TRANSCOM-2022 meeting @ Wageningen, Netherland | 16 - 17 September, 2022

Bayesian inverse estimation of urban carbon emissions over Seoul

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Introduction

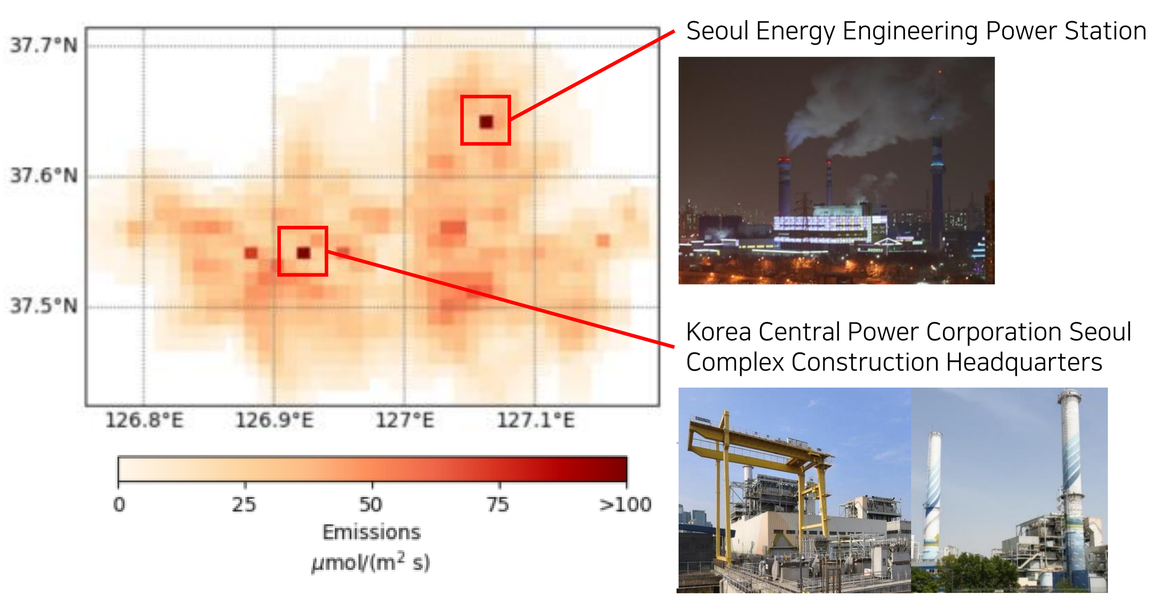
- More than 125 countries, including Korea, have declared 2050 carbon neutrality to cope with climate change.
- In order to achieve carbon neutrality, it is necessary to accurately estimate urban carbon emissions, which account for more than 70% of global greenhouse gas emissions.
- For scientific support, the Megacity CO_2-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 CO_2 concentration data measured continuously at four sites, high-resolution emission inventory (prior estimate), and the WRF-STILT model for April 2020 were used.

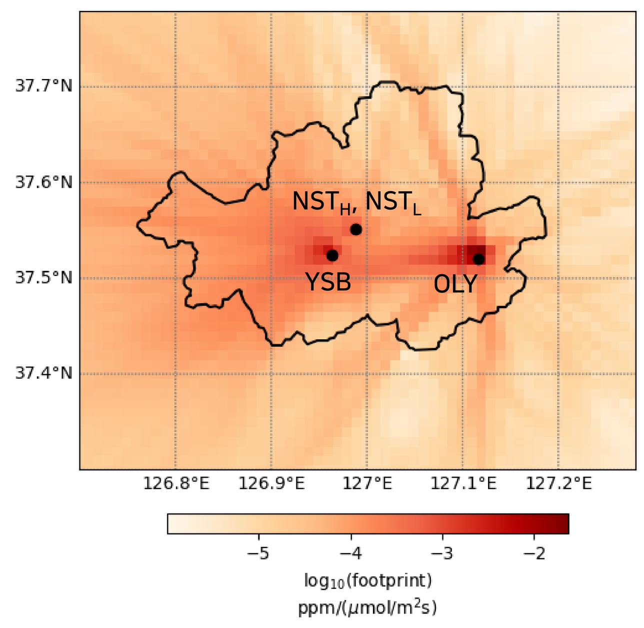
Carbon emission (ISAAC)

