Point-by-Point Response to Referee #1

We sincerely thank the editors and reviewers for dedicating your time and effort in handling and reviewing our manuscript (**ID: Egusphere-2025-5982**). We greatly appreciate the reviewers' positive and encouraging feedback on our work. We have carefully considered all comments raised, which have been instrumental and invaluable in revising and improving the paper. In this response letter, the reviewers' comments are shown in *black italics*, followed by our point-by-point replies in red roman font, with all line numbers referenced to the track-changes manuscript. Moreover, in the track-changes version of the manuscript, newly added or revised text is underlined in blue, while removed content is marked with light gray strikethrough (e.g., ~~Deleted~~), and the revisions we include in this response letter are formatted consistently. We hope that these revisions and improvements have sufficiently addressed the comments. Thank you once again for your time and expert input.

General Comments:

Comment 1: *The paper provides a detailed analysis of CO_2 and CO measurements taken over a two-year period at the top of the Shanghai Tower. The originality of the study lies in the unique height (632m) at which the measurements were taken, in the heart of a city. The article also makes interesting use of measurements of other tracers taken at an air quality station at the foot of the tower. The procedure for estimating background signals and concentration excesses associated with regional activities is clearly explained and well suited to the specific conditions of the measurement site at the top of the building. Overall, the results obtained are consistent with the expected processes, particularly in relation to a two-month lockdown period. I therefore recommend publication of the article in the ACP journal, after correction of certain inaccuracies and a few revisions. Please note that several figure captions are incomplete.*

Response: Thank you very much for your positive assessment of our work and insightful comments on this manuscript. Your professional comments and constructive suggestions are highly beneficial for revising and improving our paper. In the current version, we have carefully addressed all the issues you raised point by point, and we have revised the figure captions to ensure they provide complete and clear information. We greatly appreciate your supportive recommendation and thoughtful feedback.

Main comments:

Comment 2: *Line 49: "…with cities responsible for ~85% of its carbon emissions": Is it really 85% of emissions that occur in cities, or is it rather the carbon footprint of cities? Please clarify.*

Response: Thank you very much for your careful observation. You are correct that the original wording conflated urban territorial emissions with consumption-based carbon footprint. We have revised the sentence to refer specifically to direct carbon emissions occurring within cities and have updated the citations accordingly. The original citations (Mi et al., 2016; Guo et al., 2023) primarily addressed consumption-based carbon footprints; we have therefore replaced them with references that specifically report urban territorial emissions.

The revision marks in the manuscript are as follows:

Revised L50-52: "As the world's largest GHG emitter, with cities ~~responsible for ~85% of its carbon emissions (Mi et al., 2016; Guo et al., 2023)~~ accounting for a large share of direct carbon emissions (Tong et al., 2018; Meng et al., 2025), China is under mounting international scrutiny …"

The updated references are:

Tong et al. (2018): Tong, K., Fang, A., Li, Y., Shi, L., Wang, Y., Wang, S., and Ramaswami, A.: The collective contribution of Chinese cities to territorial and electricity-related CO_2 emissions, J. Cleaner Prod., 189, 910–921, *https://doi.org/10.1016/j.jclepro.2018.04.037*, 2018.

Meng et al. (2025): Meng, F., Hu, H., Sun, Y., Zhang, L., Hou, J., Zhang, Z., Pang, L., Cai, B., and Shan, Y.: Full-scope carbon dioxide emission dataset for Chinese cities in 2023, Sci. Data, 12, 1672, *https://doi.org/10.1038/s41597-025-05949-y*, 2025.

Comment 3: *Line 51 : "China has been deploying an extensive urban and suburban carbon monitoring network" : Is it possible to know how extensive this measurement network is ? How many cities, or monitoring stations ?*

Response: Thank you very much for your nice suggestion. We have incorporated additional information to better present these essential details.

The revision marks in the manuscript are as follows:

Revised L51-58: "China has been deploying an extensive urban and suburban carbon monitoring network (~~primarily in lower atmosphere or remote locales~~ comprising over 100 stations across more than 30 cities) to complement its WMO/GAW-affiliated background stations, namely one global background station (Waliguan, WLG) and seven regional background stations (WDCGG, 2025b). Although these background stations are primarily located in remote areas, ~~; however,~~ a direct outcome from this monitoring infrastructure ~~network~~ is that …"

Comment 4: *Line 121: "The manufacturer reported a measurement precision (1σ over 5 min) of approximately 50 ppb for CO_2 and 1 ppb for CO, with accuracy meeting WMO/GAW compatibility goals." : Rather than having the manufacturer's specifications, I would prefer to have the measurement precision and repeatability estimated from regular measurements of the target gas. Could you please show the time series of the target gas measurements. Please also specify the frequency of calibration sequences, and indicate which method is used to dry the air.*

Response: Thank you very much for your constructive suggestions. We have revised the CO and CO_2 measurement precision derived from the target gas during the campaign. A time series of the target gas measurements is now provided in Fig. S1 to demonstrate the system's stability and measurement repeatability. In addition, we have specified the calibration frequency and detailed the air drying procedure in the revised manuscript as described below.

Revisions are marked in the manuscript and SI as follows:

Revised L126-128: "The ~~manufacturer reported a~~ measurement precision (1σ over 5 min) ~~of approximately 50 ppb for CO_2 and 1 ppb for CO~~ was 0.06 ppm for CO_2 and 1.2 ppb for CO during the observation period (Fig. S1)…"

