High-Resolution Inversion of Berlin City Emissions

A Synthetic Study using FLEXPART-WRF for Network Optimization within ITMS

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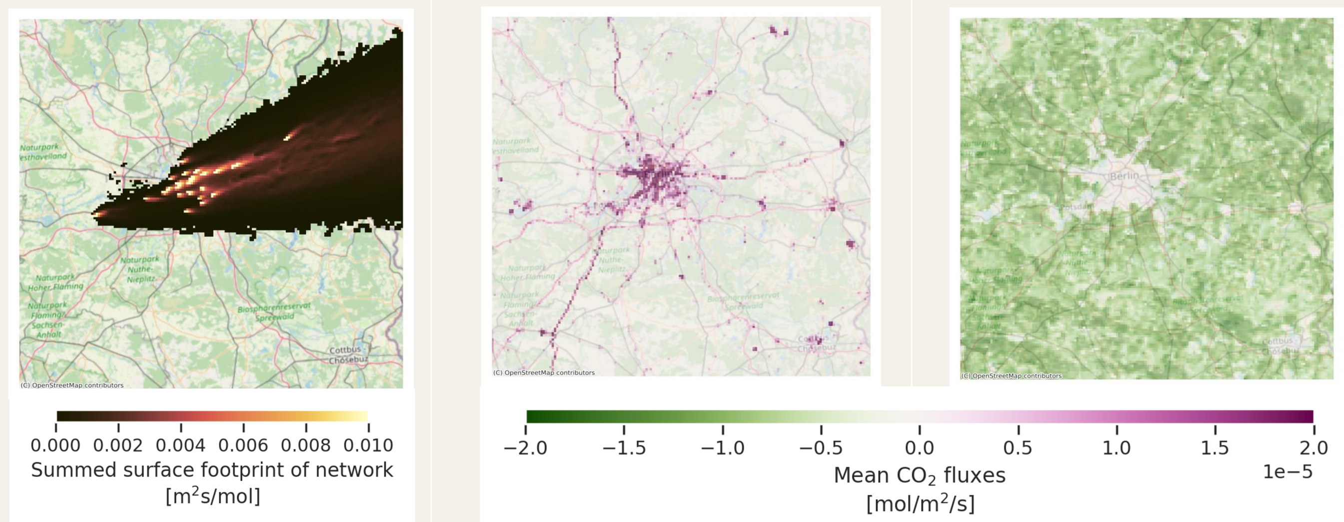
Motivation

- 70 % of anthropogenic CO_2 emissions are associated with urban areas. [1]
- Knowledge of high-resolution greenhouse gas emissions can guide and motivate future mitigation efforts. [2]
- Many urban regions are still lacking the required measurement infrastructure for emission prediction within inversions for independent verification and as supplement of bottom-up approaches.
- **Open question:** How to design measurement networks to inform effectively about urban CO_2 emissions?
- **Our approach:** We test various architectures in a synthetic environment in an observing system simulation experiment (OSSE) to evaluate their potential.
- **This study:** We investigate measurement networks in and around Berlin in a Bayesian inversion setup.

Data	Footprints	Anthropogenic Emissions	Biogenic Fluxes
Description	Result of FLEXPART-WRF [3]: 10^4 particles per release, transported for 1 day, WRF data: EGU24-8915 [4]	Summed-up CO_2 emissions of TNO [5] inventory	Biogenic CO_2 fluxes from VPRM [6] run
Resolution	• Spatial: 1 km in Berlin Area, 5 km in rest of Germany • Temporal: 1 h • Measurements: every hour for 2 weeks per season		

Example:

- Berlin
- Spring
- Daytime



Bayesian Inversion Setup

State Vector
- Total CO_2 (sum of anth. and bio. fluxes)
- Aggregated to 114 cells
- Aggregated to 3 hourly averages