- Inventory System for Accounting Anthropogenic CO_2
- 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

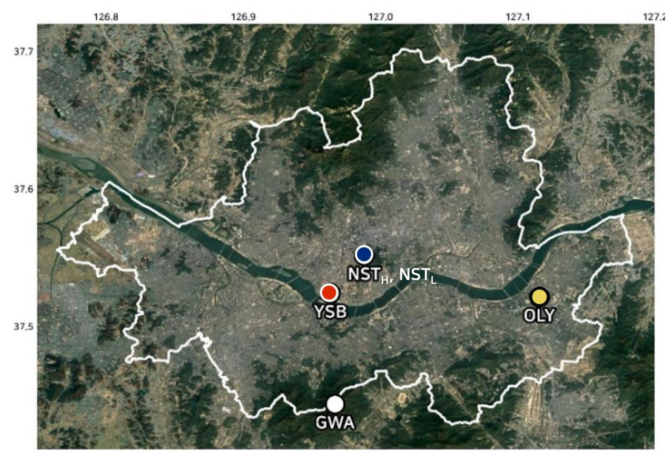


- Footprint: sensitivities of observation point to the upwind emission source area (influence)
- 1 hour & 1 km resolution, 1000 particles, 24h backward

Observation

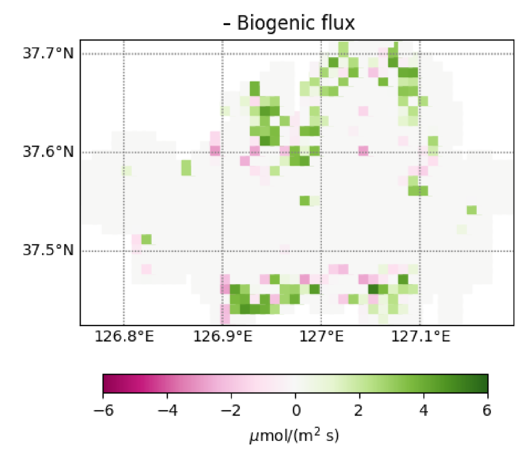
$\triangle CO_2 = CO_2$ level – (background level + vegetation)

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



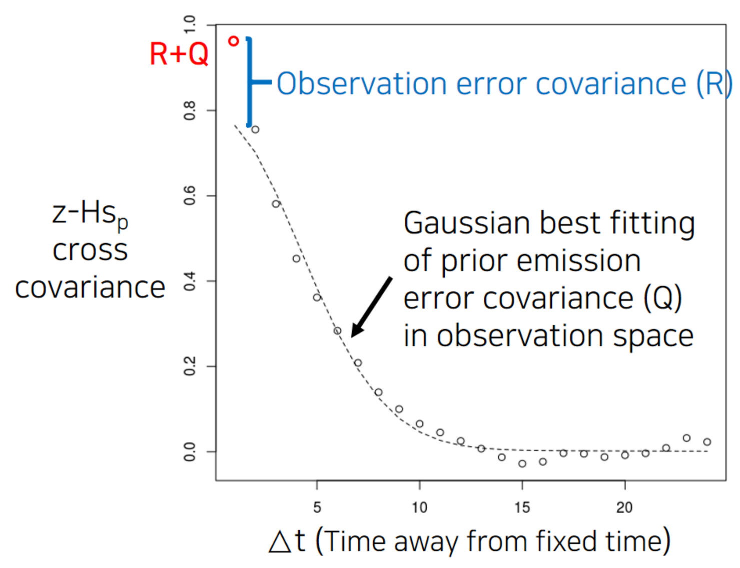
Carbon uptake (CASS)

- CArbon Simulator from Space
- CO_2 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

