

Dear the Editor of *Geoscientific Model Development*

Thank you very much for your helpful guidance and we are sorry for your inconvenience. We have revised the manuscript in accordance with your comments. Below, we provide detailed explanations of how each point has been addressed. Please do not hesitate to let us know if any additional revisions are needed.

We sincerely appreciate your continued support throughout the review process.

Sincerely,

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RC1: '[Comment on egusphere-2025-4938](#)', Anonymous Referee #1, 01 Dec 2025

This manuscript combines WRF-Chem with the DART system to perform a top-down inversion of CO₂ and CH₄ using atmospheric observations, constraining concentrations and fluxes at a 9-km resolution. Given the growing need to improve national-scale greenhouse gas estimates within the MMRV framework, the topic is timely and of scientific relevance. However, for the reasons outlined below, I believe the manuscript in its current form is not yet suitable for publication in Geoscientific Model Development.

>> We sincerely thank you for your insightful evaluation and for acknowledging the importance of high-resolution greenhouse gas (GHG) monitoring within the MMRV framework. We have carefully addressed your concerns regarding technical novelty, the necessity of an OSSE, and the justification for our modeling configurations

1. Sustainability for GMD

The manuscript does not clearly articulate the novelty of the WRF-Chem/DART modeling framework or how it differs from existing inversion systems. Details necessary for reproducibility—an essential requirement for GMD—are limited. The numerical settings and methodological choices require clearer justification to meet the journal's standards for model development papers.

>> We thank the reviewer for constructive comments and we revised our manuscript as the reviewer suggested. Our revision is based on the following:

1. As the reviewer mentioned, reproducibility is an important requirement of GMD. Our paper corresponds to the type of “MODEL DESCRIPTION PAPERS” at GMD (https://www.geoscientific-model-development.net/about/manuscript_types.html#item1) and please consider that reproducibility has been checked before the review process. At the submission and discussion state, the full model and DA codes and input data configurations have been published on a persistent public archive (zenodo with DOI number) with a unique identifier as described in the manuscript. We check if we can make better readability for the reproducibility during the revision and we further substantially expanded technical details throughout the manuscript (key DA settings including the augmented state vector updates, localization/inflation and perturbations regarding IC/BCs and emissions). As a type of “Model Description Papers in GMD”, we put more focus on presenting a general framework development and introducing its usefulness and reproducibility of the system, while reserving broader case-driven evaluations and pure scientific conclusions for follow-on work. We also document the coupled WRF-Chem/DART cycling workflow step-by-step and summarize key configuration settings used in this study for reproducibility.

2. As we described in the manuscript, our system is a regional CO₂/CH₄ top-down framework that couples online Eulerian transport (WRF-Chem) model with ensemble data assimilation

(DART/EAKF), incorporating model-physics extensions and configurations tailored to the complex urban–mountain–coastal heterogeneity of East Asia. We also revised the manuscript to better articulate novelty of our system to better show the following characteristics:

- Complementary benefits of Eulerian DA systems relative to Lagrangian inversions:

For regional inversions, an online Eulerian system offers (1) spatially continuous 4D fields of both meteorology and tracer concentrations over the full domain (rather than only receptor-based footprints), (2) dynamical–physical consistency because transport and key sub-grid physical processes (e.g., PBL mixing, mesoscale circulations) are evolved interactively within the coupled model rather than treated offline, and (3) a natural pathway to multivariate cycling in which transport-state errors (e.g., initial conditions, boundary-layer mixing, mesoscale flow errors) can be corrected within the same assimilation framework, reducing the risk that residual transport errors are aliased into flux adjustments.

- Novelty within the Eulerian paradigm: Korea-focused transport model (WRF-Chem) physics extensions and dual-species multivariate cycling. We also emphasize that this physics extension is generally applicable to other complex landscapes. Building on the Eulerian advantages above, our framework adds two system-level innovations tailored to the Korean Peninsula:

(1) Terrain-aware boundary-layer dispersion physics: we incorporate surface heterogeneity parameterizations relevant to Korea’s urban–mountain–coastal heterogeneity, including roughness sublayer effects and canopy-height adjustments. These options are implemented in our WRF-Chem configuration to better represent near-surface mixing and dispersion over complex terrain, building on previous works (Lee and Hong, 2016; Lee et al., 2020; Kim et al., 2024).

(2) Dual-species, dual-state joint updates with meteorology: Unlike standard flux-only inversions, our top-down system jointly updates a comprehensive state vector comprising CO₂ and CH₄ concentrations, their respective emissions, and meteorological fields. This multivariate framework ensures physical consistency between the atmospheric states and surface fluxes of both gases.

These two elements are explicitly documented in the revised manuscript and Supplement to enable reproducible reuse of the configuration for Korea-focused regional applications.

Kim, J., Shin, H.-J., Lee, K., and Hong, J.: Enhancement of ANN-based wind power forecasting by modification of surface roughness parameterization over complex terrain, *Journal of Environmental Management*, **362**, 121246, <https://doi.org/10.1016/j.jenvman.2024.121246>, 2024.

Lee, J. and Hong, J.: Implementation of spaceborne lidar-retrieved canopy height in the WRF model, *Journal of Geophysical Research: Atmospheres*, **121**, 6863–6876, <https://doi.org/10.1002/2015JD024299>, 2016.

Lee, J., Hong, J., Noh, Y., and Jiménez, P. A.: Implementation of a roughness sublayer parameterization in the Weather Research and Forecasting model (WRF version 3.7.1) and its evaluation for regional climate

simulations, *Geoscientific Model Development*, **13**, 521–536, <https://doi.org/10.5194/gmd-13-521-2020>, 2020.

2. Insufficient OSSE-based accuracy evaluation

Although the study focuses on developing an inversion framework, it lacks prior validation of its performance. An OSSE experiment using synthetic observations would allow the authors to quantitatively assess the accuracy and robustness of the system before applying it to real observations.

>> We agree that an OSSE (twin experiment with a known truth) provides a quantitative check of whether the inversion machinery behaves as intended. To address this point, we added a targeted OSSE to the revised manuscript, using an expanded 50-site synthetic surface network to test whether the framework can recover the intentionally imposed “missing power-industry” emission signal (a highly heterogeneous, point-source-dominated target) and to diagnose filter stability/consistency (including uncertainty reduction and innovation behavior). All OSSE configuration details and results are documented in Section 6 of the revised manuscript and Supplement for reproducibility.

We emphasize that this OSSE is included to demonstrate algorithmic consistency and stability under controlled conditions; real-world performance remains influenced by transport errors, boundary-condition biases, and representativeness errors, which we discuss explicitly. The main focus of the manuscript remains the real-data demonstration.

3. Limited description of DART and EAKF methodology

The manuscript provides only a brief description of the DART system and the Ensemble Adjustment Kalman Filter. Further explanation of the theoretical basis, implementation steps, and internal processing is needed to help readers understand how the assimilation framework functions.