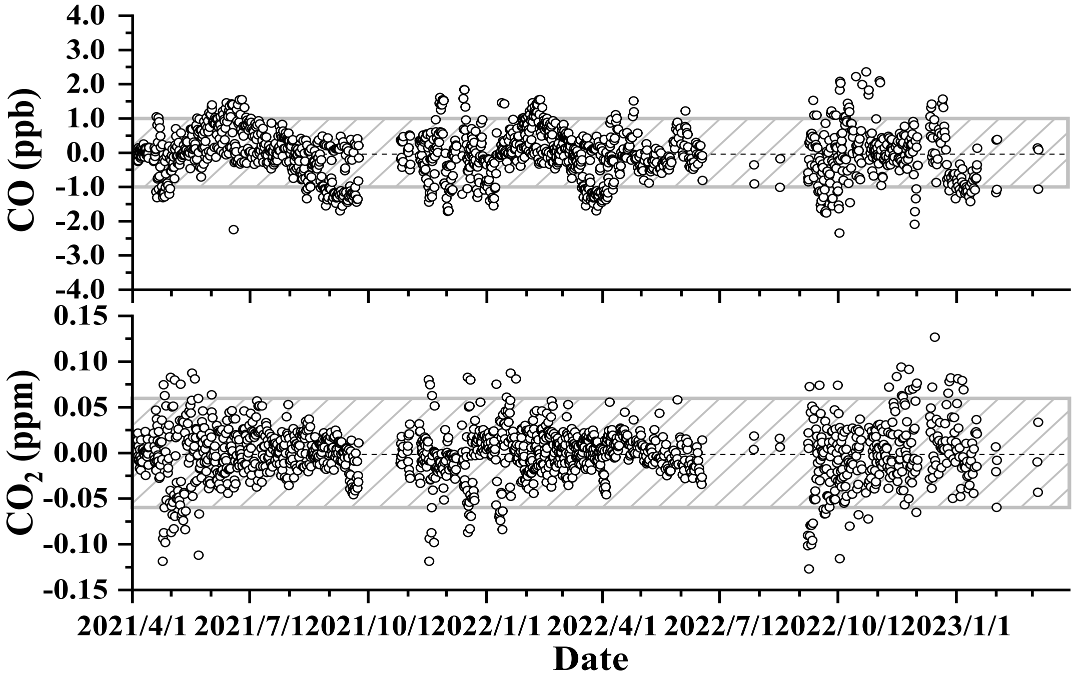


Figure S1: Differences of the measured and assigned CO and CO_2 mole fractions for the target gas (T) during the observation period. The gray shaded area indicates the ±1σ range.

Revised L123-126 (on Calibration frequency): "… and specific calibration procedures are detailed in a previous study (Fang et al., 2014). In brief, the instrument was calibrated daily using two standard gases with high and low concentrations (WH and WL) to establish a two-point linear calibration, while system performance was checked every 6 hours using a target gas (T) with a known concentration. All standards used in the campaign ~~Two standard gases and one target gas were analysed for 5 min every 6 h, which~~ are linked to the WMO-CO_2_X2019 scale for CO_2 and WMO-CO_X2014A scale for CO."

Revised L116-118 (on Air drying method): "The sample stream first passed through a three-stage self-assembled filter ~~and dryer unit (Xiong et al., 2022)~~ to remove particulate matter, and was then delivered to a glass trap immersed in a methanol bath at –50 °C (Xiong et al., 2022), where it was dried to a dew point of approximately –35 °C to reduce the influence of water vapor ..."

Comment 5: *Figure 2: Over the two-year measurement period, there is a significant amount of missing data. This is one of the difficulties involved in maintaining observations, and it would be interesting to know the reasons for the main data gaps. Could you please provide some description of the difficulties you encountered, and why the monitoring program has been discontinued ?*

Response: Thank you for raising this important point. We acknowledge the data gaps in the 2-yr measurement period and appreciate the opportunity to explain the underlying reasons. This site was not a fixed GHG observation station, but rather a collaborative measurement campaign at the top of the Shanghai Tower. Consequently, monitoring was concluded after the project ended.

The observation period overlapped with COVID-19 lockdowns in Shanghai, during which material shortages and transportation disruptions presented significant challenges. Specifically, the supply of working standards was interrupted during summer 2022 and the 2022–2023 winter holiday period, further compounded by restricted site access. Despite these difficulties, substantial efforts were made to obtain the valuable observational dataset presented in this study.

To further clarify, we have added a brief note to the caption of Figure 2 to provide context for the data gaps.

Revised L246-247: "Intermittent data gaps occurred during the campaign, mainly due to logistical disruptions (e.g., standard gas shortages) and restricted site access."

Comment 6: *Figure 2: Also the CO concentrations measured at SHT in winter 2022 are higher than the previous winter, which is not seen in ground based measurements of CO,* NO_2*,* SO_2*. Do you have any explanation on this year to year wintertime variability which doesn't seem to be related to the local surface emissions ?*

Response: Thank you for raising this thoughtful comment. We agree that the difference between the elevated SHT site and ground-based measurements warrants further explanation. The elevated SHT site captures a vertically integrated signal that reflects both broader regional background conditions and contributions from the Shanghai metropolitan area, whereas ground-based measurements are inherently local and can be dominated by nearby point sources.

The higher CO at SHT in winter 2022 reflects a year-on-year increase in regional background conditions. In winter 2021, extensive lockdowns across upwind regions substantially suppressed anthropogenic emissions, creating an unusually low regional background. This reduction was more detectable at the elevated site due to its regional representativeness. By winter 2022, following the nationwide relaxation of COVID-19 restrictions, emissions had largely rebounded. In contrast, ground-based measurements showed little change between the two winters, as surface source activity experienced minimal disruption throughout 2021 in Shanghai and society had undergone a dynamic recovery by winter 2022.

To clarify, we have added the following relevant analysis on interannual variability in Section 3.1:

Revised L223-229: "Beyond meteorological factors, the interannual variability also reflects differences in regional anthropogenic emissions. In 2021, extensive lockdowns across regions upwind of Shanghai—particularly the North China Plain and central China—substantially suppressed anthropogenic mobile source emissions, contributing to a lower background. Given its elevated location, the SHT site was particularly sensitive to this reduction, capturing the long-range transport signal from distant upwind regions more effectively than surface sites. In contrast, by late 2022, following Shanghai's prolonged citywide lockdown (March–June 2022) and subsequent nationwide relaxation of COVID-19 restrictions, anthropogenic emissions had rebounded. These emission differences, together with the distinct meteorological conditions noted above, shaped the observed pronounced interannual CO pattern at the elevated SHT site."

Comment 7: *Section 3.4: The value used as the CO_2/CO ratio is not very clear to me. Do you use the average value for the entire measurement period? This ratio kCO_2/CO, derived from atmospheric observations, corresponds to the total CO_2 signal (ff and bio combined), and therefore, in my opinion, the justification for using it to deduce the CO_{2ff} fraction is not sufficiently explained.*

Response: Thank you for this thoughtful comment. We appreciate the opportunity to clarify the methodology for deriving the $k_{CO_2/CO}$ ratio and its application for estimating fossil-derived CO_2 ($CO_{2,\ ff}$). Accordingly, we have revised Section 3.4 to provide a more detailed justification and to more clearly reference the existing supporting figures (updated Figs. S13 and S14) that underpin our methodological approach. The specific revisions are as follows:

(1) **Temporal scale of the $k_{CO_2/CO}$ ratio.** We did not use a single average value for the entire period. Instead, we derived seasonally varying $k_{CO_2/CO}$ ratios from the reduced major axis regression between CO_{ex} and $CO_{2,\ ex}$ for each season (Fig. 7a). For summer, we further tested a time-dependent $k_{CO_2/CO}$ as a function of local time. As shown in Fig. S13, the time-dependent ratio varies over the diurnal cycle, but using it yields minimal impact on daily mean $CO_{2,\ ff}$ estimates compared to the seasonal constant ratio, supporting the robustness of our seasonal approach.