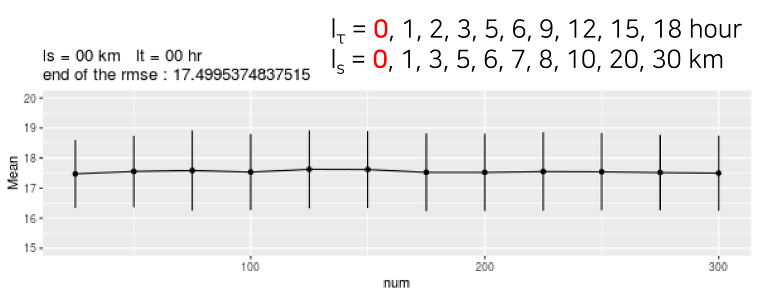


Prior emission error covariance

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

1) I_σ: Diagonal matrix of emission anomalies by grid
2) D: Temporal covariance $\mathbf{D} = \left[\exp\left(-\frac{\mathbf{X}_\tau}{l_\tau} \right) \right]$
3) E: Spatial covariance $\mathbf{E} = \left[\exp\left(-\frac{\mathbf{X}_s}{l_s} \right) \right]$

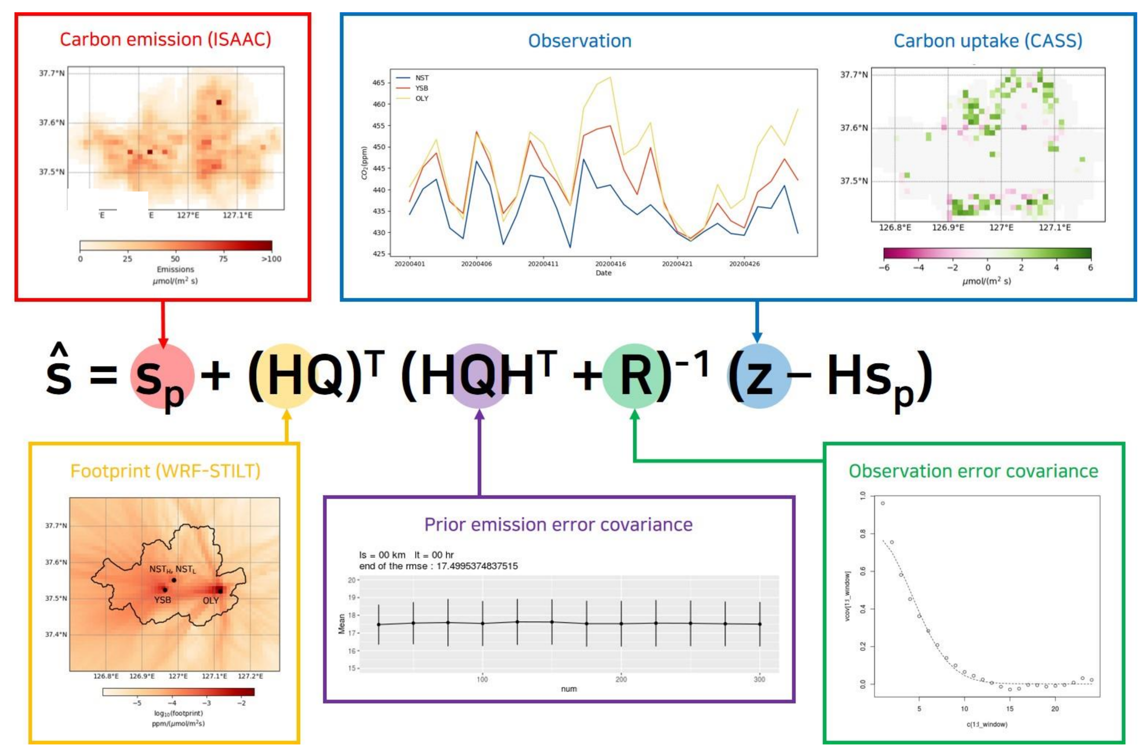
l_τ = 0, 1, 2, 3, 5, 6, 9, 12, 15, 18 hour
l_s = 0, 1, 3, 5, 6, 7, 8, 10, 20, 30 km