>> As suggested by the reviewer, we substantially expanded the description of the DART system and the Ensemble Adjustment Kalman Filter (EAKF). In the revised manuscript (section 2.2), we explicitly define the augmented state vector used in this study and provide a concise mathematical summary of the EAKF analysis update. We also document the coupled WRF-Chem/DART cycling workflow step-by-step and summarize key configuration settings used in this study for reproducibility. Finally, we include more standard DART/EAKF references and documentation for readers who want additional algorithmic details.

4. Unclear scope of assimilated variables

Lines 133–134 suggest that both greenhouse gases and meteorological fields are assimilated, but the specific meteorological variables (e.g., temperature, wind components, humidity, surface variables) are not identified. Clarifying the full set of assimilated variables is essential.

>> As suggested by the reviewer, we revised the manuscript to explicitly list the model state variables directly updated by the EAKF analysis and the observation data used to constrain each variable. This revision clarifies that our configuration is a joint state and parameter estimation system: meteorology and tracer concentrations are updated directly, while fluxes are updated via ensemble-estimated cross-covariances with the observed tracers.

Specifically, the system assimilates conventional meteorological observations provided via NCEP PREPBUFR (e.g., surface and upper-air observation reports), which update the 3-D meteorological state variables (zonal and meridional winds, air temperature, and specific humidity) and the 2-D surface pressure in the state vector. In addition, the analysis updates the CO₂ and CH₄ tracer mixing ratios using high precision in situ observations from WMO/GAW stations. A complete list of assimilated state variables and corresponding observation types is now provided in Section 2.2.

5. Insufficient justification for uncertainty settings

The rationale for applying 5% uncertainty to initial/lateral boundary conditions and 30% to anthropogenic emissions is not provided. Given that CO₂ and CH₄ exhibit different source characteristics and variability, using identical uncertainty ratios is difficult to justify. Supporting evidence from previous studies or sensitivity analyses is needed. Moreover, observational and model uncertainties are not adequately discussed.

>> As the reviewer suggested, we revised the manuscript to clarify the prior uncertainty magnitudes using region-specific information and to document how observational and model uncertainties are represented in the assimilation.

1. Ensemble perturbations: The initial and lateral boundary conditions for CO₂/CH₄ concentrations are prescribed from the CAMS EGG4 reanalysis, which is observation-constrained rather than a free-running forecast. Previous evaluation studies indicate that EGG4 concentration errors are typically on the order of ~1% on large scales, although regional performance can vary (e.g., over East Asia) depending on period and diagnostics (Agustí-Panareda et al., 2023). In our DART/EAKF cycling, we apply a small multiplicative boundary perturbation (5%) primarily as a spread-maintenance choice to ensure non-zero ensemble variance at the domain inflow and to avoid filter collapse, while preventing unrealistically large boundary-driven dispersion that could dominate the regional increments driven by in-domain observations. We clarify in the revised text that this setting represents a

pragmatic balance between acknowledging residual boundary uncertainty and avoiding over-spreading.

2. Prior emissions uncertainty for CO₂ and CH₄: Previous studies indicate that anthropogenic emission at national scale has relatively smaller uncertainties (< 5%) but increased to 30 - 250% at city scales (e.g., Solazzo et al., 2021). In this case study, the 30% prior spread was selected to encompass the empirically observed inter-inventory spread for South Korea (2020), as summarized in Fig. 11. We therefore use 30% as a conservative, inventory-informed prior flexibility that is large enough to admit meaningful correction while remaining within the envelope of plausible bottom-up discrepancies for both gases in the study region. We clarify that this value is tied to the observed inter-inventory spread (rather than an arbitrary tuning choice) and note that gas- and sector-specific uncertainty characterization would be preferable when robust spatially resolved uncertainty information becomes available.
3. Observational and model uncertainties: We now explicitly define the observation error treatment for GHG data as $\sigma_{\text{obs}}^2 = \sigma_{\text{meas}}^2 + \sigma_{\text{repr}}^2$, where σ_{meas} is consistent with the WMO/GAW station measurement reports and σ_{repr} represents the dominant representativeness and model–observation mismatch when mapping point observations to 9-km grid-cell means. In the revision, we clarify how σ_{repr} is parameterized and the adopted values (Section 2.2). Uncertainties in model and prior are represented through the ensemble perturbations and the standard DART/EAKF controls (localization and adaptive inflation) too.

As a model description paper, we note that the uncertainty specifications in the DART-based system are configurable and can be adapted to the application scale (e.g., national versus city). Nevertheless, in this study we document and justify the specific settings used (5% boundary perturbations and 30% prior emission uncertainty) based on published evaluations and region-specific inventory spread (e.g. Zhang et al., 2021a, b).

Agustí-Panareda, A., Barré, J., Massart, S., Inness, A., Aben, I., Ades, M., Baier, B. C., Balsamo, G., Borsdorff, T., Bousserez, N., Boussetta, S., Buchwitz, M., Cantarello, L., Crevoisier, C., Engelen, R., Eskes, H., Flemming, J., Garrigues, S., Hasekamp, O., Huijnen, V., Jones, L., Kipling, Z., Langerock, B., McNorton, J., Meilhac, N., Noël, S., Parrington, M., Peuch, V.-H., Ramonet, M., Razinger, M., Reuter, M., Ribas, R., Suttie, M., Sweeney, C., Tarniewicz, J., and Wu, L.: Technical note: The CAMS greenhouse gas reanalysis from 2003 to 2020, *Atmospheric Chemistry and Physics*, 23, 3829–3859, <https://doi.org/10.5194/acp-23-3829-2023>, 2023.

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- Zhang, Q., Li, M., Wei, C., Mizzi, A. P., Huang, Y., and Gu, Q.: Assimilation of OCO-2 retrievals with WRF-Chem/DART: A case study for the Midwestern United States, *Atmospheric Environment*, 246, 118106, <https://doi.org/10.1016/j.atmosenv.2020.118106>, 2021a.
- Zhang, Q., Li, M., Wang, M., Mizzi, A. P., Huang, Y., Wei, C., Jin, J., and Gu, Q.: CO₂ Flux over the Contiguous United States in 2016 Inverted by WRF-Chem/DART from OCO-2 XCO₂ Retrievals, *Remote Sensing*, 13, 2996, <https://doi.org/10.3390/rs13152996>, 2021b.

6. Lack of meteorological field evaluation

The manuscript does not evaluate the WRF-Chem meteorological fields (e.g., wind speed and direction), which directly influence transport and mixing. A comparison of modeled meteorology with observational data is necessary to quantify biases and assess their effects on the inversion.

