

Bayesian inverse estimation of urban carbon emissions over Seoul

Sojung Sim* (simsj0304@snu.ac.kr), Sujong Jeong
Seoul National University

Introduction

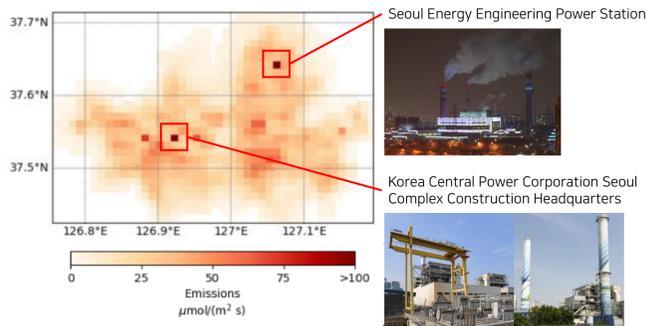
- More than 125 countries, including Korea, have declared **2050 carbon neutrality** to cope with climate change.
- In order to achieve carbon neutrality, it is necessary to **accurately estimate urban carbon emissions**, which account for more than 70% of global greenhouse gas emissions.
- For scientific support, the **Megacity CO₂-Seoul Project** has evaluated urban carbon emissions and established a greenhouse gas observation network for Seoul, one of the largest carbon emitting city in the world.
- Merging the bottom-up carbon emission estimates and the top-down method using observation and atmospheric transport model provides optimized emissions with high accuracy.
- To grasp the optimized urban carbon emissions with high spatiotemporal resolution, we conducted an **atmospheric observation-based Bayesian inverse modeling over Seoul**.

Data & Method

Atmospheric CO₂ concentration data measured continuously at four sites, high-resolution emission inventory (prior estimate), and the WRF-STILT model for April 2020 were used.

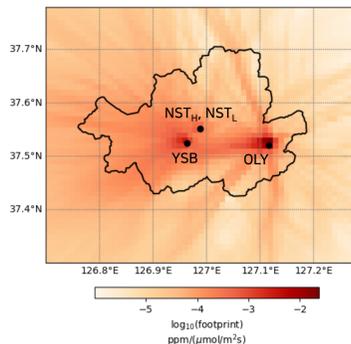
Carbon emission (ISAAC)

- Inventory System for Accounting Anthropogenic CO₂
- Sectors like electricity, transportation, manufacturing, and buildings in 1 hour and 1 km resolution



Footprint (WRF-STILT)

- Weather Research and Forecasting-Stochastic Time-Inverted Lagrangian Transport model



- Footprint: sensitivities of observation point to the upwind emission source area (influence)
- 1 hour & 1 km resolution, 1000 particles, 24h backward

Observation

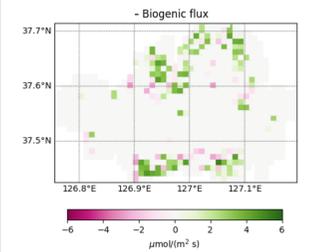
$\Delta\text{CO}_2 = \text{CO}_2 \text{ level} - (\text{background level} + \text{vegetation})$

Site code	Full name	Height (m)
YSB	Yongsan Building	113
NST _H	Namsan Seoul Tower-High	420
NST _L	Namsan Seoul Tower-Low	265
OLY	Olympic Park	27
GWA (background)	Gwanak Mountain	629



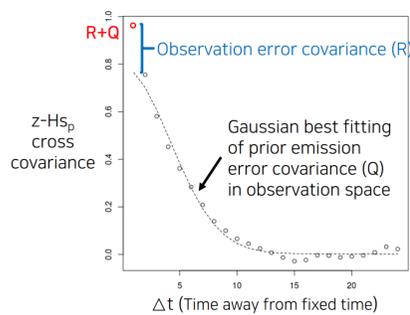
Carbon uptake (CASS)

- Carbon Simulator from Space
- CO₂ absorption by various vegetation resources like forests, urban forests, park



Observation error covariance

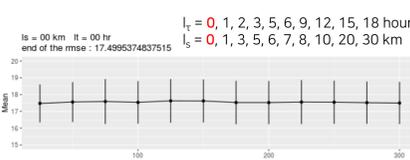
- Using the Gaussian best fitting method by Hollingsworth & Lonnberg (1986)
- Assume that observation error and prior emission error are not correlated



