

Reply on RC1

We sincerely thank the reviewer for the careful evaluation of our manuscript and for the constructive and insightful comments. We greatly appreciate the time and effort devoted to reviewing our work. The comments have helped us improve both the scientific presentation and the clarity of the manuscript. We have carefully considered all suggestions and revised the manuscript accordingly. In this response, your original comments are completely unedited and are given in yellow highlight, our responses are given in blue text and updates to the paper are given in purple text.

The revisions include: (1) clarifying the potential influence of biomass burning and residential solid-fuel combustion; (2) distinguishing the study domain from the facilities used in the source-category analysis; (3) clarifying the propagation of observational uncertainty into CO emission estimates and distinguishing this contribution from total emission uncertainty; (4) moderating claims regarding independent validation, EDGAR bias, policy effectiveness, and coal-fire seasonality; (5) adding a seasonally adjusted trend analysis with HAC standard errors and a seasonal Mann-Kendall robustness test; (6) quantifying the 37.9% endpoint decline and the 40.8% reduction in hotspot intensity; and (7) revising the text, captions, terminology, and statistical interpretation throughout the manuscript.

This study quantified daily gridded CO emissions in Central Asia for 2019-2024 and assessed CO trends and hotspots. This study provided actionable insights for inventory improvement and migration strategies. This topic is interesting and meaningful to readers. I only have some small suggestions.

Special comments:

1 Lines 35-37. CO is also emitted by biomass burning. What about biomass burning emissions in the research region? For example, anthropogenic biomass burning for cooking and heating from wood and yak dung in rural areas.

Response: We appreciate the reviewer's valuable suggestion. Biomass burning and residential solid-fuel combustion may contribute to regional CO concentrations and seasonal variability, particularly during the heating season. MFIEF estimates daily grid-scale CO emissions from atmospheric observations without explicitly separating individual source sectors. Contributions from these sources may therefore be included in the retrieved emissions. We have acknowledged these contributions in Section 2.1 and Section 3.1. The Discussion also clarifies that differences between MFIEF and EDGAR may reflect differences in source coverage, spatial and temporal allocation, and estimation methodology. The present analysis characterizes grid-scale emission patterns and selected source environments; it does not quantify the separate contributions of biomass burning and fossil-fuel combustion. One strength to our approach however is a more robust uncertainty in the emissions on the grid and how the uncertainty changes over time as well (Qin et al., 2023).

Revised manuscript, Sect. 2.1, lines 97-98: “The region also contains rural areas where residential solid fuel combustion and occasional biomass burning may contribute to seasonal CO variability.”

Revised manuscript, Sect. 3.1, lines 254-256: “Elevated CO is also found in parts of northwestern Kazakhstan, where biomass burning and residential solid fuel combustion may contribute to seasonal variations in the regional background CO, particularly during the heating season.”

Revised manuscript, Sect. 4 Discussion, lines 437-444: “EDGAR estimates anthropogenic emissions using sector-specific activity data and emission factors on a monthly time scale and locates them based on a priori information, whereas MFIEF derives a grid-scale signal constrained by atmospheric observations. Differences are due to a mixture of additional emitting sources on the same grid cell, new or missing sources not included in EDGAR, sources which are located at a different location than where the a priori information provides, or sources which genuinely are emitting more or less than the bottom-up approach calculates. Differences in atmospheric transport, satellite sampling and retrievals, and inversion assumptions including chemistry, physics, and long-range-transport may all contribute to the observed variability and uncertainty in the top-down estimate.”

2 Figure 1. Strangely, there are no power/steel plants or coal bases in the Central Asian countries. I also suggest adding the province or country names in Figure 1; otherwise, readers may be confused by the regions mentioned in the text.