>> As suggested by the reviewer, we agree that evaluating meteorological fields is necessary because transport and mixing directly affect CO₂/CH₄ simulations and the inferred fluxes. Accordingly, our coupled system assimilates meteorological observations together with GHG concentrations so that meteorological analyses are continuously constrained during the inversion period. We also emphasize that the new surface parameterizations adopted in this study improve wind simulations near the surface (e.g., Lee et al., 2015; Lee and Hong, 2016; Lim et al., 2019; Lee et al., 2020; Kim et al., 2024; Lee et al., 2024; Jo et al., 2025; WMO, 2025). In the revised manuscript, we added a concise meteorological verification section alongside the inversion framework. Specifically, we evaluate near-surface winds (speed and direction) and report bias in Supplement (Fig. S12, Fig. S13 and Table S1). The results show that the cycling assimilation of NCEP PREPBUFR observations in the WRF-Chem/DART EAKF configuration substantially reduces transport errors during the inversion period, thereby increasing confidence that the inferred flux adjustments are not driven by gross meteorological biases. Relevant prior WRF-Chem/DART studies using similar configurations are now cited for context (Mizzi et al., 2016; Mizzi et al., 2018; Pouyaei et al., 2023).

- Jo, Y., Kim, S., Lee, Y., Kim, C., Hong, J., Lee, J., and Jang, K.: Evaluation of topographic effect parameterizations in Weather Research and Forecasting model over complex mountainous terrain in wildfire-prone regions, *Fire*, 8, 196, <https://doi.org/10.3390/fire8050196>, 2025.

- Kim, J. W., Shin, H., Lee, K., and Hong, J.: Enhancement of ANN-based wind power forecasting by modification of surface roughness parameterizations over complex terrain, *J. Environ. Manage.*, 362, 121246, <https://doi.org/10.1016/j.jenvman.2024.121246>, 2024.
- Lee, J. and Hong, J.: Implementation of space borne LiDAR-retrieved forest canopy height in the WRF model, *J. Geophys. Res. Atmos.*, 121, <https://doi.org/10.1002/2015JD024299>, 2016.
- Lee, J., Shin, H. H., Hong, S.-Y., Jimenez, P. A., Dudhia, J., and Hong, J.: Impacts of sub-grid scale orography parameterization on simulated surface-layer wind and monsoonal precipitation over Korea, *J. Geophys. Res. Atmos.*, 120, 644–653, <https://doi.org/10.1002/2014JD022747>, 2015.
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- Lim, K., Lim, J., Shin, H., Hong, J., and Ji, Y.: Impacts of subgrid-scale orography parameterization on simulated atmospheric fields in the high-resolution atmospheric forecast model, *Meteorol. Atmos. Phys.*, <https://doi.org/10.1007/s00703-018-0615-4>, 2019.
- Mizzi, A. P., Arellano Jr., A. F., Edwards, D. P., Anderson, J. L., and Pfister, G. G.: Assimilating compact phase space retrievals of atmospheric composition with WRF-Chem/DART: a regional chemical transport/ensemble Kalman filter data assimilation system, *Geoscientific Model Development*, 9, 965–978, <https://doi.org/10.5194/gmd-9-965-2016>, 2016.
- Mizzi, A. P., Edwards, D. P., and Anderson, J. L.: Assimilating compact phase space retrievals (CPSRs): comparison with independent observations (MOZAIC in situ and IASI retrievals) and extension to assimilation of truncated retrieval profiles, *Geoscientific Model Development*, **11**, 3727–3745, <https://doi.org/10.5194/gmd-11-3727-2018>, 2018.
- Pouyaei, A., Mizzi, A. P., Choi, Y., Mousavinezhad, S., and Khorshidian, N.: Downwind Ozone Changes of the 2019 Williams Flats Wildfire: Insights From WRF-Chem/DART Assimilation of OMI NO₂, HCHO, and MODIS AOD Retrievals, *Journal of Geophysical Research: Atmospheres*, **128**, e2022JD038019, <https://doi.org/10.1029/2022JD038019>, 2023.
- World Meteorological Organization (WMO): Integrated Global Greenhouse Gas Information System Good Practice Guidance for Estimating National-scale Greenhouse Gas Emissions using Atmospheric Observations, 2025 Edition, GAW Report No. 319, World Meteorological Organization, Geneva, Switzerland, 2025.

7. Unclear treatment of initial and boundary conditions & need for sensitivity analysis

It is not specified whether WRF-Chem/DART updates initial and boundary conditions in the single-domain configuration. And additional justification is needed to demonstrate that a single-domain setup is sufficient for obtaining reliable posterior estimates. Given that regional inversions are highly sensitive to boundary conditions—and considering the known negative CH₄ bias in EGG4—

additional sensitivity tests using alternative boundary conditions would help evaluate the robustness of the posterior estimates.

>> We acknowledge that boundary-condition biases (including CH₄ biases documented for EGG4) remain an important structural uncertainty for regional inversions. We have revised Section 2.2 to remove ambiguity about how initial and lateral boundary conditions are treated in our single-domain WRF-Chem/DART configuration. Initial conditions are updated every cycle through standard cycling (the next-cycle background is initialized from the previous analyzed ensemble). Time-varying lateral boundary conditions are prescribed from the external product and perturbed across the ensemble to maintain boundary spread. After each analysis, the DART “update_wrf_bc” procedure is used to apply the analysis increments consistently near the lateral boundaries to avoid spurious discontinuities, rather than to “optimize” the external boundary forcing itself.

We also clarify why a single 9-km domain is adequate for the framework demonstration in this manuscript. First, in our WRF configuration the lateral boundary forcing is applied through a boundary blending (“sponge”) region (specified zone + relaxation zone); we use 1 grid point for the specified zone and 4 grid points for the relaxation zone, and therefore restrict posterior diagnostics and station-based evaluations to the domain interior, excluding the outer 5 grid points where boundary relaxation is active. Second, the observing network and region of interest are well separated from the lateral boundaries, reducing the likelihood that boundary errors directly dominate the interior increments. This is consistent with recent theoretical work showing that BC-induced posterior flux errors depend on transport and information content and can be mitigated either by directly optimizing BC terms (boundary method) or by excluding an outer buffer region from the final analysis (Nesser et al., 2025).

Finally, our cycling strategy follows standard WRF/DART practice with 6-hour synoptic analysis times, with observations collected within approximately ± 3 hours of each analysis time. While a comprehensive exploration of alternative boundary products and domain/nesting configurations is beyond the scope of this model-description paper, we now explicitly outline a robustness protocol (alternative boundary prescriptions and bias-correction sensitivity tests) and identify multi-BC and/or nesting sensitivity experiments as an important follow-on step for application studies. The single-domain design was chosen to balance computational cost and resolution for high-resolution inversions, and the framework can be readily extended to alternative domain configurations.