(2) **Methodological justification for using $k_{CO_2/CO}$ to derive $CO_{2,\ ff}$.** Indeed, $k_{CO_2/CO}$ values derived from observations reflect the combined signal of fossil and biogenic CO_2. We justify its use for estimating $CO_{2,\ ff}$ on the following. First, CO is a well-established tracer for combustion processes, as its atmospheric sources are overwhelmingly dominated by fossil fuel combustion, with negligible biogenic contributions in urban environments. So, when CO_{ex} and $CO_{2,\ ex}$ show a strong positive correlation, the observed covariance is primarily driven by shared combustion sources. Second, we conducted independent validation using ^{14}C measurements at a nearby site (Hengxiwu, Anji), as detailed in L458-465. Radiocarbon (^{14}C) is a definitive tracer for fossil-derived CO_2 because fossil fuels are completely depleted in ^{14}C. As presented in Fig. S14, the strong linear correlation (R = 0.98) between $CO_{2,\ ff}$ derived from ^{14}C mass balance and CO_{ex} (Fig. S14) yielded a k_{CO/CO_2} of 1.45 ± 0.13%, which is highly consistent with the SHT-derived ratio of 1.5 ± 0.4%. These results could reasonably support the validity of our approach. Moreover, we explicitly addressed biogenic interference by attributing the residual $CO_{2,\ ex}$ after subtracting $CO_{2,\ ff}$ to biogenic activity ($CO_{2,\ bio\text{-}dominated}$) and noting the weaker $CO_{2,\ ex}$–CO_{ex} correlation in summer due to biospheric processes.

> **L458-L465 in the manuscript:** "It should be noted that our team conducted simultaneous ^{14}C measurements in atmospheric CO_2 and CO at the site of Hengxiwu (HXW, 119.48°E, 30.60°N; 200 m a.s.l.) in Anji, Zhejiang, a representative area of intensive urbanization in the YRD region. Based on these observations, $CO_{2,\ ff}$ concentrations were quantified via radiocarbon mass balance (according to Levin et al. (2003) and Vásquez et al. (2022)), and the results (Fig. S14) revealed a strong positive correlation (R = 0.98) between $CO_{2,\ ff}$ and CO_{ex}, with an averaged k_{CO/CO_2} of 1.45 ± 0.13% that was highly consistent with estimates from the SHT site (1.5 ± 0.4%). These findings further confirm that CO emissions in the YRD region originate predominantly from fossil fuel combustion and high combustion efficiency there, thereby validating the application of Eq. (4) with an empirically constrained $k_{CO_2/CO}$ for determining regional $CO_{2,\ ff}$."

Comment 8: *Section 3.5: Most of the variations described during and after the spring 2022 lockdown appear consistent and are well explained. There are still a few points that need to be discussed:*

- "…with limited disruption to industrial operations. This explains why ground-level SO_2 *(largely tied to industrial activities) rose 6.3–153.6%": At this level of increase, it seems more likely that there has been an increase in industrial activity. Is this conceivable? At the same time there is a sharp increase of* CO_{gl} *despite the decrease of traffic (as indicated by the sharp decrease of* NO_2*). What is the possible driving force for this increase of CO ?*
- The increase in CO and CO_2 *concentrations is also striking when measurements resume in September 2022, both when using all measurements, or only background measurements. Therefore, it seems a bit difficult to reconcile the huge increase of the background signal at SHT compare to the regional DMS background station (a signal which was not seen in 2021), with the stability or decrease of CO at the surface level in Shanghai.*

Response: Thank you very much for your pertinent and thoughtful comment. We have carefully verified our original measurements and daily calibration and standard gas checks on CO and CO_2 mole fractions during the SHT observation, confirming that the data collected during the campaign are accurate and reliable. Your concern reflects a central theme of our study—that the elevated SHT site captures a vertically integrated signal distinct from ground-level measurements. We acknowledge that our analysis of ground-based observations was insufficient, which may have made this point less clear. Combined with these points you mentioned, we have made the following corresponding revisions and improvements.

(1) Ground-level SO_2 and CO variations during the lockdown:

We agree that the increase in SO_2 during the lockdown warrants further explanation. While industrial activities during the lockdown may have been minimally disrupted or even experienced a slight increase, the observed SO_2 increase of several ppb is more likely driven by weakened atmospheric loss due to reduced OH regeneration following a significant NO_x decline. Moreover, ground-level CO, primarily from incomplete combustion, is likely influenced more by localized sources near the site, and we have considered several possible contributing factors to its variations during the lockdown. The relevant text has been revised as follows:

Revised L487-495: "Thus, the most prominent change during this campaign was ~~This explains why ground-level SO2 (largely tied to industrial activities) rose 6.3–153.6%, alongside~~ a sharp 56.2 ± 78.7% drop in traffic-related NO_2 during lockdown, followed by post-lockdown declines of 21.4 ± 12.2% in NO_2 and 9.4 ± 4.1% in CO. … It should be noted that SO_2 (largely tied to industrial activities) increased significantly during the lockdown, likely due in part to a certain increase in industrial emissions, but driven more by reduced OH regeneration from NO_x decline, which weakened its atmospheric loss (Ye et al., 2023; Zhang et al., 2023). Ground-level CO also exhibited variable patterns (e.g., between May and June, 2021–2022), likely more influenced by localized sources such as residential fuel use and emissions from emergency services during the pandemic peak than by regional transport."

(2) Post-lockdown differences of SHT vs DMS and surface site:

SHT, situated above the urban area of Shanghai, is more sensitive to emission changes in the Yangtze River Delta and upwind regions, thus capturing a stronger signal of the regional emission rebound following the lockdown. Based on the updated Fig. 6 in the manuscript, a separate display of the DMS data is shown below (**Figure 1 in the response**). In contrast, **DMS** (located in western Lin'an, Hangzhou, Zhejiang), serves as a regional background site where anthropogenic sources are weak, intermittent and associated with tourism activities. It exhibited a slight decrease in carbon concentrations during the lockdown, and its subsequent increase during the post-lockdown period was relatively modest, much less pronounced than that observed at the urban tower-top SHT site.

You specifically noted the difference between the two sites after September 2022. In this regard, the autumn backward trajectories (**Fig. 4c**; see response to Comment 12) also show that the air masses arriving at SHT were influenced by polluted areas in the northwest upwind region as well as by nearby urban emissions. In contrast, the DMS site lies outside these major source regions, which may partly explain its relatively modest increase in carbon concentrations.

Regarding vertical decoupling between the elevated signal at SHT and the stable or decreasing CO concentrations at the Shanghai surface site, we note that surface sites are more strongly influenced by local emissions and meteorological conditions, which may mask or differ from the regional trend. Similar phenomena have also been confirmed in previous tower-based hierarchical observations, though observation results may vary depending on site locations. Combined with the reviewers' suggestions, we have provided relevant supplementary explanations and revisions in Section 3.2.