Response: We thank the reviewer for this helpful suggestion. We agree that the original Figure 1 could give the impression that the mapped industrial facilities represent the entire Central Asian study domain. The inversion covers 35°–50° N and 70°–100° E, whereas the source-category analysis uses facilities in Xinjiang and adjacent parts of Gansu and Qinghai. To make the category-level comparison temporally consistent, we further restricted the industrial sample to facilities that operated continuously throughout 2019–2024. After excluding intermittently operating facilities and non-coal-fired power plants, the final sample comprised 53 coal-fired power plants and 4 steel plants. We revised the Figure 1 caption and the corresponding description in Section 2.1 to state this scope explicitly and retained the geographic labels added to improve readability.

Revised manuscript, Sect. 2.1, lines 101–102: “Fig. 1 illustrates the study area together with the coal bases, steel plants, and power plants included in the source-category

analysis.”

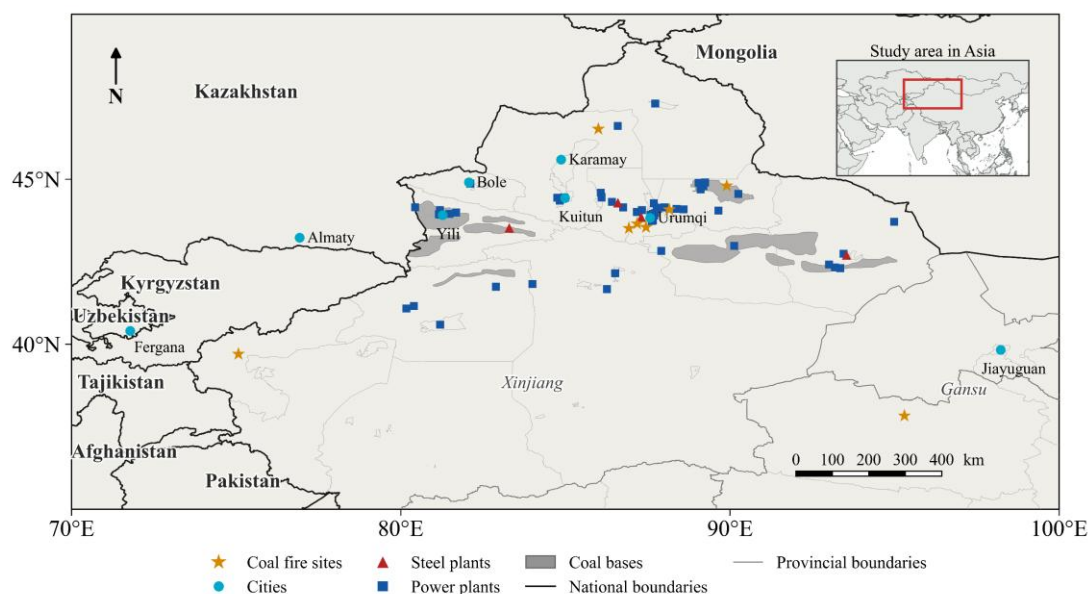


Figure 1. Study area (35°–50° N, 70°–100° E). The mapped coal bases and industrial facilities provide geographic context for the source-category analysis and are located in Xinjiang and adjacent parts of Gansu and Qinghai. For the 2019–2024 category-level statistics, only continuously operating facilities were retained, comprising 4 steel plants and 53 coal-fired power plants.

3 Line 195-200. Equation 2 was used to calculate the change in CO emissions. But uncertainty is usually not defined as the change of certain values.

Response: We appreciate the reviewer's valuable comment. We have considered that the observed CO column loadings have an amount of uncertainty and have perturbed these observations and then run these through MFIEF in an attempt to quantify the impact that this uncertainty has on the emissions range. I believe that it is a quantitative way by which to start to constrain the uncertainty of CO emissions. However, I agree that it may not represent the absolute magnitude of uncertainty of CO emissions and likely underestimates it, since additional pieces of information and uncertainties may also be present which have not been accounted for by our observational perturbation ranges or MFIEF model. Our intention was to attempt to place a quantitative range on the emission uncertainty by considering the effects of how observational uncertainties propagate through the inversion and affect the stability of retrieved emissions. For more details on the method as applied to NO_x see Lu et al., (2025) and as applied to CH₄ see Zheng et al., (2026) .