Nesser, H., K. Bowman, M. Thill, D. Varon, C. Randles, A. Tewari, F. Cardoso-Saldaña, E. Reidy, J. Maasakkers, and D. Jacob (2025) Predicting and correcting the influence of boundary conditions in regional inverse analyses, *Geoscientific Model Development*, 18, 9279-9291, <https://doi.org/10.5194/gmd-18-9279-2025>.

8. Limited ground observation network & questionable ability to constrain emissions

The number and spatial distribution of ground sites appear insufficient to constrain national-scale emissions. The sites used are located near the national borders and represent background conditions, making it uncertain whether they provide meaningful constraints for South Korea's total emissions. Figures 6 and 7 also indicate limited uncertainty reduction in several high-uncertainty regions. Inclusion of satellite observations would likely enhance spatial representativeness.

>> We appreciate the reviewer's focus on observational representativeness and network adequacy. To avoid any confusion, we clarify that the inversion system presented here is not a Lagrangian (trajectory/footprint) inversion. Instead, it is an Eulerian regional inversion based on WRF-Chem forward transport coupled with DART's ensemble Kalman filtering, in which meteorological fields and tracer concentrations are evolved and updated on the model grid through cycling data assimilation. We have revised Section 2.2 to state this more explicitly and to distinguish our approach from commonly used Lagrangian frameworks. That said, the reviewer's underlying point, "how well the available observations constrain national-scale emissions" applies to both Eulerian and Lagrangian inversions. We therefore address it directly using our system's diagnostics (e.g., flow-dependent sensitivity/footprint implied by the ensemble, localization, and OSSE-style tests) and by discussing the implications for spatially non-uniform uncertainty reduction.

We agree that the current surface network limits fine-scale spatial attribution, and we do not claim that the present station set can uniquely resolve grid-scale emissions everywhere. However, limited station numbers do not necessarily preclude useful national-scale constraints when background handling, data selection, and transport sensitivity are carefully designed (e.g., Kenea et al., 2024; Steiner et al., 2024; Vardag and Maiwald, 2024). For example, national inversions have demonstrated robust national-scale CO₂ flux estimates using only a small number of well-characterized sites by focusing on well-mixed periods and carefully treating background conditions (e.g., the New Zealand national inversion using Baring Head and Lauder; Bukosa et al., 2025 and Supplement).

In our configuration, the effective constraint is expected to be spatially non-uniform because it depends on (1) the flow-dependent footprint of each site under the prevailing synoptic conditions, (2) boundary-layer mixing, and (3) covariance localization. Therefore, regions that are weakly coupled to the observing sites during the study period can show limited uncertainty reduction even when prior uncertainty is large. Transport and dispersion uncertainties further limit the recoverable spatial detail and can dominate the model–data mismatch, particularly at fine scales.

To separate observation limitations from methodological limitations, we add an OSSE-style capability test with a substantially denser surface-network scenario, showing that the same framework

yields stronger and more localized uncertainty reduction when observational coverage is increased, consistent with previous OSSE-based network-design studies.

We agree that satellite observations can enhance spatial representativeness and are a natural extension of the framework. We therefore state this explicitly as a planned follow-on development, while noting that satellite integration requires careful treatment of retrieval biases and vertical sensitivity and is beyond the scope of the present model-description manuscript.

Bukosa, B., Mikaloff-Fletcher, S., Brailsford, G., Smale, D., Keller, E. D., Baisden, W. T., Kirschbaum, M. U. F., Giltrap, D. L., Liang, L., Moore, S., Moss, R., Nichol, S., Turnbull, J., Geddes, A., Kennett, D., Hidy, D., Barcza, Z., Schipper, L. A., Wall, A. M., Nakaoka, S.-I., Mukai, H., and Brandon, A.: Inverse modelling of New Zealand's carbon dioxide balance estimates a larger than expected carbon sink, *Atmospheric Chemistry and Physics*, 25, 6445–6473, <https://doi.org/10.5194/acp-25-6445-2025>, 2025.

Kenea, S., Shin, D., Li, S., Joo, S., Kim, S., and Labzovskii, L.: Designing additional CO₂ in-situ surface observation networks over south Korea using Bayesian inversion coupled with Lagrangian modelling, *Atmos. Environ.*, 326, 120471, <https://doi.org/10.1016/j.atmosenv.2024.120471>, 2024.

Steiner, M., Cantarello, L., Henne, S., and Brunner, D.: Flow-dependent observation errors for greenhouse gas inversions in an ensemble Kalman smoother, *Atmos. Chem. Phys.*, 24, 12447–12463, <https://doi.org/10.5194/acp-24-12447-2024>, 2024.

Vardag, S. N. and Maiwald, R.: Optimising urban measurement networks for CO₂ flux estimation: a high-resolution OSSE using GRAMM/GRAL, *Geosci. Model Dev.*, 17, 1885–1902, <https://doi.org/10.5194/gmd-17-1885-2024>, 2024.

9. Filtering of WMO/GAW background-site observations

WMO/GAW stations typically apply data filtering to remove local source influences. It is unclear whether filtered or unfiltered measurements were used in this study, and this point should be clarified. If filtered data were used, the reduced local variability may limit the ability of the assimilation system to effectively constrain regional emissions.

>> We clarify that we assimilated the Level-2 quality-assured WMO/GAW in situ mole-fraction products. As documented in the station measurement reports (Lee et al., 2019; Lee et al., 2023), Level-2 processing focuses on QA/QC to remove instrument-related artifacts (e.g., malfunction periods, calibration intervals, and sampling instabilities) and is distinct from Level-3 “background-selected” products that apply additional selection to isolate baseline conditions. No additional Level-3 baseline selection/background filtering was applied in this study, and therefore short-term enhancements potentially attributable to regional emissions were retained for assimilation. We revised Section 3 to remove any ambiguity about the data product level, the applied filtering, and the rationale for retaining enhancements.

Lee, H., Han, S.-O., Ryoo, S.-B., Lee, J.-S., and Lee, G.-W.: The measurement of atmospheric CO₂ at KMA GAW regional stations, its characteristics, and comparisons with other East Asian sites, *Atmospheric Chemistry and Physics*, **19**, 2149–2163, <https://doi.org/10.5194/acp-19-2149-2019>, 2019.

Lee, H., Seo, W., Li, S., Lee, S., Kenea, S. T., and Joo, S.: Measurement report: Atmospheric CH₄ at regional stations of the Korea Meteorological Administration–Global Atmosphere Watch Programme: measurement, characteristics, and long-term changes of its drivers, *Atmos. Chem. Phys.*, **23**, 7141–7159, <https://doi.org/10.5194/acp-23-7141-2023>, 2023.

10. Missing wetland emissions for CH₄ and lack of chemistry description

Wetland CH₄ emissions—one of the dominant natural CH₄ sources—are not included, and the potential impact of this omission is not discussed. In addition, CH₄ oxidation by OH radicals should be addressed, but the manuscript does not describe how WRF-Chem handles this chemistry.