Prior emission error covariance

$$\mathbf{Q} = \mathbf{I}_\sigma (\mathbf{D} \otimes \mathbf{E}) \mathbf{I}_\sigma$$

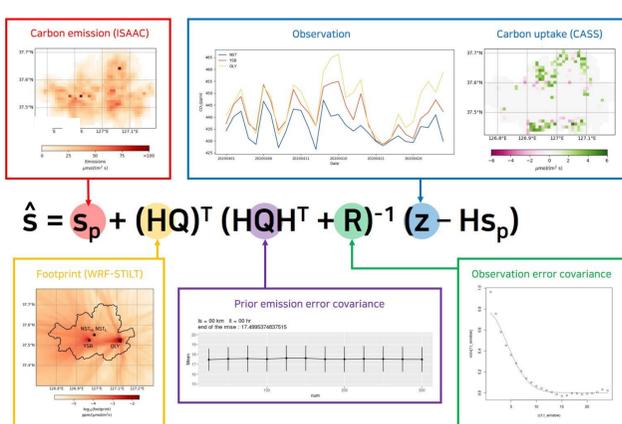
- 1) \mathbf{I}_σ : Diagonal matrix of emission anomalies by grid
- 2) \mathbf{D} : Temporal covariance $\mathbf{D} = \begin{bmatrix} \exp(-\frac{\Delta t}{I_t}) \\ \vdots \end{bmatrix}$
- 3) \mathbf{E} : Spatial covariance $\mathbf{E} = \begin{bmatrix} \exp(-\frac{\Delta x}{I_s}) \\ \vdots \end{bmatrix}$



→ Q inflation to match Gaussian best fitting

Bayesian inverse model

Calculate optimized emissions through the minimization of cost function



$$L_s = \frac{1}{2} (\mathbf{z} - \mathbf{H}\mathbf{s})^T \mathbf{R}^{-1} (\mathbf{z} - \mathbf{H}\mathbf{s}) + \frac{1}{2} (\mathbf{s} - \mathbf{s}_p)^T \mathbf{Q}^{-1} (\mathbf{s} - \mathbf{s}_p)$$

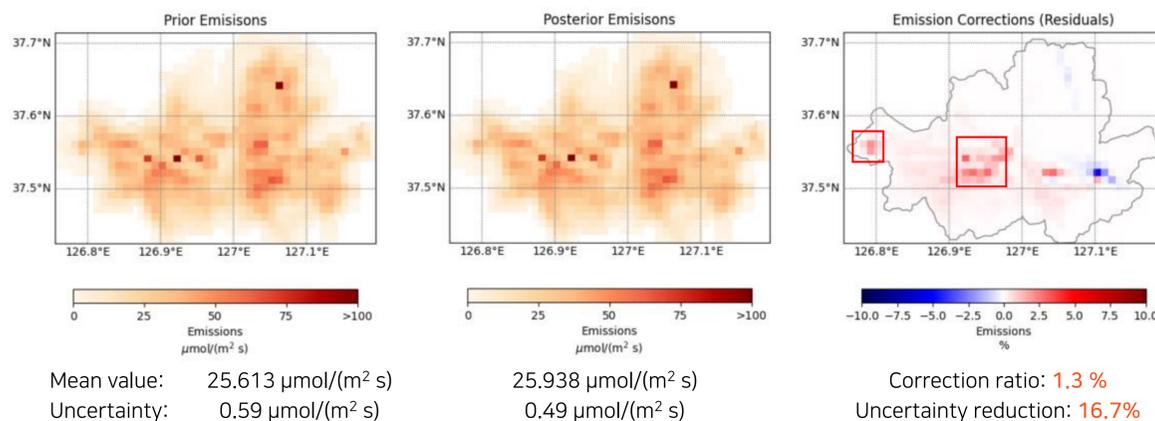
$$\hat{\mathbf{s}} = \mathbf{s}_p + (\mathbf{H}\mathbf{Q})^T (\mathbf{H}\mathbf{Q}\mathbf{H}^T + \mathbf{R})^{-1} (\mathbf{z} - \mathbf{H}\mathbf{s}_p)$$