→ Q inflation to match Gaussian best fitting

Bayesian inverse model

Calculate optimized emissions through the minimization of cost function



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

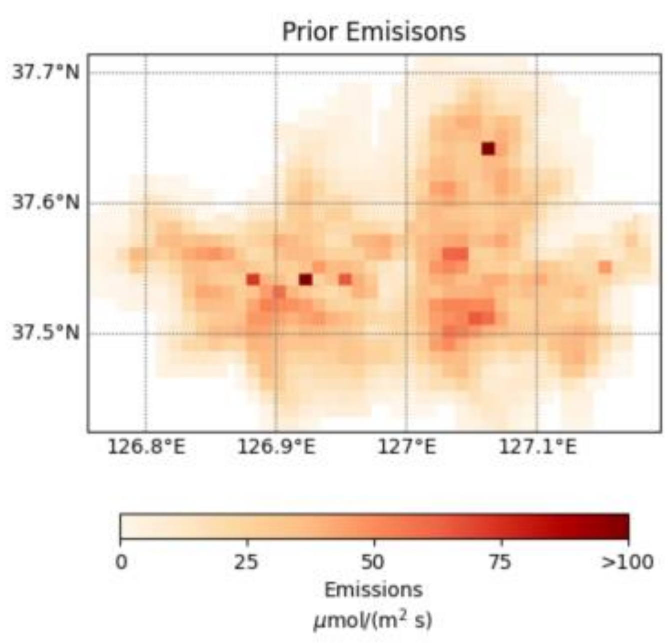
$$\hat{\mathbf{s}} = \mathbf{s}_p + (\mathbf{HQ})^T \left(\mathbf{HQH}^T + \mathbf{R} \right)^{-1} (\mathbf{z} - \mathbf{Hs}_p)$$

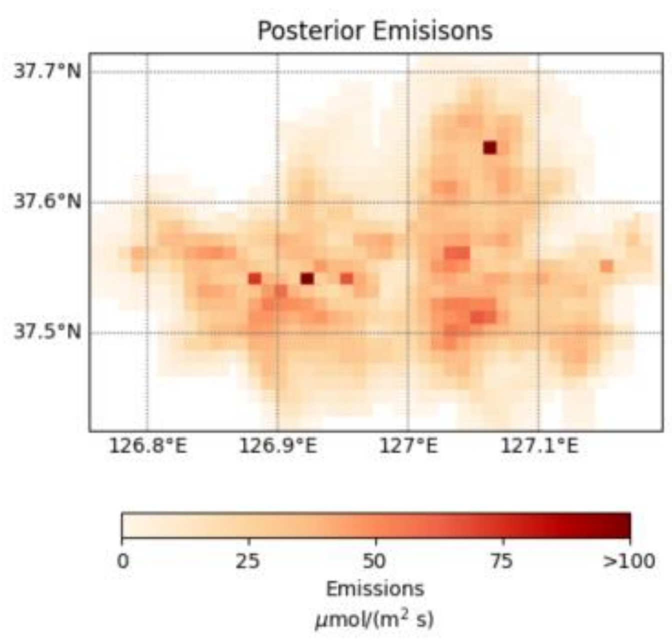
s: posterior best estimate of emissions
s_p: prior emission
H: Jacobian matrix of footprint
Q: Prior emission error covariance
R; Observation error covariance
z: Observed enhancement

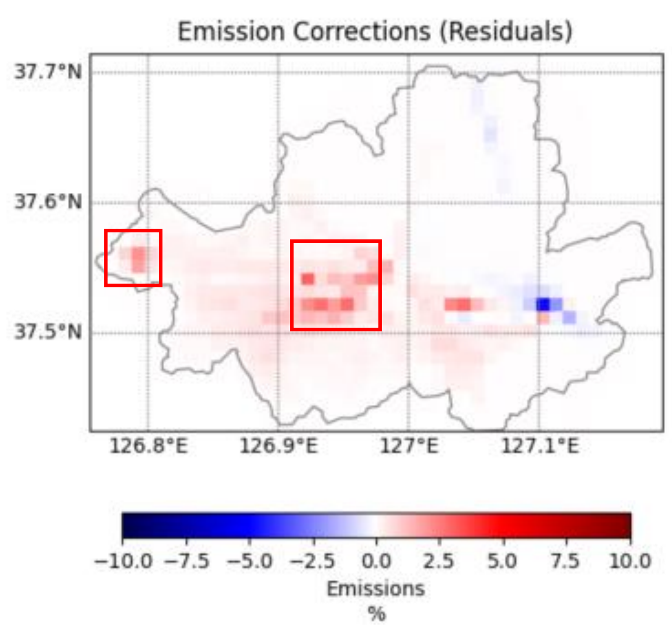
To verify the inversion model,
- compare error reductions
- compute RMSE and R^2
- calculate the reduced chi-squared value

