Referee 2:

General Comments

The manuscript presents a comprehensive analysis of two years of continuous ground-based in-situ carbon dioxide and methane measurements at a suburban site in India. The authors compare these observations with satellite products, simulated CO_2 data, and other measured variables such as planetary boundary layer height and carbon monoxide. The study covers a wide range of approaches and datasets, which is commendable.

However, the manuscript suffers from several issues that require major revision:

> The language is often imprecise, wordy, and repetitive.
> The conclusions largely reiterate textbook knowledge and remain qualitative, even when quantitative data is presented.
> Methodological details are sometimes unclear or inconsistent.
> Figures and data presentation could be improved for clarity and comparability.

The manuscript would benefit significantly from major language editing and restructuring to improve clarity and conciseness.

We sincerely thank the reviewer for the thorough evaluation of our manuscript and for acknowledging the comprehensiveness of the dataset and the integration of multiple data products. We appreciate the constructive comments and have carefully addressed each concern in the revised version. Specifically:

1. The language has been carefully edited to improve clarity and conciseness. The repetitive sentences have been avoided.

2. The conclusions have been rewritten to emphasise quantitative results rather than qualitative statements.

3. Methodological descriptions have been clarified and made consistent to improve clarity.

4. Figures have been revised for improved clarity and better comparability.

We believe these revisions significantly strengthen the manuscript and improve its overall scientific rigour and presentation.

Specific Comments

1. CO_2, expressed as parts per million (ppm), refers to mole fractions, not concentrations.

Noted. In the revised manuscript, CO_2 is now consistently referred to as mole fractions, throughout the manuscript.

2. Line 20: Add height above sea level (asl).

We modified the text as *"Given the paramount significance of the IGP, a GHG observatory was established at a suburban monitoring station in Sonipat, Haryana (28.95 °N, 77.10 °E; 228m asl), within the Delhi National Capital Region."*

3. Line 23: Clarify how an annual average is determined over a two-year period.

We have modified the text as follows: *"We observed an annual average CO_2 mole fraction of 440.8 ± 19.7 parts per million (ppm) between January and December 2024, with unusually strong seasonal variability, ranging from 422.6 ± 23.3 to 456.4 ± 30.8 ppm during the monsoon and post-monsoon periods, respectively."*

4. Section 2.1: Include station location relative to Delhi (direction, distance).

We have modified the text to "*Sonipat is an upwind suburban region of the Delhi National Capital Region (NCR), situated in the northern Indian state of Haryana, approximately 45 kilometres north of Delhi*" for clarity in the manuscript in section 2.1

5. Line 118: A cavity temperature of 45°C is standard and not user-adjustable.

The text has been rephrased as *"The standard cavity temperature of 45°C (throughout the measurement period) ensures the necessary etalon mechanical stability of the measurement cavity."*

6. Lines 120–121: Clarify what is located 10 m above the instrument housing. Specify building height, canopy height, and inlet height above ground.

We have included this additional information into the manuscript: *"A pole is positioned on top of the roof, on which the inlet is mounted (about 15 m above ground level). The building is 3 stories tall, with the roof serving as the fourth floor. The inlet on the pole is positioned well above the surrounding canopy at the monitoring site."*

7. Line 121: Teflon tubing is permeable to CO_2 and thus inappropriate. Include tubing size, sample residence time, and any checks for CO_2 losses or contamination.

Teflon (PTFE) tubing was used for sampling because of its widespread use in atmospheric trace gas measurements due to its chemical inertness and low adsorption properties (Li et al., 2023). Ambient air samples were drawn using a 5 m-long PTFE tube with an inner diameter of 4mm, connected to an external vacuum pump operating at approximately 400 SCCM (residence time ~5.9 s). Given the short residence time and continuous sampling configuration, CO_2 losses or contamination due to permeation through the tubing are expected to be negligible relative to the observed atmospheric variability. In addition, the stability of the CO_2 measurements was routinely monitored using calibrations and instrument diagnostics, and no systematic offsets or drifts attributable to the sampling line were detected.