>> We thank the reviewer for highlighting the missing treatment of natural wetland CH₄ emissions and the need to clarify CH₄ chemistry. The inventory data used in this study, EDGAR does not include natural wetland methane emission and it is reported that annual CH₄ emission from natural wetlands in Korea is about 0.001 – 0.01 Tg CH₄ (Zhang et al., 2025). This is less than 0.5% of national total anthropogenic CH₄ emissions. OH chemistry is still challenging to simulate in the atmospheric chemistry model and many methane-focused 3-D inversion systems and even CAMS EGG4 uses prescribed OH fields (or climatological OH-driven loss rates) rather than simulating OH interactively, therefore treat the CH₄ sink in an empirical/parameterized manner; this can contribute to systematic biases in CH₄, particularly when the assumed loss rate is imperfect (e.g., Zhao et al., 2020; Agustí-Panareda et al., 2023). CO₂ and CH₄ can be treated as a passive tracer for our regional application because the chemical lifetime of CH₄ against OH is on the order of years (about 9 years) (See WRF-GHG official document and Saunio et al. (2020) for more information), whereas typical air-mass residence times across our regional domain are <1 day. The implied fractional loss over 1 day is therefore $< 1 / (9 \times 365) \approx 0.03\%$, which is negligible compared to transport and emission uncertainties. Finally, large-scale chemical aging and seasonality are already reflected in the CAMS EGG4 concentration fields used to prescribe the initial and lateral boundary conditions; thus our regional system focuses on resolving transport and source-driven enhancements within the domain rather than re-simulating a negligible local chemical sink.

Callewaert, S.: User guide for the greenhouse gas option of WRF-Chem (WRF-GHG), Royal Belgian Institute for Space Aeronomy (BIRA-IASB), <https://doi.org/10.18758/q6rapneu>, 2024.

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- Zhao, Y., Saunois, M., Bousquet, P., Lin, X., Berchet, A., Hegglin, M. I., Canadell, J. G., Jackson, R. B., Dlugokencky, E. J., Langenfelds, R. L., Ramonet, M., Worthy, D., and Zheng, B.: Influences of hydroxyl radicals (OH) on top-down estimates of the global and regional methane budgets, *Atmos. Chem. Phys.*, 20, 9525–9546, <https://doi.org/10.5194/acp-20-9525-2020>, 2020.

11. Insufficient discussion of results

The evaluation of top-down estimates lacks depth. For example, the reasons behind the strong improvements at AMY and GSN, the pronounced summer behavior, and the underestimation of CH₄ in vertical profiles are not explained. In particular, the manuscript mentions "underlying mechanisms for the maritime CH₄" but does not clarify what those mechanisms are or how they influence the vertical structure. Similar gaps appear in the CO₂ increment patterns across different regions; for instance, negative increments in SMA and MWI and positive increments in SCI and SEI are reported without any discussion of potential drivers. Without addressing these points, it is difficult to assess the reliability of the results.

>> We agree that additional interpretation is needed to help readers assess the reliability of the top-down results. We therefore expanded Section 7 (formerly Section 6 in the preprint) and added mechanism-oriented explanations for each point raised by the reviewer, with explicit cross-references to the relevant diagnostics.

- (1) The strong improvements at AMY and GSN and the associated seasonal (summer) behavior are now discussed in Section 7.1 using the monthly distributions and performance statistics (Fig. 5 and Table 1). We also explicitly relate the pronounced summertime CH₄ features to large-scale/background behavior in the boundary forcing (Fig. S9).
- (2) The systematic CH₄ underestimation in vertical profiles is now documented and discussed in Section 7.2 using independent aircraft vertical profiles (Fig. 6; flight information in Fig. S7). In the same subsection, we clarify the maritime CH₄ issue as a possible discrepancy between EGG4 and EDGAR over ocean grids that can affect coastal/marine baseline concentrations and thus the vertical structure (Section 7.2; Fig. 6).
- (3) The regional CO₂ increment sign patterns (negative in SMA/MWI and positive in SCI/SEI) are now explicitly described in Section 7.4 with the corresponding increment map (Fig. 10b). The associated CH₄ increment behavior is discussed alongside (Fig. 10d), including a brief cautionary interpretation regarding potential boundary-related effects (Section 7.4).

These additions provide the essential physical context needed to assess consistency and limitations of the presented results, while keeping the overall scope aligned with a model-description manuscript.

12. Limitations of bottom-up inventory comparisons

When comparing total anthropogenic emissions with bottom-up inventories, sectoral coverage should be consistent across datasets. If they are not harmonized, the manuscript must explain the sectoral differences for proper interpretation. The discussion of why posterior emissions align with ROK-BTR but differ substantially from ODIAC is also insufficient. Lines 399–400 are unclear and require revision.

>> As suggested by the reviewer, we revised the manuscript to make explicit what is compared: national-total anthropogenic CO₂ excluding LULUCF, aggregated consistently over the South Korea domain and the analysis period. We also clarify that full sector-by-sector harmonization is not always possible across products with fundamentally different constructions; however, we now document the remaining scope differences so that the comparison is interpreted correctly.

Specifically, ROK-BTR is an official national inventory compiled from detailed activity data and reported following IPCC sector definitions, whereas ODIAC is a global fossil-fuel CO₂ product that estimates emissions and downscales them spatially using proxy information (e.g., point sources and nightlights). Therefore, differences can arise from (1) scope/coverage (e.g., treatment of industrial process CO₂, international bunkers, and other non-combustion categories), (2) methodological choices in spatial disaggregation and temporal allocation, and (3) uncertainty in proxy assumptions that can affect both the national total and its distribution. We frame the inventory comparison as a consistency check for policy-relevant totals rather than as a validation claim. This is consistent with prior inter-comparisons showing that high-resolution fossil-fuel CO₂ inventories can differ substantially due to differing methodological choices and proxy assumptions (Hutchins et al., 2017). In this context, Lines 399–400 have been rewritten to explicitly state these scope and methodological differences and to avoid implying that ODIAC is directly comparable to a full IPCC inventory without caveats (Lines 592, “*We note that these products differ in scope and construction ...*”).

Hutchins, M. G., Colby, J. D., Marland, G., and Marland, E.: A comparison of five high-resolution spatially-explicit, fossil-fuel, carbon dioxide emission inventories for the United States, *Mitig Adapt Strateg Glob Change*, **22**, 947–972, <https://doi.org/10.1007/s11027-016-9709-9>, 2017.

13. Additional issues

Lack of contextual clarity for EGG4 CO₂ and CH₄ errors: The discussion of EGG4 biases in Lines 185–190 does not clearly connect with the surrounding text. The purpose and relevance of this information within the flow of the manuscript are unclear.