Results

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



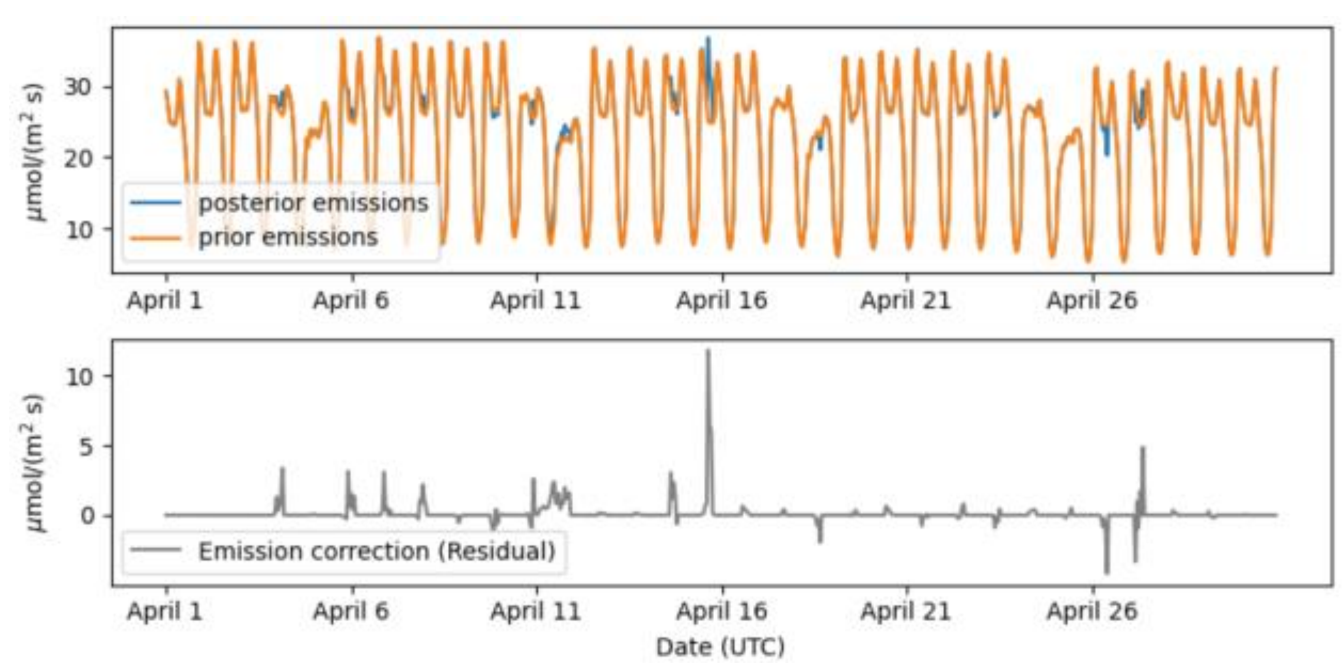




	Prior	Posterior	
Mean value:	25.613 μmol/(m² s)	25.938 μmol/(m² s)	Correction ratio: 1.3 %
Uncertainty:	0.59 μmol/(m² s)	0.49 μmol/(m² s)	Uncertainty reduction: 16.7%