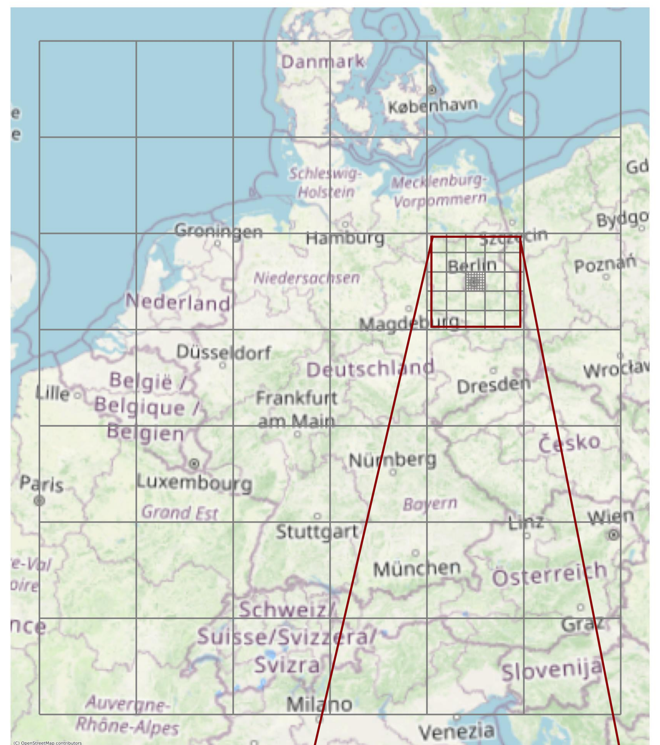
Prior Emissions
- Emissions shifted from anthropogenic to the biospheric
- Prior error of 100% with spatial correlation scale: 5km

Measurements
- Convolution of footprints and emissions
- Varying errors without correlations

Posterior emissions

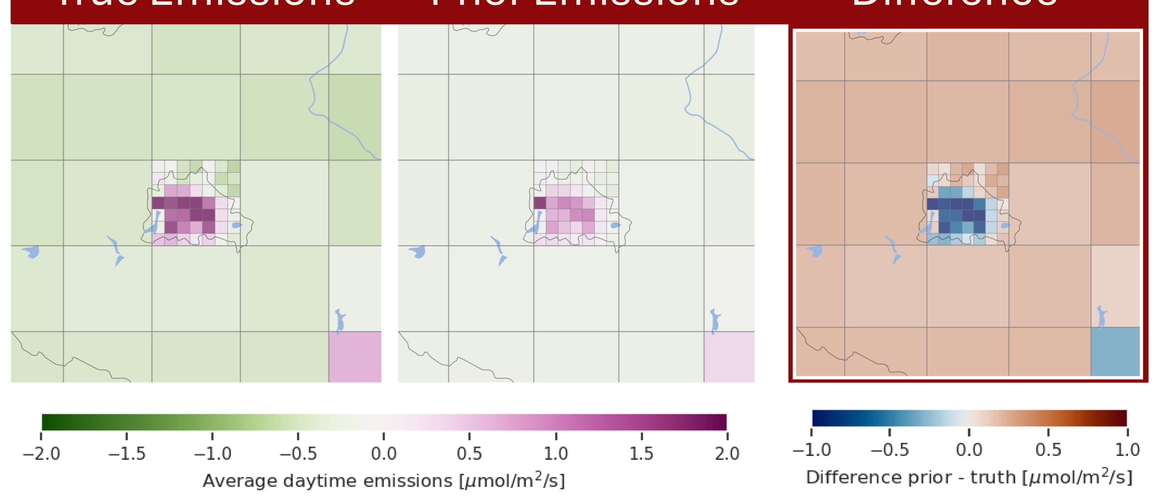
$$\hat{\mathbf{x}} = \mathbf{x}_0 + (\mathbf{K}^T\mathbf{S}_y^{-1}\mathbf{K}^T + \mathbf{S}_{x_0}^{-1})^{-1}\mathbf{K}^T\mathbf{S}_y^{-1}(\mathbf{y} - \mathbf{K}\mathbf{x}_0)$$

$$\hat{\mathbf{S}} = (\mathbf{K}^T\mathbf{S}_y^{-1}\mathbf{K} + \mathbf{S}_{x_0}^{-1})^{-1}$$