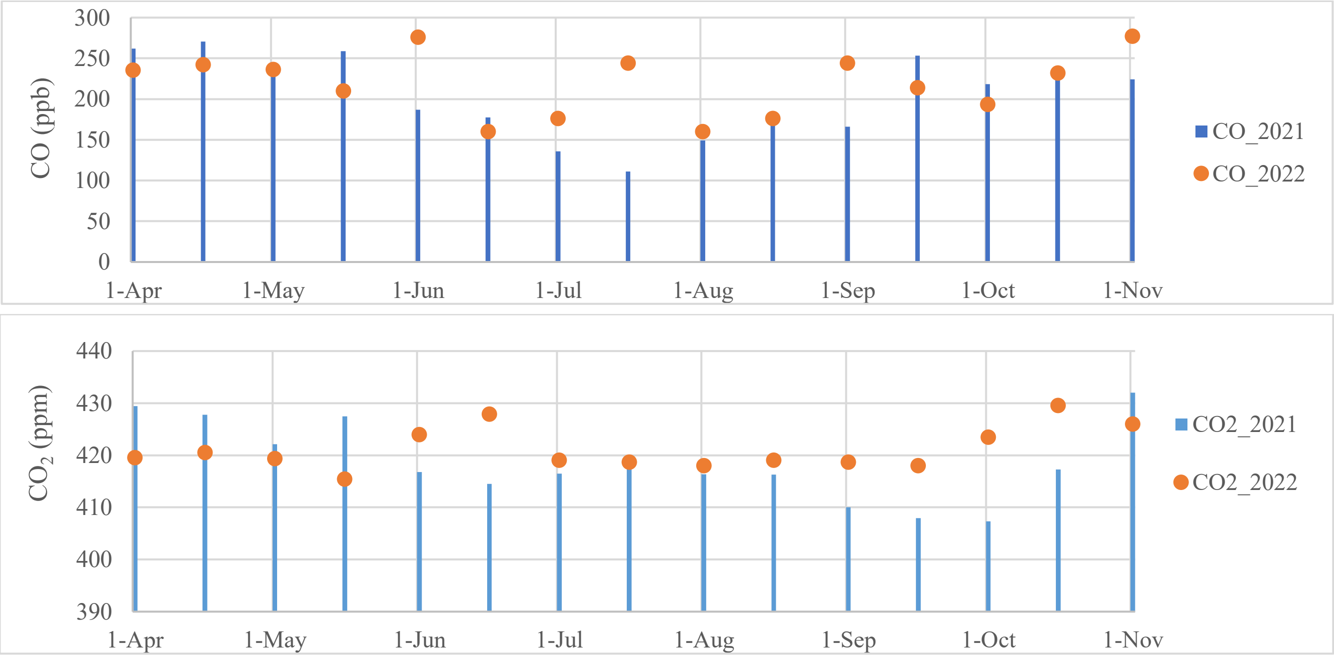


Figure 1 in the response: CO and CO_2 mole fractions at DMS site.

Revised L270-273: "At night, CO_2 and CO measurements at the SHT site (UCL top; above urban PBLH, ca. 329.5 ± 246.2 m; Fig. S3) were largely free from ground influence, contrasting with the near-surface accumulation of pollutants in the stable nocturnal layer, a pattern consistent with previous hierarchical tower observations that also recorded limited nighttime concentration variability at upper levels (Denning et al., 2008; Winderlich et al., 2014). This vertical decoupling also aligns with tethered-balloon-based observations ....";

Revised L278-282: "However, it is worth noting that, in contrast to the diurnal cycles observed at background tall towers (e.g., KRE; Fig. S4), the SHT-based measurements from an elevated urban core site were subject to pronounced daytime urban emissions, whereas the nighttime data remained more representative of regional surface flux influences. In this context, tower-top nocturnal measurements at SHT site were considered suitable proxies for the regional background …".

Supplementary references on previous tall-tower observational studies:

Denning et al. (2008): Denning, A. S., Zhang, N., Yi, C., Branson, M., Davis, K., Kleist, J., and Bakwin, P.: Evaluation of modeled atmospheric boundary layer depth at the WLEF tower, Agric. For. Meteorol., 148, 206–215, https://doi.org/10.1016/j.agrformet.2007.08.012, 2008.

Winderlich et al .(2014): Winderlich, J., Gerbig, C., Kolle, O., and Heimann, M.: Inferences from CO_2 and CH_4 concentration profiles at the Zotino Tall Tower Observatory (ZOTTO) on regional summertime ecosystem fluxes, Biogeosciences, 11, 2055–2068, https://doi.org/10.5194/bg-11-2055-2014, 2014.

Minor comments:

Comment 9: Line 55: "*To extract regionally representative data with minimal emission influence*": I suggest to mention "Local' emission.

Response: Thank you very much for your nice suggestion. We have added the term "local" here as suggested to emphasize that the filtering methods aim to minimize the influence of local emissions.

Comment 10: *2.1.2. Additional Environmental Data : can you please provide the elevation a.g.l. of the two air quality & meteorological stations ? I guess they are very close to the ground.*

Response: Thank you for your thoughtful comment. You are right. Both supplementary stations are located close to the ground. For BSMH, the air quality sampling inlets are installed on a rooftop; the value of 12–15 m a.g.l. accounts for both the building height and the height of the sampling inlet above the rooftop. For the Baoshan Meteorological Station, the 1.5 m a.g.l. corresponds to the standard installation height for sensors (with an elevation of 6.7 m above sea level). These values have been added to improve the clarity and completeness of the site description.

Revised L134-137: "(i) China's air quality monitoring station of Baoshan Miaohang (BSMH; 121.43°E, 31.33°N; 12–15 m a.g.l.; 5.6 km from SHT) …; and (ii) the Baoshan Meteorological Station (BS; 31.23°N, 121.29°E; 1.5 m a.g.l.; 20.9 km from SHT), …".