>> As suggested by the reviewer, we revised Section 4 of our manuscript to clarify why EGG4 CO₂/CH₄ bias information is introduced at this point in the manuscript. Specifically, we now state explicitly that the EGG4 bias information is provided as diagnostic context for boundary-condition uncertainty, which is a known driver of structural error in regional inversions, and that it is used to interpret posterior behaviors and limitations discussed later in Section 7. To improve the flow, we also added a short transition sentence linking this diagnostic context to the subsequent configuration description (boundary/initial condition specification and perturbation strategy). The revised text makes clear that the EGG4 bias discussion motivates our boundary-uncertainty treatment and frames the later sensitivity/limitation discussion.

Input data preprocessing: The manuscript does not describe how datasets with differing spatial and temporal resolutions were regridded and harmonized.

>> As suggested by the reviewer, we revised the manuscript to describe the harmonization procedures at the points where each input is introduced (Sections 4 and 5.1–5.4). In brief, all heterogeneous inputs are mapped to the 9-km WRF grid and hourly cycling timeline using the following steps:

- (1) Spatial mapping: gridded flux inventories are reprojected to the WRF Lambert Conformal Conic (LCC) grid and regridded using area-weighted conservative remapping to preserve domain-integrated emissions; fields that represent state variables (e.g., mixing ratios) are interpolated using bilinear methods.
- (2) Temporal harmonization: sub-daily cycling inputs are obtained by applying documented temporal profiles (e.g., sector-dependent diurnal/weekly scaling for EDGAR; hourly injection for FINN; monthly-to-hourly prescription for SeaFlux; VPRM computed at the model time step), ensuring that the time-integrated totals are conserved over the parent interval (daily/monthly).
- (3) EGG4 GHG IC/BCs: EGG4 3-D mole fractions are horizontally interpolated to the WRF boundary/initial fields and linearly interpolated in time between analysis times; vertical interpolation is performed from the native EGG4 vertical levels to WRF's hybrid vertical coordinate used for chemical/tracer initialization.

These additions clarify how differing spatial/temporal resolutions are handled without changing the underlying methodology.

VPRM parameters: The text states that parameters were adopted but does not specify which ones or why

>> We used the VPRM parameter set calibrated for East Asia reported by Li et al. (2020). As suggested by the reviewer, we revised Section 5.4 to explicitly list the adopted VPRM parameters (e.g., $\lambda, \alpha, \beta, PAR_0$) for each land-cover/vegetation class used in this study (now provided in Table Sx), and to explain the rationale for this choice. Specifically, we adopted Li et al. (2020) because it provides a regionally robust parameterizations evaluated with East Asian ecosystems.

Figure 7: Prior flux exists over the ocean, yet its uncertainty is zero; the rationale should be explained. The reduction of uncertainty over North Korea and China also requires discussion.

>> We acknowledge that Fig. 7 (now Fig. 8 after revision) can be misread without clarification and we revised the texts and figure. The prior uncertainty over the ocean is not set to zero; rather, the ensemble spread is prescribed as a fractional perturbation of the flux (e.g., 30%), so oceanic flux components with much smaller magnitudes yield correspondingly small absolute uncertainties. In this figure, these values can appear near-zero because the color scale is dominated by large terrestrial/urban sources; however, they are treated as non-zero variances in the filter under the same multiplicative uncertainty formulation. We have updated the figure caption to clarify this interpretation.

Regarding the small uncertainty reductions over North Korea and some parts of China, these arise from weak but non-zero concentration–flux cross-covariances within the localization radius under occasional transport connectivity across the domain boundaries. We interpret these as marginal numerical effects rather than robust observational constraints. We therefore add a brief note stating that transboundary updates are not quantitatively interpreted in this study and that our discussion focuses on the South Korean domain where observational constraints are strongest.

RC2: '[Comment on egusphere-2025-4938](#)', Anonymous Referee #2, 12 Dec 2025

The manuscript presents a dual state inversion framework developed at Yonsei University to estimate CO₂ and CH₄ emissions over Korea. The inversion is based on a coupling of DART and WRF-Chem, two widely used (and published) tools, so there is not a lot of technical novelty, but the setup itself is rather uncommon (at least in the GHG inversion field).

I guess the aim of publishing this in GMD is to have a published setup for referencing in future studies? This is totally fine, but then the authors need to do a little more than just presenting their coupling and one use case. They should clarify the interest (and drawbacks) of their dual-state setup, and justify the settings they used (uncertainties, correlations, resolution, choice of variables to be optimized, data selection, etc.). This should be demonstrated (e.g. through sensitivity experiments), not just stated. Currently the paper just shows the results of one single experiment, without really delving into what makes it a good experimental setup. That's a bit light. I also don't think that the comparison with the CAMS global GHG reanalysis is very insightful.

Overall though, what is written is well written, the topic is important and the setup is interesting, so the paper should eventually get published, once these comments have been addressed.

>> We thank the reviewer for this overall assessment. As suggested by the reviewer, we revised our GMD model-description paper to demonstrate the value of the configuration beyond a single use case. The goal of this study is to provide a fully documented, reproducible WRF-Chem/DART dual-state, dual-species (CO₂/CH₄) regional inversion workflow, and to demonstrate its behavior using both real-data experiments and a controlled OSSE, so that the community can apply and extend the system to other regions and observing systems. Accordingly, in the revised manuscript we demonstrated these issues by (1) clearly articulating what is enabled by our specific dual-state, dual-species configuration, (2) transparently documenting and justifying the numerical and methodological settings (uncertainties, correlations/localization, resolution, optimized variables, and data selection), and (3) providing targeted demonstrations (e.g., OSSE/sensitivity tests) that the setup behaves as intended.

To address these concerns, we substantially revised the manuscript as follows:

1. Clarified the interest and architecture of the current model system configuration.

We now explicitly provide detailed descriptions of our DA configuration with the augmented state vector and the explanation of the dual-state mechanism: meteorology and tracer concentrations are updated directly, while emissions/flux parameters are updated through ensemble-estimated concentration–flux cross-covariances. (Section 2.2). We also added a concise discussion of key trade-offs such as computational cost to other kinds of inversion systems.

2. Made the configuration choices traceable and reproducible, and justified “why these settings.”

We expanded the technical description (Section 2.2) with a step-by-step cycling workflow

and a compact configuration summary covering: optimized variables, cycling window, localization/inflation, observation types and selection, and prior uncertainty magnitudes. We also added input harmonization details (regridding and temporal disaggregation) at each data introduction point (Sections 4 and 5.1–5.4). In addition, we clarified the rationale for key uncertainty settings: 5% IC/BC perturbations as a pragmatic spread-maintenance choice for EGG4-based inflow fields, and 30% prior emission uncertainty tied to the empirically observed inter-inventory spread for South Korea (EDGAR/ODIAC/ROK-BTR), with explicit scope caveats and harmonization statements (anthropogenic CO₂ excluding LULUCF; consistent spatial aggregation and units).