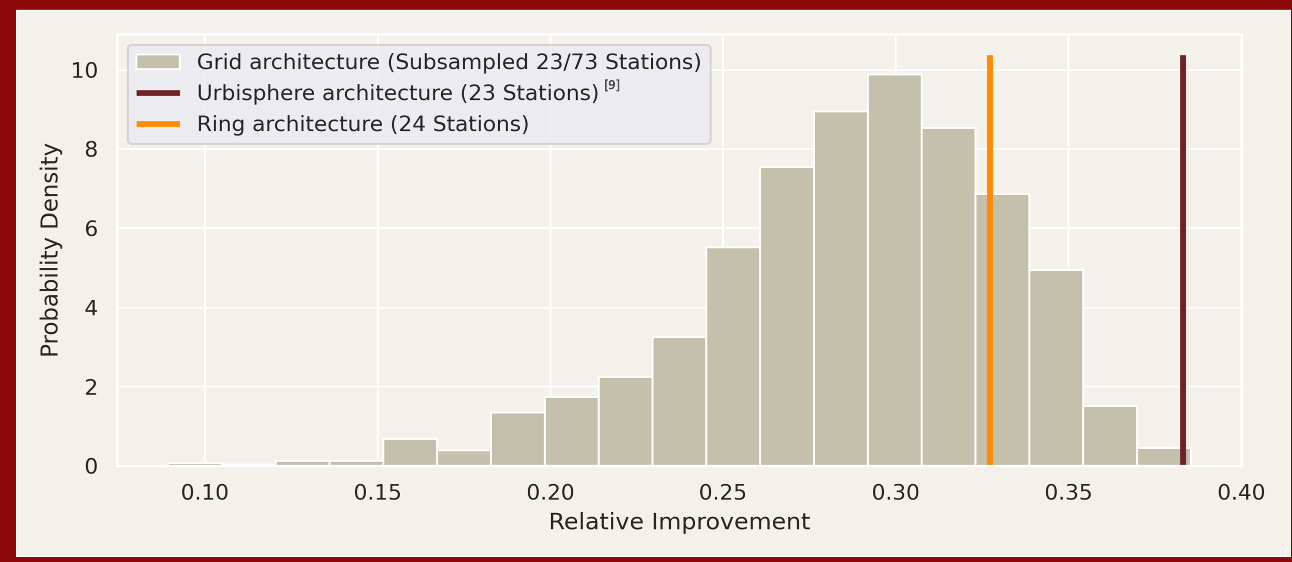


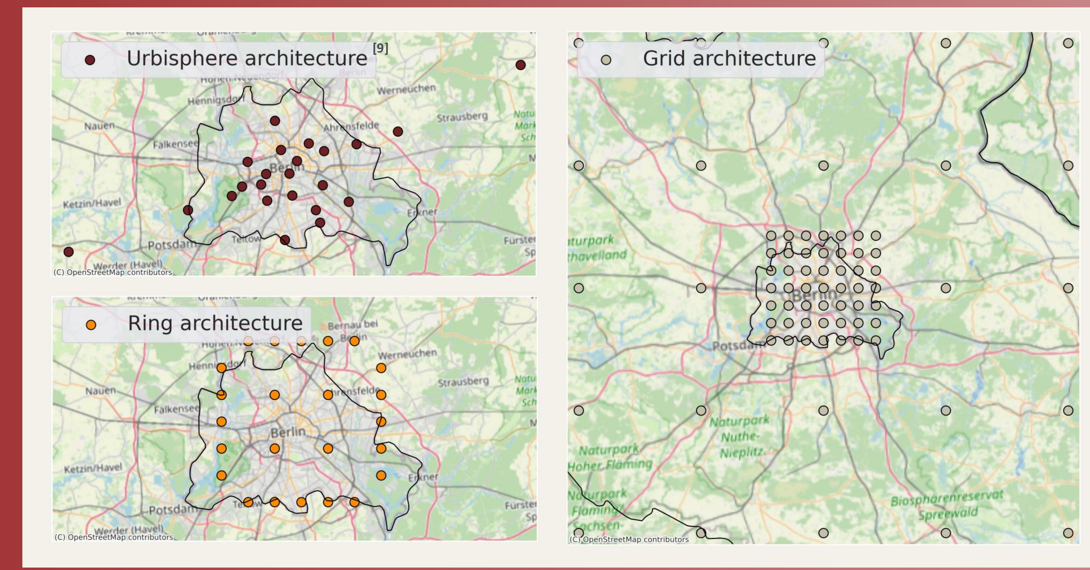
- $\mathbf{x}_0$: Prior emissions
- $\mathbf{S}_{x_0}$: Prior covariance
- $\hat{\mathbf{x}}$: Posterior emissions
- $\hat{\mathbf{S}}$: Posterior covariance
- $\mathbf{y}$: Measurements
- $\mathbf{S}_y$: Measurement covariance
- $\mathbf{K}$: Forward model/ Footprints