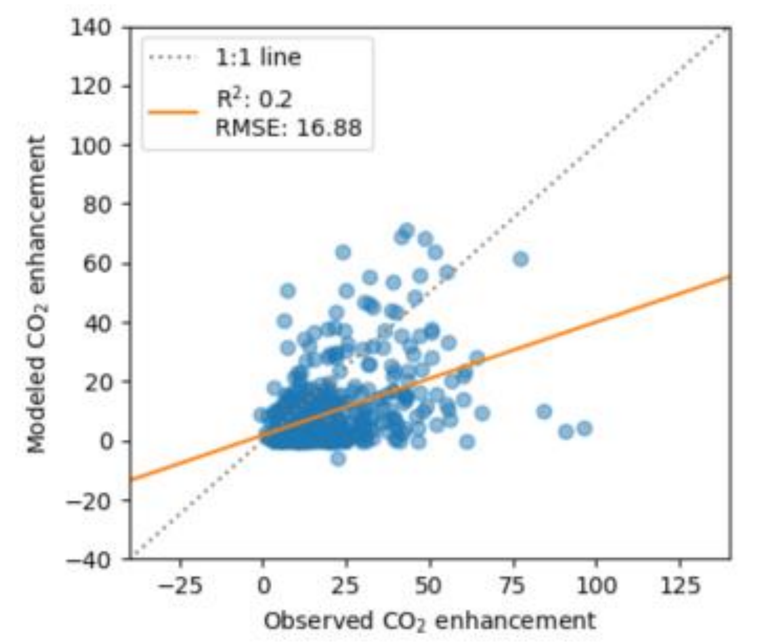
- The average value of prior and posterior carbon emissions in April 2020 were 25.61 μmol/(m² s) and 25.94 μmol/(m² s), respectively.
- As a result of verifying urban carbon emissions over Seoul through the Bayesian inverse model, it was found that posterior carbon emissions increased by 1.3%.
- In other 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.

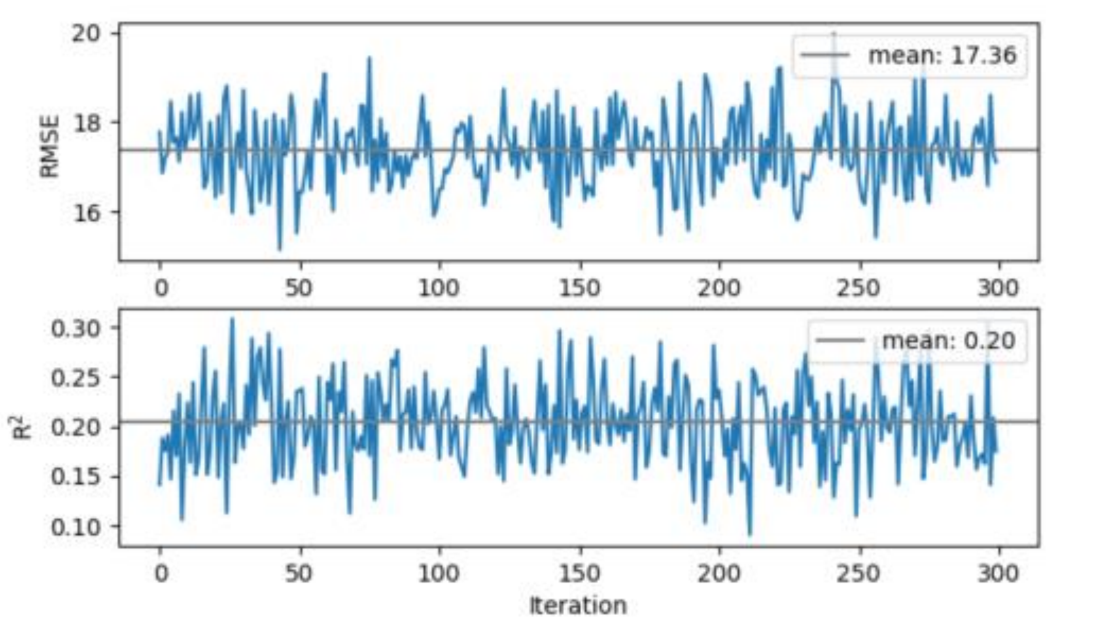
Time series of prior, posterior, and correction of carbon emissions



- 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 CO_2 enhancement





- In order to calculate the degree of prediction of the CO_2 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 (R^2: 0.2) on average.

Conclusion

- The Bayesian inverse model built as part of Megacity CO_2-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 ^{14}C data use for model verification will be improved.

* This work was supported by Korea Environment Industry &Technology Institute (KEITI) through "Climate Change R&D Project for New Climate Regime", funded by Korea Ministry of Environment (MOE) (2022003560006)