3. Added controlled demonstrations and sensitivity-style tests to go beyond a single experiment. To provide quantitative evidence that the configuration is a sound experimental setup, we added a twin-style OSSE (Section 6) to test algorithmic consistency and flux recoverability under a known truth (imposed prescription of sector-specific emissions), reporting uncertainty reductions. Our OSSE-style denser-network scenario illustrates how increased information content leads to stronger and more spatially localized uncertainty reduction within the same framework, thereby effectively recovering regional emission signals and separating observing-system limitations from methodological limitations.

4. Reframed the CAMS/EGG4 comparison to increase relevance.

We clarify that EGG4 is used as the prescribed IC/BC product; discussion of documented EGG4 biases is included only as diagnostic context for boundary-condition uncertainty that helps interpret posterior behavior and limitations (especially for CH₄), rather than as a validation target.

5. Better Documentation of parameterization and configurations incorporated in the system for complex terrain.

Our system is based on established community tools, enabling the wider research community to apply it with different options. In addition, because near-surface transport is critical for high-resolution inversions over complex terrain, we note that our WRF configuration incorporated surface-layer/canopy-related options (e.g., roughness sublayer and canopy-height adjustments, Section 2.1).

Overall, these revisions are intended to make the manuscript a useful, citable reference for future studies: a fully specified and reproducible coupled WRF-Chem/DART dual-state, dual-species regional inversion workflow, accompanied by clear design rationale, documented configuration choices, and targeted controlled tests that demonstrate stability/consistency while transparently stating limitations and robustness considerations. We appreciate for your constructive comments.

Specific comments:

- The method description isn't sufficiently clear around what exactly is solved for by the data assimilation system. It seems to adjust the emissions (so it's an inversion?), but, according to Section 2.1, it adjusts meteorological and tracer fields (so it's an atmospheric state data assimilation?). Having some mathematical description of what happens (i.e. some equations) would help a lot. I assume it's an inversion, because emission adjustments are presented. I wonder if the tracer fields are directly modified by the assimilation as well?

>> As suggested by the reviewer, we substantially expanded the methodology description. In the revised manuscript (Section 2.2), we explicitly define the system as a joint state and parameter estimation framework using state augmentation. We also document the coupled WRF-Chem/DART cycling workflow step-by-step and summarize key configuration settings used in this study for reproducibility. Finally, we include more standard DART/EAKF references and documentation for readers who want additional algorithmic details. We also clarify that the 3-D tracer fields are directly modified by the analysis step. We now clearly articulate that:

(1) Atmospheric State (Direct Update): Meteorological variables and the 3-D CO₂/CH₄ concentration fields are included in the state vector (x_{met}, x_{chem}) and are directly updated at each analysis time using observations (i.e., standard sequential atmospheric state data assimilation). This joint update helps to maintain dynamical and transport–concentration consistency throughout cycling.

(2) Surface Fluxes (Indirect Update): Anthropogenic emission fluxes (x_{flux}) are included as unobserved parameters in the augmented state. They are updated indirectly through flow-dependent ensemble cross-covariances between the flux parameters and concentration innovations.

(3) A quantitative check of the data assimilation. We added a targeted OSSE to the revised manuscript, using an expanded 50-site synthetic surface network to test whether the framework can recover the intentionally imposed “missing power-industry” emission signal (a highly heterogeneous, point-source-dominated target) and to diagnose filter stability/consistency (including uncertainty reduction and innovation behavior). All OSSE configuration details and results are documented in Section 6 of the revised manuscript and Supplement for reproducibility. We emphasize that this OSSE is included to demonstrate algorithmic consistency and stability under controlled conditions; real-world performance remains influenced by transport errors, boundary-condition biases, and representativeness errors, which we discuss explicitly. The main focus of the manuscript remains the real-data demonstration.

To address the reviewer's request for explicit equations, we have added the concise mathematical description to Section 2.2 with proper references, including the definition of the augmented state vector ($\mathbf{x} = [\mathbf{x}_{met}, \mathbf{x}_{chem}, \mathbf{x}_{flux}]^T$) and the EAKF update equations that show how tracer-state updates occur directly while flux updates arise via ensemble-estimated cross-covariances (with covariance localization).

- The dual-tracer, dual-state setup is rather uncommon: what benefit does it provide upon a more classical inversion, solving only for emissions? What are the costs? This should be demonstrated, not just stated (i.e. through sensitivity experiments, at least). Even for more classical aspects (choices of uncertainties, correlations, data filtering, treatment of the boundary condition), at least some idea of what are the most impactful settings (within that particular inversion framework) should be provided.

>> As suggested by the reviewer, we revised the manuscript to address this point quantitatively, consistent with the scope of a GMD model description paper.

1. Rationale and benefits of dual-state setup:

While emission-only inversions are computationally cheaper, we chose a coupled Eulerian framework to address the critical issue of transport error aliasing. By assimilating meteorological observations alongside tracers, we constrain the meteorological fields during the cycling window, reducing the likelihood that persistent transport biases are spuriously mapped onto flux corrections. In addition, the direct analysis update of 3-D tracer fields provides a necessary “state reset” at each cycle. This reduces the accumulation of background tracer errors in the cycling EAKF system, thereby limiting systematic over-adjustment of flux parameters across successive cycles in a sequential (cycling) inversion setting. The framework also yields a unified, dynamically consistent analysis of meteorology, tracer concentrations, and fluxes, which is essential for diagnosing transport-driven anomalies in complex terrain. Furthermore, the choice of a dual-tracer configuration reflects the primacy of CO₂ and CH₄ as the two most policy-relevant anthropogenic greenhouse gases in terms of their emissions and climate relevance, and they dominate national-scale mitigation and verification priorities. This setup allows the same regional DA and transport framework to be applied consistently to both primary target species within a unified workflow; however, we emphasize that we do not apply cross-species covariances and the two tracers are updated independently under the same constrained transport environment.

2. Costs and trade-offs:

Running a full ensemble of online WRF-Chem forecasts is significantly more expensive than offline transport-driven inversions. Moreover, the dual-state approach requires careful tuning of localization and inflation to manage sampling errors and maintain filter stability, making the setup more complex

than simple flux-scaling methods. We therefore document these controls explicitly to support reproducibility and clarify the primary tuning knobs for users.

3. Quantitative demonstration with a controlled twin-experiment (OSSE) and targeted sensitivities

To provide a controlled quantitative check, we added a twin-style OSSE (Section 6) showing that the system can recover a known truth (e.g., a prescribed power-sector emission perturbation), with associated uncertainty reduction and ensemble-consistency diagnostics. This OSSE also tests whether the chosen localization and error statistics propagate information from concentration innovations to flux parameters in a physically consistent manner. While a full emissions-only versus dual-state intercomparison across multiple cases would be a valuable follow-on, it is beyond the scope of this model-description paper.