These details are included in the supplementary information. Also, the text has been modified as "The *sample air was taken from the top of the building and above the tree canopy (5 meters above the instrument housing) through a Teflon (PTFE) tube with an inner diameter of 2 mm using an external vacuum pump with ~400 SCCM flow rate (residence time ~5.9 s)*."

8. Line 149: Provide specifications for low-cost sensors (e.g. precision, accuracy, drift).

We have added these lines to the text: "*The sensitivity of the $PM_{2.5}$ and CO sensors was evaluated in Nagasaki, Japan, through intercomparisons with reference-grade instruments employing a beta attenuation monitor (BAM) for $PM_{2.5}$ and non-dispersive infrared (NDIR) spectroscopy for CO measurements. The estimated unit-to-unit variability was 29% for $PM_{2.5}$ sensors and 21% for CO sensors. Further details on the sensor specifications and the calibration methodology are described in Mangaraj et al. (2025).*"

9. Clarify the distance between the 1-Techpark building and the CRDS location.

The inlet is located on the roof of the I-Tech building, positioned on a pole approximately 3 metres above the roof. The roof is on the fourth floor of the I-Tech building. The instrument is placed inside the laboratory on the third floor. We have this information into the manuscript.

10. Lines 165–166: Describe calibration procedures for low-cost sensors.

We have addressed this in comment 8.

11. Line 175: Justify exclusion of Boulder Laboratory data.

We have modified the text as follows: "*We used the five-year averaged data for all sites in the same latitudinal band as India (5 ºN - 40 ºN). The data was averaged for five years from 2018 to 2022 for all stations except Boulder Atmospheric Observatory, Colorado (2011-2016), to compare the seasonality over different locations across the globe*". The Boulder Atmospheric Observatory data is not excluded, rather a different time period is used. Our intention in this section was to compare Sonipat CO_2 seasonality against some data from similar latitudinal bands (not all stations) across different regions, based on the availability of data.

Line 180: Confirm whether all 625 datasets were used.

Thanks for noting this misleading text in the manuscript. Note that we have selected available datasets from monitoring stations corresponding to similar latitudinal bands as Sonipat. Therefore, the misleading sentences (which described the ObsPack data in general) were removed from the manuscript: "*This product includes 625 atmospheric carbon dioxide datasets from observations made by 79 laboratories from 28 countries. The ObsPack dataset provides data for the period 1957-2023.*"

Line 252: Add missing citation.

Added. Moreover, all references have been carefully cross-checked to ensure completeness throughout the manuscript.

12. Figure 1c: Add boundaries of the Indo-Gangetic Plain.

We have added the boundaries of the Indo-Gangetic Plain in the new Figure 1b.

13. Split Figure 1 into two: one for spatial context (Fig. 1b, c, d), one for time series, add CH4 and CO (new Fig. 2).

The new figures 1 and 2 have been added in section 3.1

Line 299: Clarify that the "annual mean" is a two-year average.

Throughout the manuscript, it has been corrected that the annual mean refers to the mean value of CO_2 from January 2024 to December 2024, for better clarity.

14. Lines 300–302: Rephrase for clarity.

The sentence has been rephrased as *"Interestingly, despite differences in site characteristics, the annual mean CO_2 levels at rural stations like Gadanki and urban stations such as Ahmedabad are comparable, whereas Sonipat exhibits distinctly higher values."*

15. Figure 2: Highlight seasonal regimes (monsoon, pre-monsoon, post-monsoon, winter) with background colors. Define pre-monsoon explicitly. Not done yet. Do you exclude any data when regimes transition?

We appreciate this suggestion. In the revised manuscript, the seasons have been highlighted using background colours for better clarity. Pre-monsoon has been defined in section 2.1 now. The modified text is given here: *"The climatic conditions over this site are similar to Delhi which has sweltering summers (March - May), damp or moist monsoons (June - September), and extreme winters. Similar to Delhi, this region also has frequent haze and smog with low visibility during winter (December - February) and post-monsoon (October - November) seasons."*

16. Monthly separation is coarse given the availability of hourly data. Consider using meteorological indicators (humidity, precipitation, temperature) for regime classification.