True Emissions | Prior Emissions | Difference

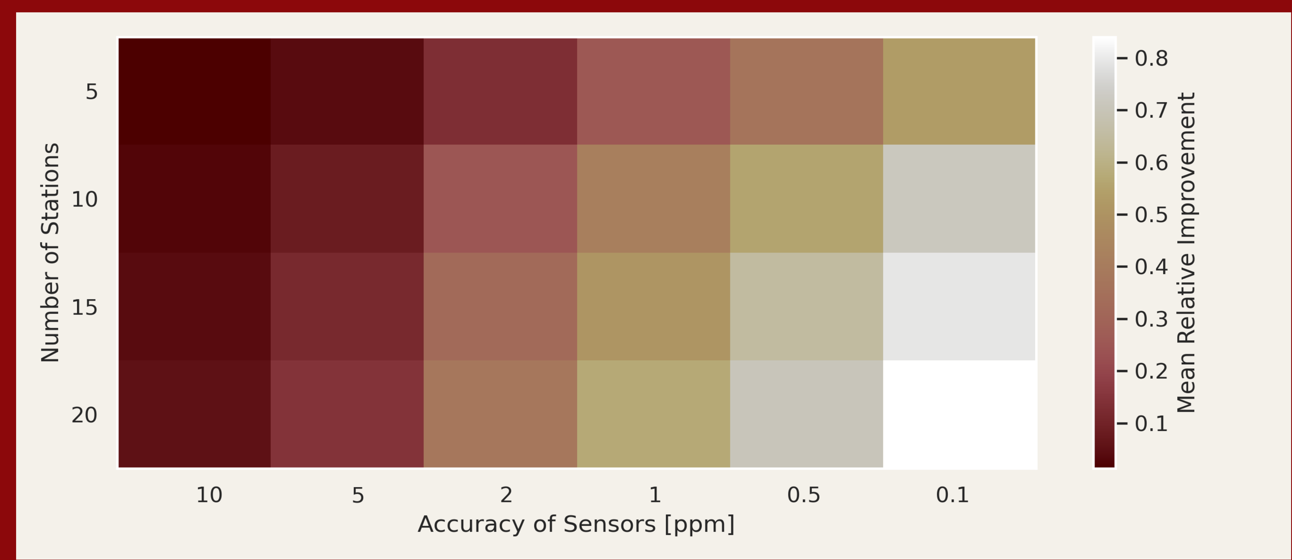


Comparison of Monitoring Network Architectures





Evaluation of Realizations



Experiment Setup [7, 8]:

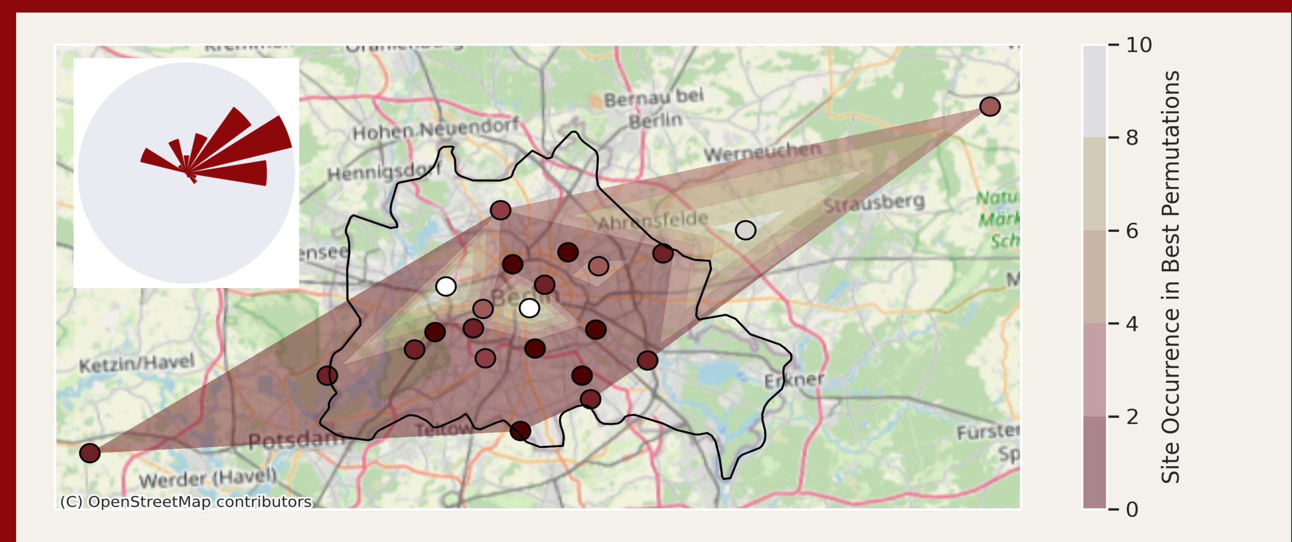
For each combination:
- Select 2000 subsets of n stations from the network
- Run 2 weeks of Inversions and calculate relative improvement
- Average over all subsets
- Results are shown for Urbisphere architecture [9] in spring

Relative Improvement:

$$\eta = 1 - \frac{\|\mathbf{x} - \hat{\mathbf{x}}\|}{\|\mathbf{x} - \mathbf{x}_0\|}$$

Measure of performance in OSSE
- Value of 1: posterior = truth
- Value of 0: No improvement against prior
- Evaluation only in Berlin city region with Land use type "urban"

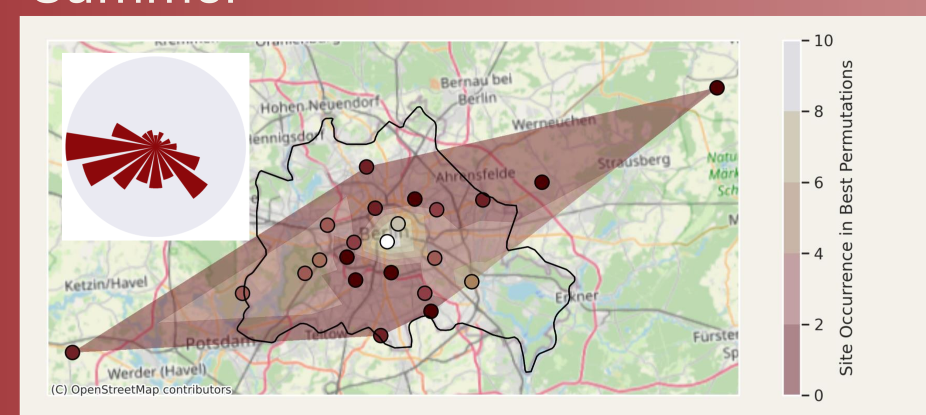
Location of Most Important Stations (Spring)