4. Most impactful settings

We now explicitly document the controls that most strongly influence the posterior flux estimates within this framework, including localization (to filter spurious long-range correlations in the augmented state), the balance between prior spread and observation error (which determines the effective magnitude or “stiffness” of flux updates), and inflation (critical for preventing ensemble collapse in a cycling system). We also document the treatment of initial/lateral boundary conditions and the QC/filtering procedures, which strongly influence baseline gradients and the stability of cycling updates in a regional domain.

We believe this balanced discussion, acknowledging both the transport advantages and the computational costs, provides the transparency required for a GMD model description paper and responds to the request to indicate which settings are most impactful within this specific inversion framework.

- I think there is some confusion between high resolution transport and high resolution inversion. At line 369, you claim that: "the $0.75^\circ \times 0.75^\circ$ resolution of EGG4 is not enough to resolve the sharp urban-industrial emission heterogeneity and fine scale sources and sinks across Korea. They motivate the use of high resolution regional inversion". It's quite obvious that fine scale processes will be better represented in a higher resolution model. But that doesn't mean that you "resolve" (as in, robustly constrain) the emissions at that resolution. You have three observation points, distant from each other by a few hundreds of kms, so you can't resolve emissions pattern at much finer scale. Finer-scale components of the posterior are mainly just carried forward from the prior. So at line 375, the statement that "Local increments of anthropogenic CO₂ and CH₄ emissions (...) are evident" is not really true: the increments appear local only in absolute magnitude. If they were shown as proportion to the prior uncertainties, they would appear as smooth, wide scale patterns. This is in fact very visible in Figure 10.

>> As suggested by the reviewer, we revised our manuscript to address this point properly, consistent with the scope of a GMD model description paper.

1. Clarification of “resolution” vs. “constraint.”

We acknowledge that, with the current sparse network (three sites), the system primarily constrains broad, regional-scale modes of the flux field rather than independently resolving grid-scale emissions. We therefore revised the Results/Discussion text to remove wording that could be interpreted as “resolving” fine-scale sources at 9 km under the present observational coverage. We clarify that the motivation for the 9-km configuration is to reduce transport representation errors (e.g., complex topography, coastal circulations, and urban heterogeneity) that are critical for linking observations to regional fluxes, while the effective spatial scale of posterior flux constraint is set by network information content. Accordingly, at 9 km the posterior should be interpreted as a transport-consistent flux field whose independently constrained degrees of freedom are coarser than the grid spacing under the present network.

2. Reinterpretation of local increments

We agree that the term “local increments” in the original text could be misleading. We revised the phrasing to describe the posterior as “spatially varying adjustments within the localization-supported influence region,” rather than evidence of independently resolved grid-scale corrections. Consistent with the reviewer’s point (visible in Fig. 10; renumbered as Fig. 8 in the revised manuscript), the smoothness of posterior adjustments is an expected outcome of covariance localization and limited information content: with sparse observations, the posterior retains much of the prior’s fine-scale spatial structure and mainly adjusts the large-scale modes that are observable given the network geometry and the imposed covariance and localization. We also delineate that apparent localization in absolute increments should not be interpreted as grid-scale resolvability when assessed relative to prior uncertainty or uncertainty reduction. In addition, the map shown is time-aggregated (period mean), so short-lived, flow-dependent increment patterns are smoothed and the figure primarily reflects robust, low-frequency adjustments supported by the available information content. We also clarify that the present application targets regional/national-scale constraints under the current network, rather than city-scale attribution as implied by the title.

3. Capability under denser coverage (controlled demonstration).

To separate observing-system limitations from methodological limitations, we added a controlled OSSE (Section 6) with a substantially denser synthetic surface network. Under this increased information content, the same framework yields stronger and more spatially localized posterior constraints and uncertainty reduction compared to the real-data three-site configuration. We present this OSSE as a capability demonstration under controlled conditions, without implying that the real-data three-site configuration achieves 9-km flux “resolution.”

- The comparison with the surface concentrations in EGG4 ... just shows that EGG4 had a lower resolution, nothing more (so something that was known beforehand). In particular, it says nothing about the emissions, which is not a variable that EGG4 solves for, but which are your real target. Besides this comparison, the presentation of the results focuses mainly on the emissions, except for Figure 6 which shows the uncertainty reduction in the concentration space. I am however wondering how much the direct adjustment of the tracers (if it is done) compares with the adjustment of the emissions, and with that of the boundary condition, in contributing to improving the fit to observations. And does it make sense to adjust all of them? This needs to be better presented and justified.

>> As suggested by the reviewer, we clarified in the revised manuscript that CAMS EGG4 is used primarily as the prescribed IC/BC product. This revision addresses the reviewer's concern by clarifying that the EGG4 is used as the prescribed IC/BC forcing and by explicitly presenting the complementary roles of state and flux updates under prescribed boundary forcing. For better readability, we moved the corresponding figure(s) to the Supplement and revised the surrounding text accordingly.

1. Role of EGG4: not an emission comparison and a validation target

In this study, CAMS EGG4 provides CO₂/CH₄ initial and lateral boundary mole fractions for the WRF-Chem/DART cycling simulations (with small ensemble perturbations to maintain boundary spread). We have revised the text to clearly state that the comparison with EGG4 concentrations is not intended as an emissions evaluation. Instead, it is used only to provide context on the limitations of coarse-resolution background forcing and to motivate why high-resolution regional transport is needed to represent sharp gradients and mesoscale flow-terrain effects over Korea.

2. Drivers of improved fit to concentration observations in our configuration

We revised Section 2.2 and Results section to make the roles of each component explicit. In our cycling EAKF configuration, meteorological variables and 3-D tracer mixing ratios are updated directly with their respective observations at analysis times, while emissions/flux parameters are updated indirectly through flow-dependent ensemble cross-covariances between flux parameters and tracer innovations (state augmentation). Consequently, the immediate improvement in the analysis-time fit is driven primarily by the direct state update, whereas emission updates contribute to the persistence of improvements across cycles by correcting the emission input for subsequent forecasts (e.g., reduced recurring innovations and improved short-term forecasts). We emphasize in the revised text that updating both state and flux is therefore meaningful and complementary in a cycling inversion framework.

3. Why boundary conditions are not competing “controls” in this configuration.

Lateral boundary mole fractions are prescribed from CAMS EGG4 and are not treated as state vector (control variables) in the analysis. The post-analysis boundary procedure (`update_wrf_bc`) is applied solely to maintain numerical consistency near the boundary relaxation zone and avoid discontinuities, rather than to tune external inflow. Therefore, the system does not involve a trade-off between boundary tuning and emission estimation; boundaries are prescribed, while within-domain state and flux updates operate as described above. We note, however, that residual errors in prescribed boundary forcing can still project partially onto within-domain concentrations and inferred flux adjustments; we therefore interpret boundary-related diagnostics separately from within-domain emission increments.