We appreciate the reviewer's suggestion to use meteorological indicators such as humidity, precipitation, and temperature for regime classification. We acknowledge that monthly separation is still coarse. However, the analysis using monthly and seasonal regimes could lead to sufficient insights into the seasonal variability of the CO_2 dynamics over the region. Moreover, the seasonal regimes adopted in this study follow the standard classification prescribed by the India Meteorological Department (IMD), which is widely used in climatological and atmospheric studies over the Indian region. Furthermore, we have updated the figure in the supplementary information (Figure S2) to examine the regime transition in relation to meteorological parameters.

17. Lines 321 ff.: Detrend data before comparing seasonal regimes to avoid bias from annual trends (~2.5–3 ppm/year).

The point we highlighted in this figure was about the monthly variation of atmospheric CO_2 mole fraction over the monitoring station. Detrending was intentionally applied in Figure 8 to isolate the influence of the long-term growth rate when examining the drivers of CO_2 variability.

18. Lines 360 ff.: The association between increased CO_2 and ecosystem productivity is unclear.

We thank the reviewer for the comment. During the post-monsoon season (October to mid-November), before crop harvest, the ecosystem exhibits higher nocturnal respiration and enhanced soil microbial activity, which contribute to elevated CO_2 mole fractions. We have clarified this in the manuscript for better clarity: *"Further, an increase in CO_2 mole fraction (~ 34 ppm) is observed during post-monsoon, reflecting higher ecosystem productivity (Sharma et al., 2014) and an enhancement in soil microbial activity (Fan & Forkel, 2025; Munksgaard et al., 2022), particularly from nocturnal respiration prior to crop harvest."*

19. Seasonality discussion is verbose and based on coarse temporal resolution. Regime transitions likely do not align with calendar months, leading to blurred results.

We agree with the reviewer that regime transitions do not strictly follow calendar months, however, the seasonal classification is used only as a regime-labelling framework. The seasons follow the IMD-defined regimes, which represent physically distinct and well-established meteorological conditions over India. This approach ensures consistency with prior studies and enables robust interpretation of CO_2 variability under dominant regional regimes.

20. Figures 3 & 4: Use consistent scales for observed and simulated data. Current presentation is misleading due to scale differences (e.g., 60 ppm vs. 8 ppm (Fig. 3) and 70 ppm vs. 20 ppm (Fig. 4)).

The point of this comparison was to demonstrate that the model can capture the seasonal pattern, but not the actual values. Using the same scale would hinder the depiction of the comparable seasonal pattern due to the totally different amplitudes.

21. Section 3.2.3: Clarify why only 12 ObsPack stations are used and why Boulder data is treated inconsistently. Above, it is mentioned that Boulder data were excluded.

This point has been clarified in Section 2.3.1. The Boulder Atmospheric Observatory data is not excluded, rather a different time period is used. Our intention in this section was to compare Sonipat CO_2 seasonality against some data from similar latitudinal bands (not all stations) across different regions, based on the availability of data.

22. Figure 6: Apply detrending before calculating seasonal cycles.

We appreciate this suggestion from the reviewer. Detrending was intentionally applied in Figure 8 to isolate the influence of the long-term growth rate when examining the drivers of CO_2 variability. Seasonal analyses presented in other sections are based on the original time series.

23. Section 3.3: Explain why the growth rate is considered for diurnal cycles but not for seasonal cycles.

The intention of the seasonal and diurnal variations plots here was to present the total CO_2 mole fractions over Sonipat on a seasonal and diurnal scale. The long-term CO_2 growth rate was not explicitly removed in the diurnal analysis. Instead, the diurnal cycles are analysed separately for each year to avoid any influence of interannual CO_2 increases on the derived diurnal amplitudes. Analysing multiple years together could bias the diurnal signal due to differences in background CO_2 levels between years. We have rephrased the sentence for clarity: *"To isolate diurnal variability, the diurnal cycle is analysed separately for each year, thereby minimising the influence of the long-term CO_2 growth rate on the estimated diurnal amplitude."* Note that the growth rate has been removed while studying the drivers of CO_2. In the revised manuscript, an analysis is added by removing the growth rates from both diurnal and seasonal means.