Revised manuscript, Sect. 2.4, lines 210–211: “Accordingly, this study propagates the assumed observational uncertainties through MFIEF and quantifies the corresponding range of variation in the inverted emissions and allows for a more robust product.”
Revised manuscript, Sect. 2.4, lines 219-220: “The calculated changes define the emission uncertainty range associated with propagation of the perturbed observational inputs.”

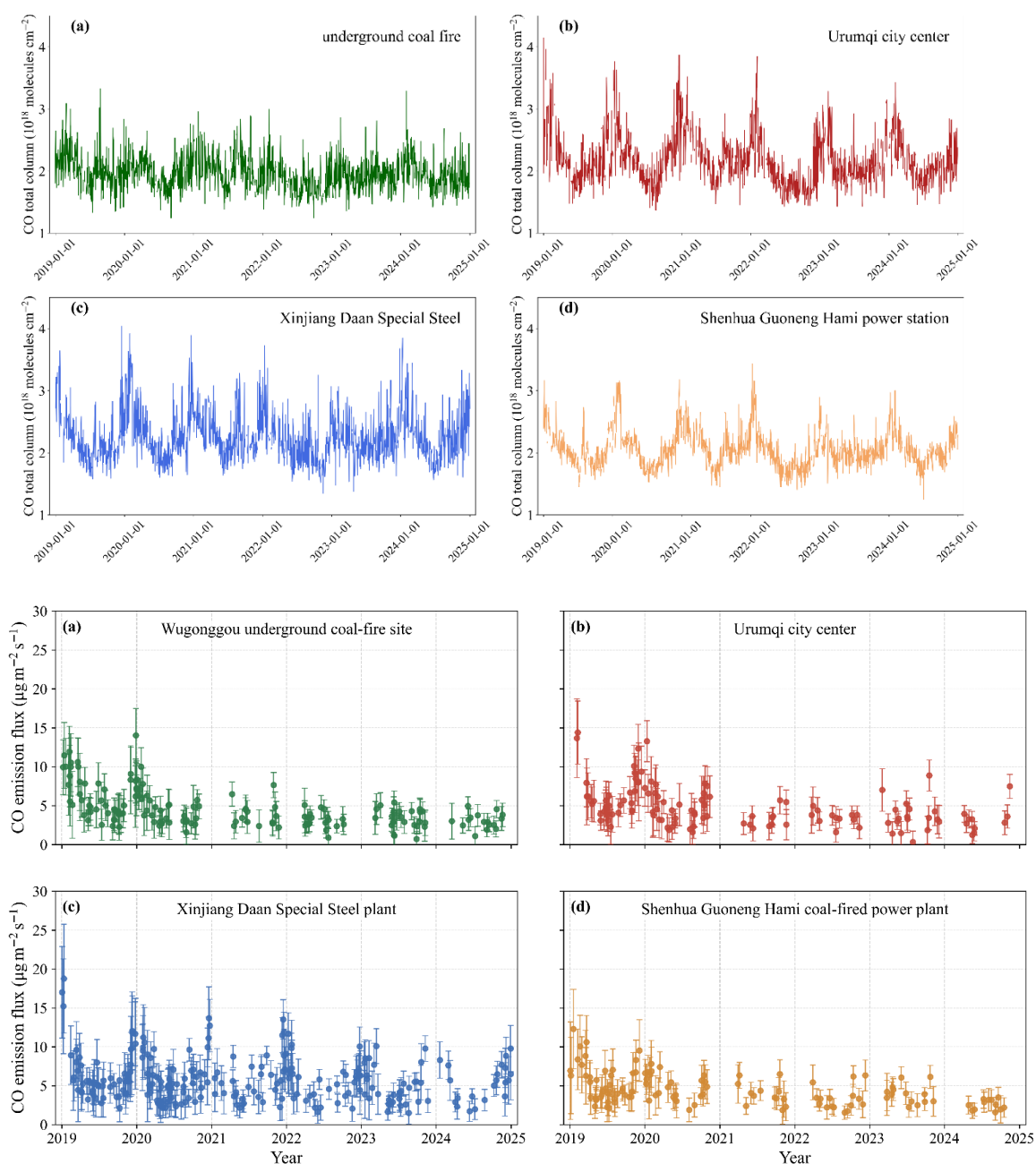
4 Figure 4A. Why coal fire also show a clear seasonal variation in CO emissions?