Comment 11: *Figure 2: are the PBLH given on hourly basis, day and night ?*

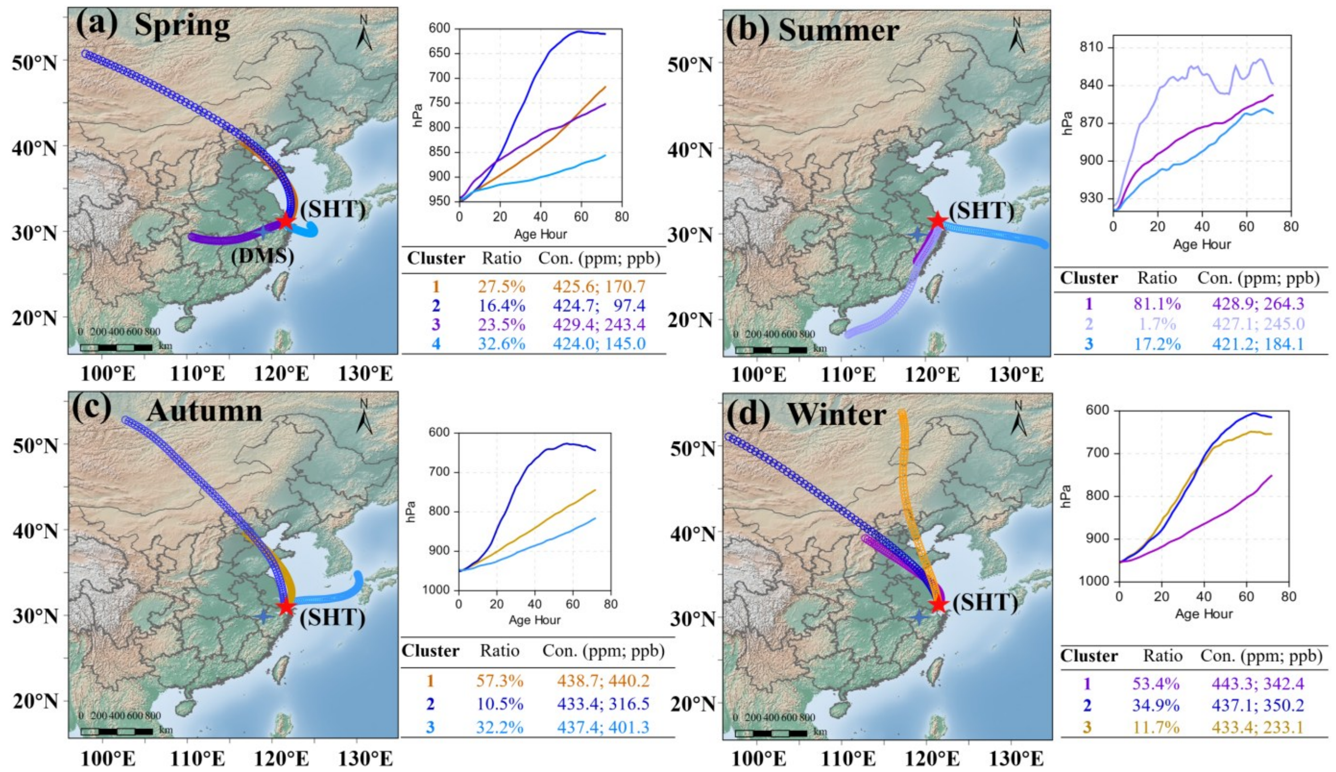
Response: Thank you for your question. The PBLH data shown in Figure 2 are hourly values. In fact, Figure S3 in the SI also presents the monthly diurnal cycles based on these hourly values. We have revised the caption of Figure 2 accordingly to clarify this.

Revised L244: "… and hourly reanalyzed planetary boundary layer height (PBLH) at the SHT site."

Comment 12: *Figure 4: could you also locate the DMS site on the maps, or at least could you precise how far it is from SHT tower ?*

Response: Thank you very much for your nice suggestion. We have marked the location of DMS on Figure 4. Table S1 in the Supplementary Materials records the information of these two sites used in this study, where DMS: 119.00°E, 30.01°N; 1489.9 m a.s.l., SHT: 121.51°E, 31.23°N; 637.0 m a.s.l.

Revised Figure 4 and its caption are shown below:



(a) Spring

Cluster	Ratio	Con. (ppm; ppb)
1	27.5%	425.6; 170.7
2	16.4%	424.7; 97.4
3	23.5%	429.4; 243.4
4	32.6%	424.0; 145.0

(b) Summer

Cluster	Ratio	Con. (ppm; ppb)
1	81.1%	428.9; 264.3
2	1.7%	427.1; 245.0
3	17.2%	421.2; 184.1

(c) Autumn

Cluster	Ratio	Con. (ppm; ppb)
1	57.3%	438.7; 440.2
2	10.5%	433.4; 316.5
3	32.2%	437.4; 401.3

(d) Winter

Cluster	Ratio	Con. (ppm; ppb)
1	53.4%	443.3; 342.4
2	34.9%	437.1; 350.2
3	11.7%	433.4; 233.1

Figure 4: Cluster analysis on 72-h back trajectories at the SHT site across different seasons. The trajectories were computed with an arrival height of 600 m a.g.l., close to the sampling intake height (632 m a.g.l.) at the SHT site. The right panels include cluster-specific pressure profiles and associated CO_2 and CO mole fractions. The SHT and DMS sites in the YRD region are marked as a red five-pointed star and a blue four-pointed star, respectively.

Comment 13: *Figure 5: In my opinion, the best practice for these wind rose figures is to use detrended and de-seasonalized dataset.*

Response: Thank you for your thoughtful suggestion. We appreciate your point regarding the use of detrended and de-seasonalized datasets for wind rose analysis to better capture the general situation. In our analysis, we intentionally used the original measurements rather than detrended or de-seasonalized data. This is because our objective in this section is to identify and extract regional background signals from the raw measurements while retaining the inherent seasonal variations. The seasonal cycle is also an important characteristic of the background signal that we aim to preserve for subsequent analysis. From this perspective, we consider that using these measurements is appropriate for the purpose of this figure.

Comment 14: *Figure 7b: there is no explanation about the dashed red line.*

Response: Thank you for pointing this out. The dashed red line in Figure 7b represents summer estimates using a time-dependent $k_{CO_2/CO}$, which we have now clarified in the revised figure caption.

L455 in the caption of Figure 7: "Solid lines: estimates using seasonally constant $k_{CO_2/CO}$ from (a); dashed red line: summer estimates using a time-dependent $k_{CO_2/CO}$."

Point-by-Point Response to Referee #2

We sincerely thank the editors and reviewers for dedicating your time and effort in handling and reviewing our manuscript (**ID: Egusphere-2025-5982**). We greatly appreciate the reviewers' positive and encouraging feedback on our work. We have carefully considered all comments raised, which have been instrumental and invaluable in revising and improving the paper. In this response letter, the reviewers' comments are shown in *black italics*, followed by our point-by-point replies in red roman font, with all line numbers referenced to the track-changes manuscript. Moreover, in the track-changes version of the manuscript, newly added or revised text is underlined in blue, while removed content is marked with light gray strikethrough (e.g., ~~Deleted~~), and the revisions we include in this response letter are formatted consistently. We hope that these revisions and improvements have sufficiently addressed the comments. Thank you once again for your time and expert input.