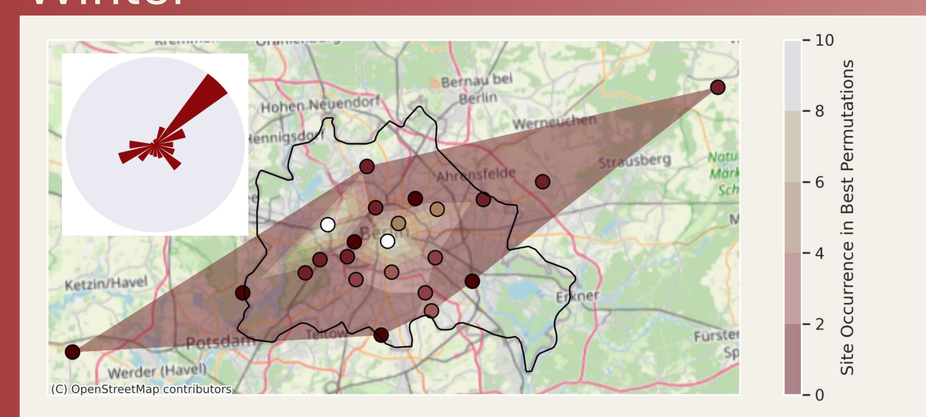
Score of Stations:

- Select 10 best samples of the 2000 inversions
- For each site count occurrences in best samples
- Examples shown: 5 stations with 2 ppm accuracy

Summer



Winter



In Development

- Explicit separation of emission sectors
- Include additional tracer CO
- Add total column measurements
- Apply to other German metropolitan areas
- Add background concentration to state vector

Refereces: [1] International Energy Agency (IEA). World energy outlook 2008. OECD Publishing, 2008. **[2]** Jungmann, M., Vardag, S. N., Kutzner, F., Keppler, F., Schmidt, M., Aeschbach, N., Gerhard, U., Zipf, A., Lautenbach, S., Siegmund, A., Goeschl, T., and Butz, A.: Zooming-in for climate action – hyperlocal greenhouse gas data for mitigation action?, Climate Action, 1, 8, https://doi.org/10.1007/s44168-022-00007-4, 2022. **[3]** J. Brioude, D. Arnold, A. Stohl, M. Cassiani, D. Morton, P. Seibert, W. Angevine, S. Evan, A. Dingwell, J. D. Fast, R. C. Easter, I. Pisso, J. Burkhart, and G. Wotawa. The lagrangian particle dispersion model flexpart-wrf version 3.1. Geoscientific Model Development, 6(6):1889– 1904, 2013. **[4]** L.Pilz et al.: High-resolution meteorological CO2 enhancements of German metropolitan areas using WRFhttps://meetingorganizer.copernicus.org/EGU24/EGU24-8915.html, **[5]** I. Super, S. N. C. Dellaert, A. J. H. Visschedijk, and H. A. C. Denier van der Gon. Uncertainty analysis of a european high-resolution emission inventory of co2 and co to support inverse modelling and network design. Atmospheric Chemistry and Physics, 20(3):1795–1816, 2020. **[6]** Pathmathevan Mahadevan, Steven C. Wofsy, Daniel M. Matross, Xiangming Xiao, Allison L. Dunn, John C. Lin, Christoph Gerbig, J. William Munger, Victoria Y. Chow, and Elaine W. Gottlieb. A satellite-based biosphere parameterization for net ecosystem co2 exchange: Vegetation photosynthesis and respiration model (vprm). Global Biogeochemical Cycles, 22(2), 2008. **[7]** Turner, A. J., Shusterman, A. A., McDonald, B. C., Teige, V., Harley, R. A., and Cohen, R. C.: Network design for quantifying urban CO2 emissions: assessing trade-offs between precision and network density, Atmos. Chem. Phys., 16, 13465–13475, https://doi.org/10.5194/acp-16-13465-2016, 2016. **[8]** Vardag, S. N. and Maiwald, R.: Optimising urban measurement networks for CO2 flux estimation: a high-resolution observing system simulation experiment using GRAMM/GRAL, Geosci. Model Dev., 17, 1885–1902, https://doi.org/10.5194/gmd-17-1885-2024, 2024. **[9]** Urbisphere positions extracted from https://urbisphere.eu/img/campaign_berlin_2.jpg

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Photography encouraged