Response: We thank the reviewer for this comment. Figure 4a shows satellite-observed CO total columns, whereas Figure 8a shows inverted CO emission fluxes. Seasonal variation in the column does not necessarily imply the same seasonal variation in local coal-fire emissions, because the column also reflects atmospheric transport, chemical loss, and contributions from surrounding sources. We have clarified this distinction in Section 3.1. The Wugonggou CO column exhibits weaker seasonality than the other selected locations, with a monthly amplitude of 0.32×10^{18} molecules cm^{-2} compared with $0.71\text{--}0.77 \times 10^{18}$ molecules cm^{-2} at the other three locations. After re-examining the emission-flux series, we found that the strongest high-emission episodes occurred near the beginning of the study period and subsequently weakened. Wintertime sampling was sparse in some years, so the seasonal differences are interpreted as descriptive temporal patterns rather than independent trends. Wugonggou is an uncontrolled underground coal-fire source rather than an engineered industrial stack, and its decline is not used as evidence of industrial emission-control policy effectiveness. Some published studies suggest that colder conditions and oxygen availability can affect underground combustion (Song et al., 2020; Zhu and Wen, 2023), but the present satellite record cannot establish that mechanism independently.

Revised manuscript, Sect. 3.1, lines 274–277: “The Wugonggou grid exhibited weaker seasonality, with a monthly amplitude of 0.32×10^{18} molecules cm^{-2} , compared with $0.71\text{--}0.77 \times 10^{18}$ molecules cm^{-2} at the other three locations. This weaker variation is consistent with the relatively persistent nature of underground coal combustion and the weaker influence of seasonally varying urban and industrial activities in the surrounding area.”

Revised manuscript, Sect. 3.2, lines 365–366: “At Wugonggou, for example, the maximum daily emission flux of $14.0 \mu\text{g m}^{-2} \text{s}^{-1}$ occurred on December 2019, while the maximum observed values in subsequent years declined to 9.98, 7.65, 5.09, 5.42, and $4.97 \mu\text{g m}^{-2} \text{s}^{-1}$ from 2020 to 2024, respectively. Its annual mean similarly decreased from $6.38 \mu\text{g m}^{-2} \text{s}^{-1}$ in 2019 to $3.03 \mu\text{g m}^{-2} \text{s}^{-1}$ in 2024.”

Revised manuscript, Sect. 3.2, lines 374–376: “In particular, Wugonggou is an uncontrolled underground coal-fire source rather than an engineered industrial stack, and its temporal evolution should not be interpreted in terms of the same emission-control mechanisms as the urban and industrial grid cells.”



5 Figure 8. It is easy to imagine the CO emission unit in coal fire and urban centers as they are area sources. But for power plants, which are point sources, how do we calculate the emission? Or using the pixel data for the power plant location?

Response: We thank the reviewer for this important clarification. The MFIEF framework produces gridded CO emission fluxes expressed in $\mu\text{g m}^{-2} \text{s}^{-1}$ averaged over the entire TROPOMI pixel rather than facility-level point-source emission rates.

For the power plant analysis, we extracted the emission value from the grid cell containing the geographic location of each power plant. Therefore, the values shown in Figure 8 represent the atmospheric CO emission enhancement within the corresponding grid cell associated with the power plant location, rather than direct measurements of the stack emission rate. This offers some obvious disadvantages, but also some

advantages, as the direction of the immediate diffusion and turbulence are not so important to the entirety of the observed TROPOMI scale resolution.