General Comments:

Comment 1: *Authors are presenting a measurement report on 2-year observations of CO_2 and CO at the top of Shanghai tower. The data are analyzed in the paper and are filtered into daytime data useful for urban emission analysis and nighttime data representative of wider surface flux influences. Seasonal variation of enhancement ratios of CO to CO_2 is also discussed. The paper can be accepted after technical corrections.*

Response: Thank you very much for taking the time to review our manuscript and for your positive assessment on our measurement work. Your thoughtful summary and constructive feedback have been invaluable in helping us strengthen our paper. In this revised version, we have carefully addressed all technical points you raised. We sincerely appreciate your supportive recommendation and hope the revisions and improvements in the current revisions could be acknowledged.

Detailed comments:

Comment 2: *As the paper gives an observation site overview, it would be good to provide details useful for model analysis of published data, for example, the sea breeze impact in wind direction and tower footprint is not mentioned (see Huang et al 2025).*

-References: Huang, Y., Li, S., Zhu, Y., Liu, Y., Hong, Y., Chen, X., et al. (2025). Increasing sea-land breeze frequencies over coastal areas of China in the past five decades. Geophysical Research Letters, 52, e2024GL112480. https://doi.org/10.1029/2024GL112480.

Response: Thank you very much for your constructive suggestion. Indeed, the SHT site is located close to the eastern coastline and is significantly influenced by sea-land breeze (SLB) circulations. While we recognized this influence in our previous version (especially analysis from Figs. 4, S6, S8, and S9), the conceptual analysis of SLB was relatively superficial. After an in-depth reading of the study of Huang et al. (2025), we have made detailed revisions to **Sections 3.2** and **3.3** to better address the impacts of SLB on transport and the carbon footprint. The main revisions are as follows:

(1) In Section 3.2 (third paragraph)– Overview of monsoon and SLB influences on SHT:

Revised L297-318 in the manuscript: "As an elevated site within a coastal metropolis, SHT is subject to pronounced sea–land breeze circulations, the periodic nature of which significantly complicates pollutant transport and dispersion (Huang et al., 2025). Accordingly, we analyzed 24-h back trajectories from three representative time periods (morning and evening rush hours, and the stable nighttime period; Fig. ~~S4~~S6), as well as 72-h trajectories and their associated cluster concentrations (Fig. 4) at the SHT site across seasons. ... In contrast, higher loads of CO and CO_2 at the SHT receptor site in winter ~~and autumn~~ were consistently linked to 3-day aged plumes from inland North China, indicating a greater influence from distant anthropogenic sources driven by land breeze. The sea breeze effect was most pronounced in autumn, with the vast majority of air masses arriving at the SHT site within 24 hours being driven by sea breeze (Fig. S6c), broadly consistent with recent findings by Huang et al. (2025). Notably, summertime patterns were characterized by ~~reflected~~ a stronger influence from sources within the YRD region and by sea breeze extending toward the eastern sea area, accompanied by smaller vertical height variations."

(2) Regarding model analysis details: We have carefully considered your suggestion to provide details useful for model analysis. Overall, daytime measurements at SHT are largely influenced by local sources, whereas nighttime data appear to be more representative of wider surface flux influences. In the revised manuscript, we have expanded the PSCF analysis to better characterize the spatial representativeness of SHT measurements.

Revised L346-349: "The PSCF-resolved potential source areas (Fig. ~~S6~~S8) further identified significant inland extensions during spring, in contrast to a contraction toward the vicinity of the SHT site in other seasons, but it can broadly characterize the overall picture of source influence for the SHT site within a radius of approximately 200 km (with PSCF values > 0.9)."

(3) Section 3.3—Focus on nocturnal transport influences: We had previously identified significant nighttime land breeze effects and have now added the following to further clarify this point in the current manuscript:

Revised L353–356: "Under nocturnal conditions, both CO_2 and CO (in terms of averages and top 10% highs) exhibited clustered hotspot patterns in the W, WNW, and NW sectors at ground wind speeds of ca. 1–4 m s^{-1}, suggesting persistent and mild upwind transport at night. These western sectors represent the upwind areas where the nighttime offshore land breeze may also partially contribute to the carbon footprint observed at the SHT receptor site (Huang et al., 2025; Zhao et al., 2022)."

We hope these revisions address your concerns. We greatly appreciate your insightful comments, which have helped us improve the manuscript.

Comment 3: *Review and discussion can mention other research on similarly tall towers protruding above nocturnal boundary layer (eg WLEF, ATTO, ZOTTO).*

Response: Thank you very much for your constructive and insightful suggestion. Our earlier discussion of comparable tall-tower observations was relatively limited. In response, we have expanded our analysis with the following main improvements: (i) expanded the comparison with other tall-tower observations by adding seven European tower sites (updated Table S1); (ii) added a discussion of vertical decoupling with supporting research on WLEF and ZOTTO; and (iii) included a new figure (Fig. S4) comparing diurnal cycles between SHT and a background tall tower (using KRE as an example). In general, since these additional sites are predominantly located in regional background areas, their observed patterns differ to some extent from those at our urban core site. These observations further support the importance of using tall-tower measurements in urban core areas to capture regional carbon footprints.

The main revisions made in the manuscript and supporting information are as follows:

Revised L197-203: "Focusing on CO_2, a crucial GHG contributor, Table S1 summarizes CO_2 values measured at various observation sites from recent reports and studies. Generally, the CO_2 measurement conducted at the SHT site was significantly higher than that of a comparable elevation (e.g., Akedala: 420.2 ± 1.4 ppm; 563.3 m a.s.l.; KRE: 427.05 ± 0.64; 534 m a.s.l) and those recorded at high-altitude stations (including LLN, WLG, MLO, JFJ, ABLECAS, TPB, TOH and DMS: ca. 417–428 ppm; above 1000 m a.s.l.), whether based on mountains or tower platforms that are situated in global/ regional background settings, and also substantially exceeded the global average value of 416.8 ± 0.20 ppm (in 2021–2022; Table S1)."

The revised Table S1, which now includes data from seven European tower sites, is shown here.

Table S1: Measured CO_2 mixing ratio (ppm) at different sites during nearly concurrent periods.