$\hat{\mathbf{s}}$: posterior best estimate of emissions
 \mathbf{s}_p : prior emission
 \mathbf{H} : Jacobian matrix of footprint
 \mathbf{Q} : Prior emission error covariance
 \mathbf{R} : Observation error covariance
 \mathbf{z} : Observed enhancement

- To verify the inversion model,
- compare error reductions
 - compute RMSE and R²
 - calculate the reduced chi-squared value

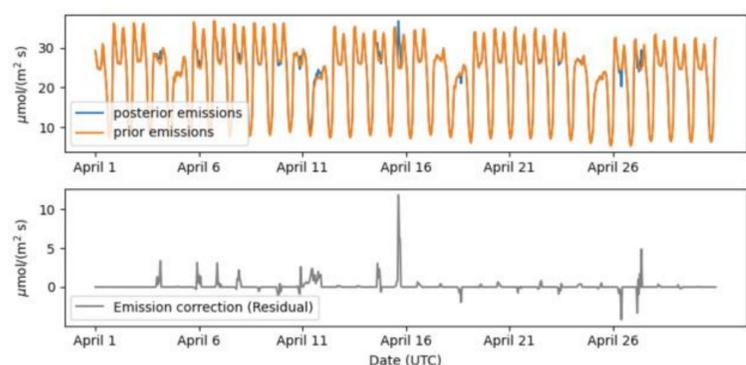
Results

Spatial distribution of prior, posterior, and correction of carbon emissions in Seoul



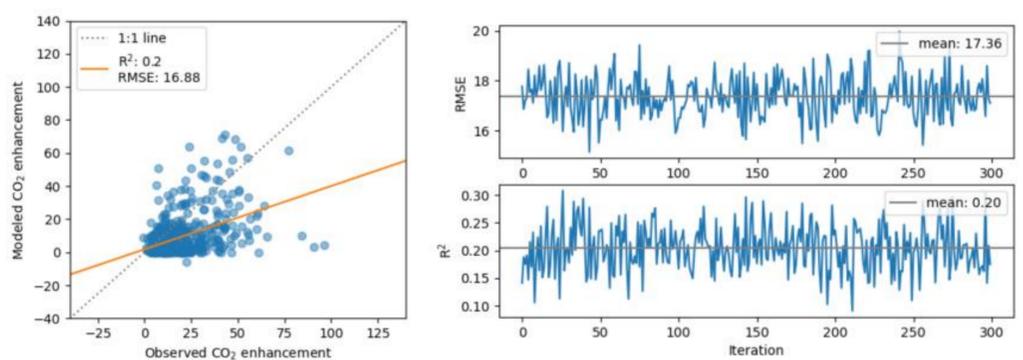
- The average value of prior and posterior carbon emissions in April 2020 were 25.61 μmol/(m² s) and 25.94 μmol/(m² s), respectively.
- As a result of verifying urban carbon emissions over Seoul through the Bayesian inverse model, it was found that **posterior carbon emissions increased by 1.3%**.
- In other words, it means that the **prior carbon emissions were underestimated**, and this trend was evident at Gimpo Airport, Yeouido and Yongsan (busy areas) in Seoul.
- The **uncertainty of carbon emissions** was compared to verify the performance of the Inverse model, and it was **reduced by 16.7%** through the Inverse model.

Time series of prior, posterior, and correction of carbon emissions



- The **reduced chi-squared value** was 24.06, but it was greatly **lowered to 1.92**, by applying Q inflation method.
- The current error covariance is appropriately calculated, as the reduced chi-squared value is closer to 1 (standard normal distribution).

Prediction of the CO₂ enhancement



- In order to calculate the degree of prediction of the CO₂ enhancement of the model, the validation sample (20% of the total observation data) was predicted using test sample (80% of the total observation data).
- As a result of 300 iterations, the **RMSE was 17.36 (R²: 0.2)** on average.

Conclusion

- The Bayesian inverse model built as part of Megacity CO₂-Seoul Project is expected to **accurately verify carbon emissions over Seoul and provide objective and scientific basis for implementing carbon reduction policies**.
- After that, observation error for each observation site, satellite data use with XSTILT, OSSE and ¹⁴C data use for model verification will be improved.