Because the TROPOMI-based inversion has a spatial resolution coarser than individual facilities, the derived emissions represent the combined influence of the power plant and nearby sources within the grid cell, as well as rapid mixing and adjustments occurring within the grid scale. We have clarified this point in the revised manuscript.

Revised manuscript, Sect. 3.2, lines 360–361: “Because the inversion is performed at a spatial resolution of $0.05^\circ \times 0.05^\circ$, these estimates represent the net emissions from all sources within the corresponding grid cell rather than emissions from an individual facility.”

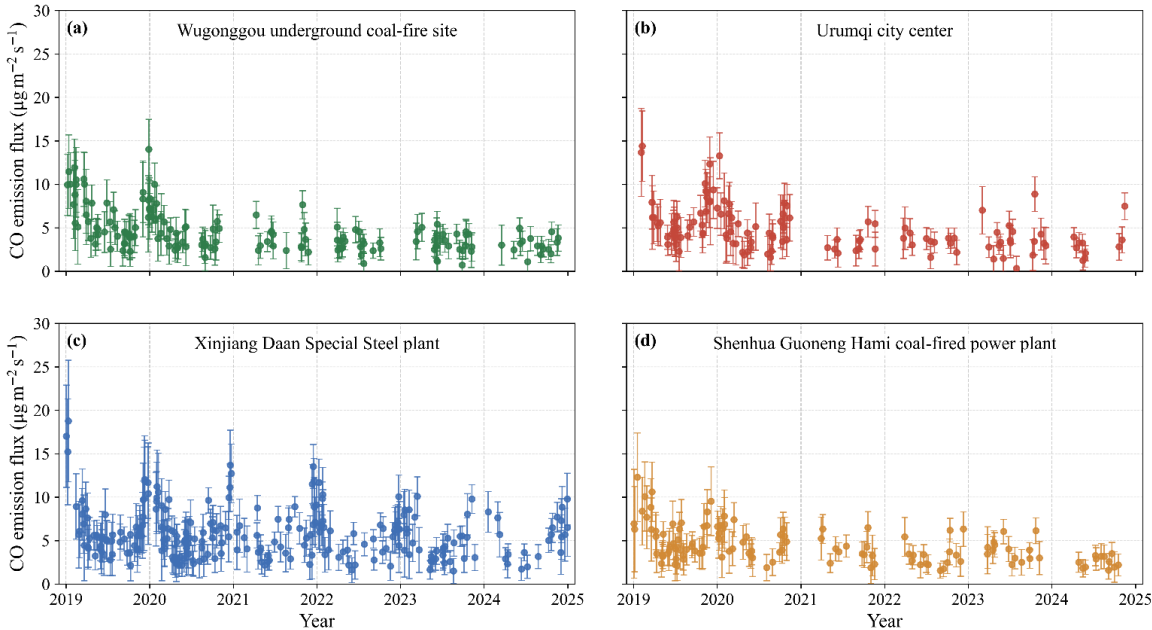


Figure 8. Temporal variations in MFIEF-derived CO emission fluxes at four representative locations from January 2019 to December 2024: (a) the Wugonggou underground coal-fire site, (b) Urumqi city center, (c) the Xinjiang Daan Special Steel plant, and (d) the Shenhua Guoneng Hami coal-fired power plant. Markers represent the mean emission fluxes, and error bars indicate ± 1 standard deviation. The values were extracted from the 0.05° grid cell containing each location.”

6 Table 1. Many cities, coal-fired sites, steel plants, and power plants are shown in Figure 1. So the data summarized in Table 1 are calculated from 1 typical site or averages of all the same types of locations?

Response: We thank the reviewer for this clarification. Table 1 reports category-level distributions rather than values from a single typical site, whereas Figure 8 presents representative individual locations. We agree that the previous description did not state the industrial-facility screening criterion clearly.

