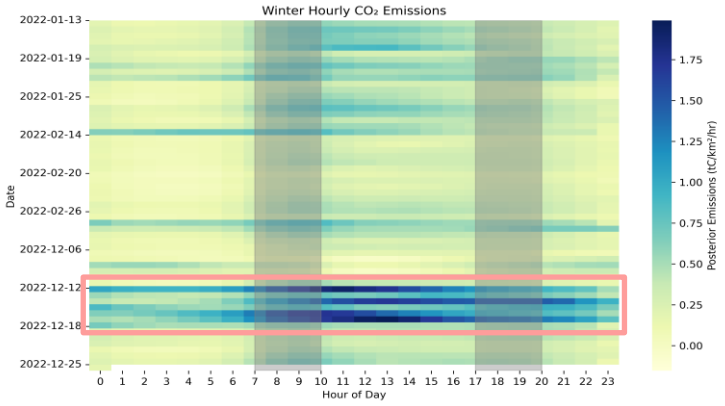
Winter Emissions

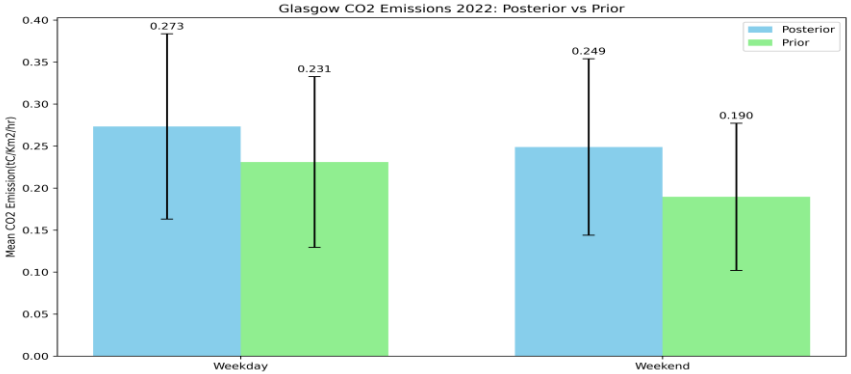
- Winter emissions rise with colder temperatures ($R^2 = 0.58$) due to heating demand.
- Little to no correlation in other seasons.
- Highlights need for efficient, low-emission heating to reduce winter CO_2.