24. Lines 540–541: Clarify what is meant by "other local sources." Define "local emissions" consistently. Is crop burning considered local? Examples show inconsistent treatment:
    a. Line 657–658: "… high concentrations of CO2 during November (post-monsoon) from local emissions and crop residue burning …"
    b. Line 32 ff.: "… CO2 variability in the IGP is driven by the interplay of local anthropogenic and biomass burning emissions …"
    c. Line 461 ff.: "Being surrounded by agricultural land, Sonipat is prone to emissions from crop residue burning."
    d. Line 417 ff.: "This enhancement during the post-monsoon season can be attributed to crop residue burning over the monitoring station and the added transport from Punjab […] This highlights the inability of high-resolution satellite data to capture enhancements from local sources."

Thank you for pointing that out. 'Other local sources' refer to vehicular emissions from the nearby highway and industrial emissions from facilities located to the northwest of the monitoring site. In addition, the station located upwind of Delhi is affected by small-scale crop residue burning during the post-monsoon season, as well as occasional biomass (wood) burning in surrounding areas. These sources collectively constitute the other local sources around the site. We have carefully reviewed the manuscript and corrected it to ensure a consistent and uniform treatment throughout.

25. Figures 8 & 9: Justify use of Mauna Loa as a baseline. Explain deviation from ADHS methodology. Specify which Mauna Loa data were used and whether a background filter was applied.

In Figure 8, the analysis focuses on examining the dominant drivers of CO_2 at Sonipat. As India currently lacks a long-term, regionally representative background CO_2 monitoring site, Mauna Loa was used as a global reference to estimate and remove the large-scale growth rate. CO_2 observations from Mauna Loa corresponding exactly to the study period were used for detrending. No additional background filtering was applied to the Mauna Loa dataset, as the objective was solely to capture the global growth rate.

Figure 9 employs the ADVS method, which is used consistently throughout this study, to estimate background CO_2 concentrations and thereby estimate enhancements relative to the background.

    26. Clarify how CH_4 and CO backgrounds were determined.

The background concentrations of CH_4 and CO were determined using the same approach applied to CO_2, namely the Adaptive Diurnal Variation Selection (ADVS) technique.

While the manuscript addresses an important topic and presents valuable observational data from a region with limited coverage, it requires substantial revisions to improve clarity, consistency, and methodological rigor. The most compelling insight is the difficulty global products have in resolving local processes—an important but not unexpected finding.

With careful revision, the study has the potential to contribute meaningfully to the understanding of regional CO_2 variability in the Indo-Gangetic Plain.

We thank the reviewer for acknowledging the dataset's comprehensiveness and potential, as well as the insights gained from analysing the local observations. This study improves our current understanding of CO_2 dynamics over the IGP region with this unique measurement dataset and analysis. Following the reviewers' suggestions, we have thoroughly revised the manuscript to clarify the analysis and strengthen its scientific rigor.

References:

Fan, N., & Forkel, M. (2025). *Drivers of the enhanced amplitude of atmospheric CO2 in northern terrestrial ecosystems*. https://doi.org/10.5194/egusphere-egu25-7279

Li, X. B., Zhang, C., Liu, A., Yuan, B., Yang, H., Liu, C., ... & Shao, M. (2023). Assessment of long tubing in measuring atmospheric trace gases: applications on tall towers. *Environmental Science: Atmospheres*, *3*(3), 506-520.

Mangaraj, P., Matsumi, Y., Nakayama, T., Biswal, A., Yamaji, K., Araki, H., ... & Mor, S. (2025). Weak coupling of observed surface PM2. 5 in Delhi-NCR with rice crop residue burning in Punjab and Haryana. *Npj Climate and Atmospheric Science*, *8*(1), 18.