For temporal comparability, we re-screened the industrial facilities and retained only coal-fired power plants and steel plants that operated continuously throughout 2019 – 2024. Facilities that were not in operation during the complete six-year period, together with non-coal-fired power plants, were excluded. This screening yielded 53 coal-fired

power plants and 4 steel plants. Table 1 and the associated text were recalculated using this fixed sample.

Using the screened sample, mean grid-scale CO emission fluxes decreased from 4.94 to 3.02 $\mu\text{g m}^{-2} \text{s}^{-1}$ at coal-fired power-plant locations and from 6.22 to 4.08 $\mu\text{g m}^{-2} \text{s}^{-1}$ at steel-plant locations between 2019 and 2024. The corresponding endpoint reductions were 38.9% and 34.4%, respectively. These values and the complete category statistics are reported in Section 3.2 and Table 1.

Revised manuscript, Sect. 3.2, lines 383–389: “Table 1 includes industrial facilities that operated continuously throughout 2019–2024. The screened sample contains 53 coal-fired power plants and 4 steel plants; the city-center and underground coal-fire categories each contain 8 locations. Based on grid-scale estimates from this fixed sample, mean emissions decreased from 6.47 to 3.74 $\mu\text{g m}^{-2} \text{s}^{-1}$ at city-center locations (42.2%), from 7.09 to 4.18 $\mu\text{g m}^{-2} \text{s}^{-1}$ at underground coal fire locations (41.0%), from 6.22 to 4.08 $\mu\text{g m}^{-2} \text{s}^{-1}$ at steel-plant locations (34.4%), and from 4.94 to 3.02 $\mu\text{g m}^{-2} \text{s}^{-1}$ at coal-fired power-plant locations (38.9%) between 2019 and 2024. The 90th-percentile values also decreased, including from 11.00 to 6.58 $\mu\text{g m}^{-2} \text{s}^{-1}$ at steel-plant locations and from 8.20 to 4.69 $\mu\text{g m}^{-2} \text{s}^{-1}$ at coal-fired power-plant locations.”

Revised manuscript, Sect. 3.2, lines 390–391: “Table 1. Annual statistics of grid-scale CO emission fluxes for selected source categories from 2019 to 2024. Steel-plant and power-plant samples include only facilities operating continuously across all six years (unit: $\mu\text{g m}^{-2} \text{s}^{-1}$).”

7 Typo errors: please check the text again during revision. Some are listed below.

a) Line 82: In addition to Kazakhstan, Kyrgyzstan, and Uzbekistan, some parts of other countries like Tajikistan, Afghanistan, and Pakistan are also shown in Figure 1. b) two “and then resampled” in line 100.

c) Line 147. (Li et al., 2025) to Li et al., (2025)

d) Use Figure or Fig. in the manuscript, not all of them.

Response: We sincerely thank the reviewer for carefully identifying these typographical and formatting issues. All of the specific errors pointed out by the reviewer have been corrected in the revised manuscript, including the study area description, duplicated wording, citation formatting, and figure citation style. In the main text, we uniformly use “Fig.”; in figure captions, we consistently use “Figure”. In addition, we conducted a thorough proofreading of the entire manuscript to improve consistency in grammar, terminology, reference formatting, and the use of figure citations throughout the text.

Revised manuscript, Sect. 2.1, lines 94–95: “The study area spans from 35° N to 50° N latitude and 70° E to 100° E longitude, including Xinjiang and parts of Kazakhstan, Kyrgyzstan, Uzbekistan, Tajikistan, Afghanistan, Pakistan, and adjacent regions.”

Revised manuscript, Sect. 2.2, lines 118–120: “In this work, the Level 3 OFFL data product from Google Earth Engine (GEE) is filtered to ensure the quality assurance flag is above 0.5, and resampled using the Weighted Polygonal Remote Sensing Toolkit HARP (<http://stcorp.github.io/harp/doc/>).”

Revised manuscript, Sect. 2.3, lines 172–173: “This mass conservation equation for CO provides a framework for understanding and quantifying the changes in CO

columns in the atmosphere, considering the various processes that influence its distribution, following Li et al. (2025)."

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