Observation Site	Category	Geography	Period	CO_2	Reference
Sutro Tower (STR), California, USA	Urban	122.45°W, 37.76°N; 254 m a.s.l	2021	420.47 ± 11.23	NOAA [a]
…	…	…	…	…	…
Heathfield (HFD), United Kingdom	Regional background[#]	0.23°E, 50.98°N; 210 m a.s.l	2021–2023	424.84 ± 0.67	WDCGG [d]
Hohenpeissenberg (HPB), Germany	Global background[#]	11.01°E, 47.80°N; 1065 m a.s.l	2021–2023	421.01 ± 0.73	WDCGG [d]
Ispra (IPR), Italy	Regional background[#]	8.63°E, 45.80°N; 250 m a.s.l	2021–2023	438.67 ± 1.42	WDCGG [d]
Kresin u Pacova (KRE), Czech Republic	Regional background[#]	15.08°E, 49.58°N; 544 m a.s.l	2021–2023	427.05 ± 0.64	WDCGG [d]
Observatoire Pérenne de l'Environnement (OPE), France	Regional background[#]	5.50°E, 48.56°N; 400 m a.s.l	2021–2023	427.00 ± 0.75	WDCGG [d]
Saclay (SAC), France	Regional background[#]	2.14°E, 48.72°N; 175 m a.s.l	2021–2023	430.76 ± 1.31	WDCGG [d]
Torfhaus (TOH), Germany	Regional background[#]	10.53°E, 51.81°N; 948 m a.s.l	2021–2023	421.08 ± 0.57	WDCGG [d]
ABLECAS site, Zhejiang, China	High-altitude mountain	119.51°E, 28.58°N; 1128 m a.s.l	2022/7/10 – 2021/6/20	426.3 ± 10.0	Ye et al. (2024)
Damingshan (DMS), Zhejiang, China	High-altitude mountain	119.00°E, 30.01°N; 1489.9 m a.s.l	2020/11–2021/10; 2021/4–2022/12	422.02 ± 10.67; 419.38 ± 2.30[*]	Chen et al. (2024); This study

Shanghai Tower (SHT), Shanghai, China	Urban[#]	121.51°E, 31.23°N; 637.0 m a.s.l.	2021/4/17 –2023/3/6	433.50 ± 0.33[*] …	This study
…	…	…	…	…	…

[a] Derived from NOAA (available at: https://gml. noaa.gov/dv/iadv/, last access: August 2025) … [#] Based on the tower platform.

Revised L270-274: "At night, CO_2 and CO measurements at the SHT site (UCL top; above urban PBLH, ca. 329.5 ± 246.2 m; Fig. S3) were largely free from ground influence, contrasting with the near-surface accumulation of pollutants in the stable nocturnal layer, a pattern consistent with previous hierarchical tower observations that also recorded limited nighttime concentration variability at upper levels (Denning et al., 2008; Winderlich et al., 2014). This vertical decoupling also aligns with tethered-balloon-based observations, ..."

Revised L278-282: "However, it is worth noting that, in contrast to the diurnal cycles observed at background tall towers (e.g., KRE; Fig. S4), the SHT-based measurements from an elevated urban core site were subject to pronounced daytime urban emissions, whereas the nighttime data remained more representative of regional surface flux influences. In this context, tower-top nocturnal measurements at SHT site were considered suitable proxies for the regional background …"

Added Fig. S4 is shown below, highlighting the distinct patterns between urban core and regional background sites, further supporting the value of urban tall-tower measurements. In addition, figure numbers in the manuscript and supporting information have been updated accordingly.

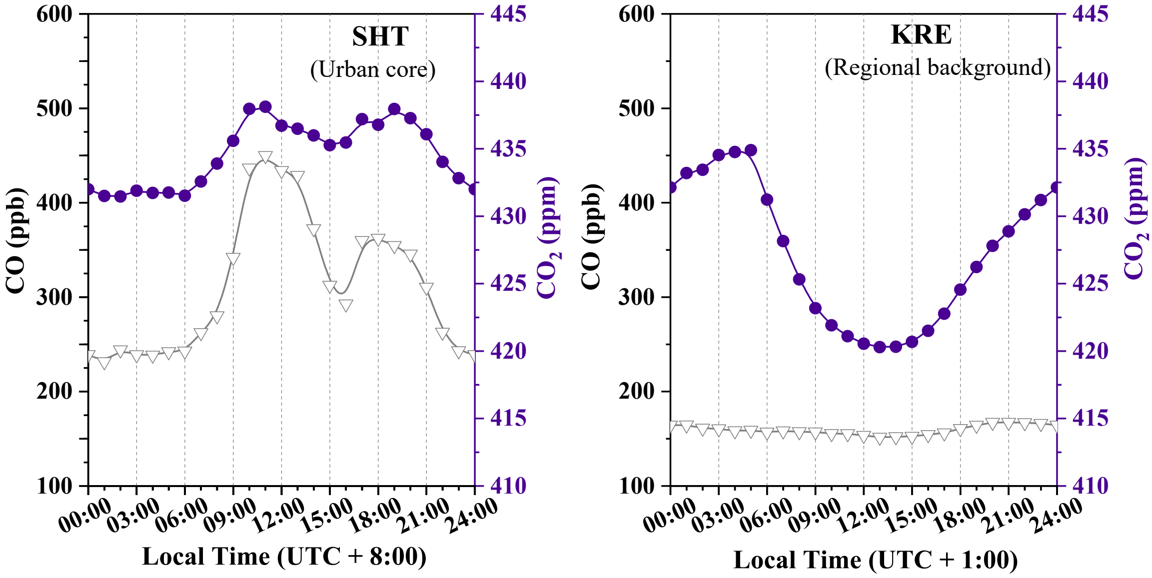


Figure S4: Diurnal cycles of CO and CO_2 observed at the SHT (urban core elevated site) and the KRE (background tall tower). See Table S1 for the site details.

Supplementary references on previous tall-tower observational studies:

Denning et al. (2008): Denning, A. S., Zhang, N., Yi, C., Branson, M., Davis, K., Kleist, J., and Bakwin, P.: Evaluation of modeled atmospheric boundary layer depth at the WLEF tower, Agric. For. Meteorol., 148, 206–215, https://doi.org/10.1016/j.agrformet.2007.08.012, 2008.

Winderlich et al .(2014): Winderlich, J., Gerbig, C., Kolle, O., and Heimann, M.: Inferences from CO_2 and CH_4 concentration profiles at the Zotino Tall Tower Observatory (ZOTTO) on regional summertime ecosystem fluxes, Biogeosciences, 11, 2055–2068, https://doi.org/10.5194/bg-11-2055-2014, 2014.

Comment 4: *L158-160 Here we see mention of "Global Data Assimilation System" and later "NCEP/NCAR reanalysis data" as data source for trajectory. Likely to be GDAS*

Response: Thank you very much for your comment. We rechecked the meteorological data source we used and confirmed that it was indeed GDAS. In the revised manuscript, we have corrected the inconsistent and inaccurate expressions as follows:

Revised L167-174: "… calculations were based on gridded meteorological data from the Global Data Assimilation System (GDAS) provided by the National Centers for Environmental Prediction (NCEP). Specifically, MeteoInfo software (version 3.3.12) combined with ~~NCEP/NCAR~~ NCEP/GDAS reanalysis data (ftp://arlftp.arlhq.noaa.gov/pub/archives/gdas1, 1°×1°; Rousseau et al., 2004) ~~at 1°×1° spatial separation rate (Rousseau et al., 2004)~~ was used to calculate 72-h back trajectories with1-h intervals."