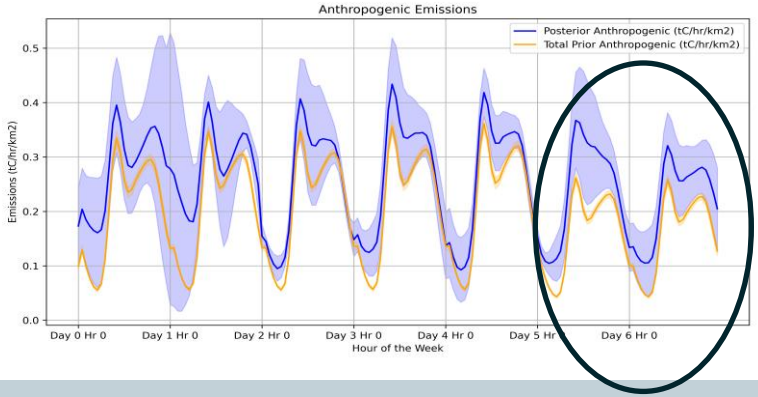






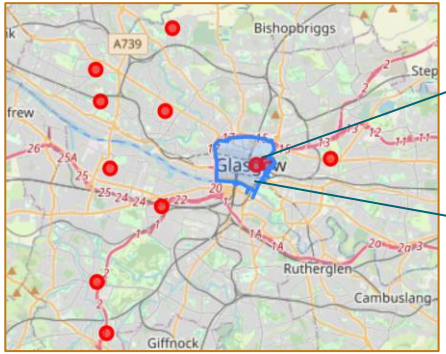
Weekday and weekend emissions

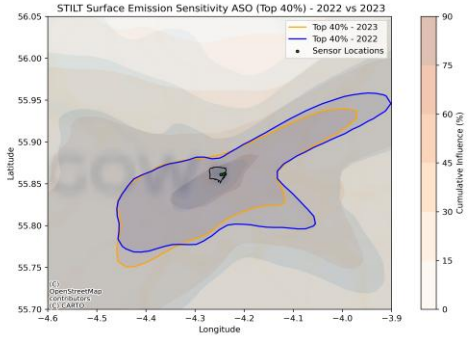


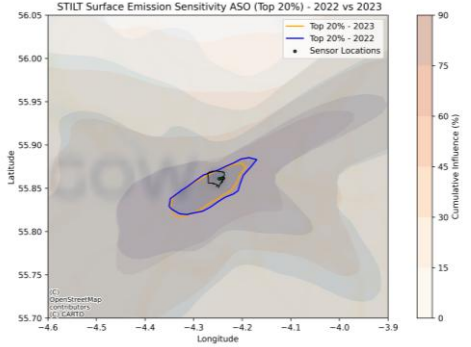


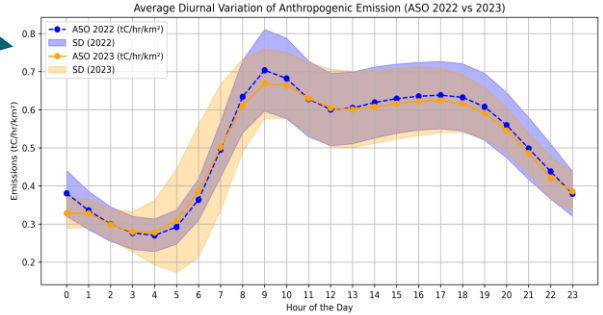
- 9.8% increase in total posterior emission in weekend compared to weekdays
- Prior values showed larger gap of 21.8%
- Reduction in overestimation of prior assumptions by inverse estimates.

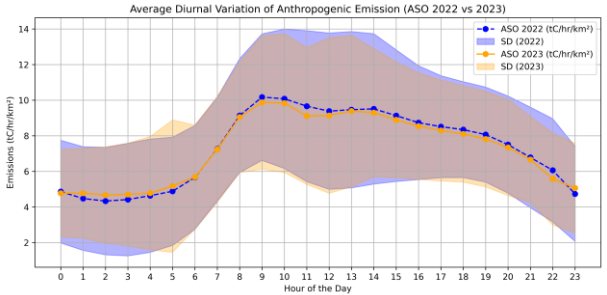
CO_2 emission comparison before and after implementation of LEZ











- CO_2 emissions in the city center decreased by 1–3% during three months (August to October) following the Low Emission Zone (LEZ) implementation, comparing 2022 and 2023 data.

Summary and Highlights

Seasonal Emissions

- Winter: Higher emissions than previous estimates, mainly due to **heating demand**.
- Summer: Lower emissions due to reduced energy use and possibly an underestimated biospheric uptake in the prior.

Urban Sensitivity

- Posterior estimates show notable refinements-especially in the city center.
- Highlights the importance of fine-scale urban emission modeling.

Traffic & Point Sources

- Traffic emissions remain steady year-round, aligning with territorial emission values.
- Point sources display clear seasonal trends.

Summary and Highlights

Model Improvements

- Posterior adjustments enhance emission accuracy by incorporating real-world activity patterns while acknoweledging possible uncertainties in transport fluxes.
- Sector-specific accuracy still requires more detailed activity data.
- Further work is needed to reduce uncertainties, particularly those arising from transport models and biospheric flux estimates.

Need for Continuous Monitoring

- Posterior adjustments enhance emission accuracy by incorporating real-world activity patterns.
- However, sector-specific accuracy still requires more detailed activity data.
- To reliably adjust emission inventories and capture long-term trends, continuous sensor-based CO_2 monitoring across the city is essential.
- Such observations allow for dynamic updating of models, better tracking of urban policy impacts,

Bridging the Gap: Science Meets Society

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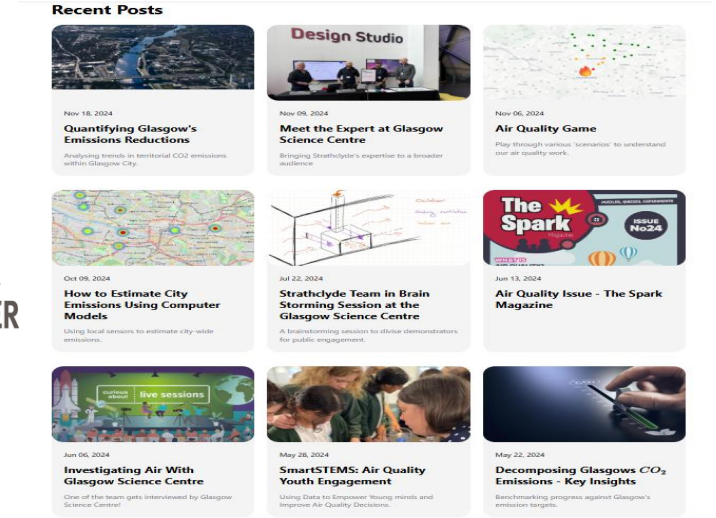

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Thank you for listening