Comment 5: *L346 MLG site could be mistype?*

Response: Thank you very much for your kind reminder. The term has been recorrected to "WLG" accordingly.

Comment 6: *L378 Can mention agricultural waste burning as possible source of autumn CO enhancement, and residential fuel burning in winter.*

Response: Thank you very much for your valuable suggestion. We have revised the manuscript accordingly as follows:

(1) Agricultural waste burning as a source of autumn CO enhancement. We have already briefly mentioned this point in the overview of Section 3.1 (L293-298): "The observed CO, … the SHT site appeared to be affected by horizontal transport (T_{H}) …, especially from the northwest upwind direction where autumn crop residue burning remains active (Wang et al., 2019), despite the long-standing prohibition of open straw burning in Shanghai (Tian et al., 2022)." We have also made the following revision to further highlight this point in Section 3.4.

Revised L427-429: "Figure 7a reveals a clear seasonal pattern in $k_{\mathrm{CO_2/CO}}$ ratios, with higher values in spring (99.9 ppm/ppm) and winter (76.5) compared to summer (64.3) and autumn (47.8). As mentioned earlier, a lower $k_{\mathrm{CO_2/CO}}$ ratio in autumn may be related to crop residue burning as a possible source of autumn CO enhancement (Wang et al., 2019). Moreover, the~~The~~ generally higher $k_{\mathrm{CO_2/CO}}$ estimates throughout this campaign reflect …".

(2) Residential fuel burning in winter. We appreciate this suggestion. In Shanghai, winter residential coal combustion is rare; elevated winter CO levels at SHT are more likely influenced by transport from upwind regions. Nevertheless, we recognize that residential fuel burning (e.g., natural gas, biomass) can still contribute to local CO emissions. As noted in Section 3.5, we have already provided a detailed case analysis of residential activities and fuel usage before and after the COVID-19 lockdown (see revised L487–495), which partially addresses this point. Thank you again for your insightful suggestion.

Comment 7: *L505 PBLH is shown to be from ECMWF open data, but variable list at https://www.ecmwf.int/en/forecasts/datasets/open-data doesn't include PBL*

Response: Thank you for pointing out this issue. We have rechecked the source of the planetary boundary layer height (PBLH) data used in our study. The PBLH data are derived from the ERA5 reanalysis produced by ECMWF. In the ERA5 dataset, the boundary layer height variable is coded in "Other: Boundary layer height". We have corrected the description in the manuscript to accurately reflect the data source.

Revised L**562-563**: "PBLH data are reanalysis products from ~~ECMWF (2024)~~ the fifth generation ECMWF reanalysis for the global climate and weather (EAR5, 2025)."

The revised dataset is referenced as required:

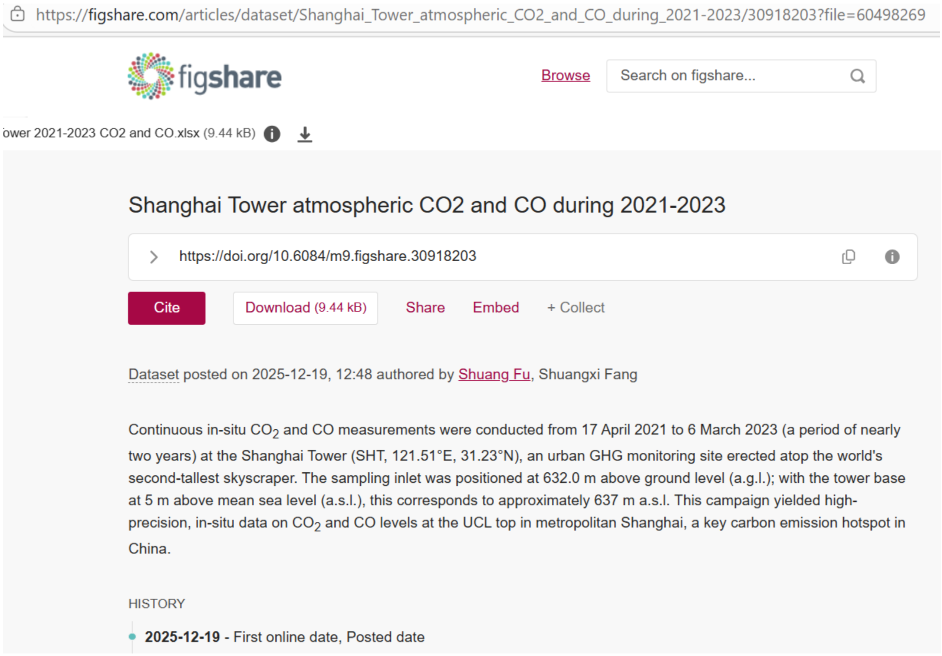
ERA5, the fifth generation ECMWF reanalysis for the global climate and weather: ERA5 hourly data on single levels from 1940 to present, Copernicus Climate Data Store [data set], https://doi.org/10.24381/cds.adbb2d47, 2025

Comment 8: *L566 doi is missing (https://doi.org/10.21957/open-data ?)*

Response: Thank you for pointing out this issue. The data source has now been replaced, and the corresponding DOI information has been provided in the response to Comment 7.

Comment 9: *L609 Fu and Fang 2025 reference not available.*

Response: Thank you very much for your interest in reviewing this reference. The reference Fu and Fang (2025) is hosted on figshare, a UK-based repository. We have checked that the reference is available (see the screenshot below for reference); however, access to this platform may be subject to regional network conditions. Should you have any difficulty accessing it, please feel free to contact us (shuangfu@zjut.edu.cn; fangsx@zjut.edu.cn. We appreciate your careful review.



https://figshare.com/articles/dataset/Shanghai_Tower_atmospheric_CO2_and_CO_during_2021-2023/30918203?file=60498269

Shanghai Tower atmospheric CO2 and CO during 2021-2023

https://doi.org/10.6084/m9.figshare.30918203

Dataset posted on 2025-12-19, 12:48 authored by Shuang Fu, Shuangxi Fang

Continuous in-situ CO_2 and CO measurements were conducted from 17 April 2021 to 6 March 2023 (a period of nearly two years) at the Shanghai Tower (SHT, 121.51°E, 31.23°N), an urban GHG monitoring site erected atop the world's second-tallest skyscraper. The sampling inlet was positioned at 632.0 m above ground level (a.g.l.); with the tower base at 5 m above mean sea level (a.s.l.), this corresponds to approximately 637 m a.s.l. This campaign yielded high-precision, in-situ data on CO_2 and CO levels at the UCL top in metropolitan Shanghai, a key carbon emission hotspot in China.

HISTORY

- **2025-12-19** - First online date, Posted date

Figure 1 in the response: Screenshot of the Fu and Fang (2025) reference on the figshare repository.