Munksgaard, N. C., Lee, I. L., Napier, T. P., Zwart, C., Cernusak, L. A., & Bird, M. I. (2022). One year of spectroscopic high-frequency measurements of atmospheric CO2, CH4, H. *Geoscience Data Journal*. https://doi.org/10.1002/gdj3.180

Sharma, N., Dadhwal, V. K., Kant, Y., Mahesh, P., Mallikarjun, K., Gadavi, H., Sharma, A., and Ali, M. M.: Atmospheric CO2 Variations in Two Contrasting Environmental Sites Over India, Air, Soil and Water Research, 7, ASWR.S13987, https://doi.org/10.4137/ASWR.S13987, 2014.
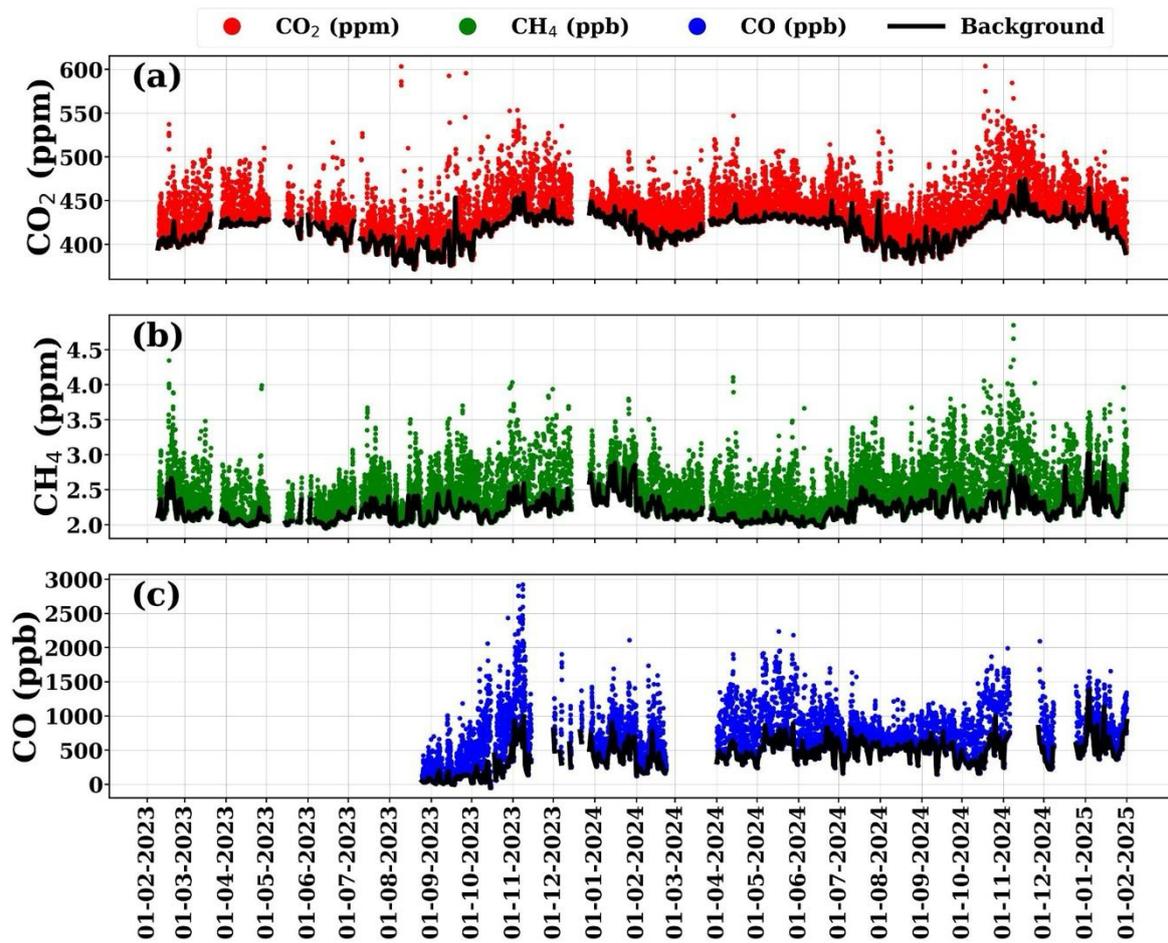
Updated figures:

Figure 1: (a) Hourly averaged time series of atmospheric (a) CO_2 (red) (b) CH_4 and (c) CO mole fraction for the study period (February 2023 to January 2025) over Sonipat. The thick black line represents the background mole fraction estimated using the Adaptive Diurnal least Variation Selection (ADVS).
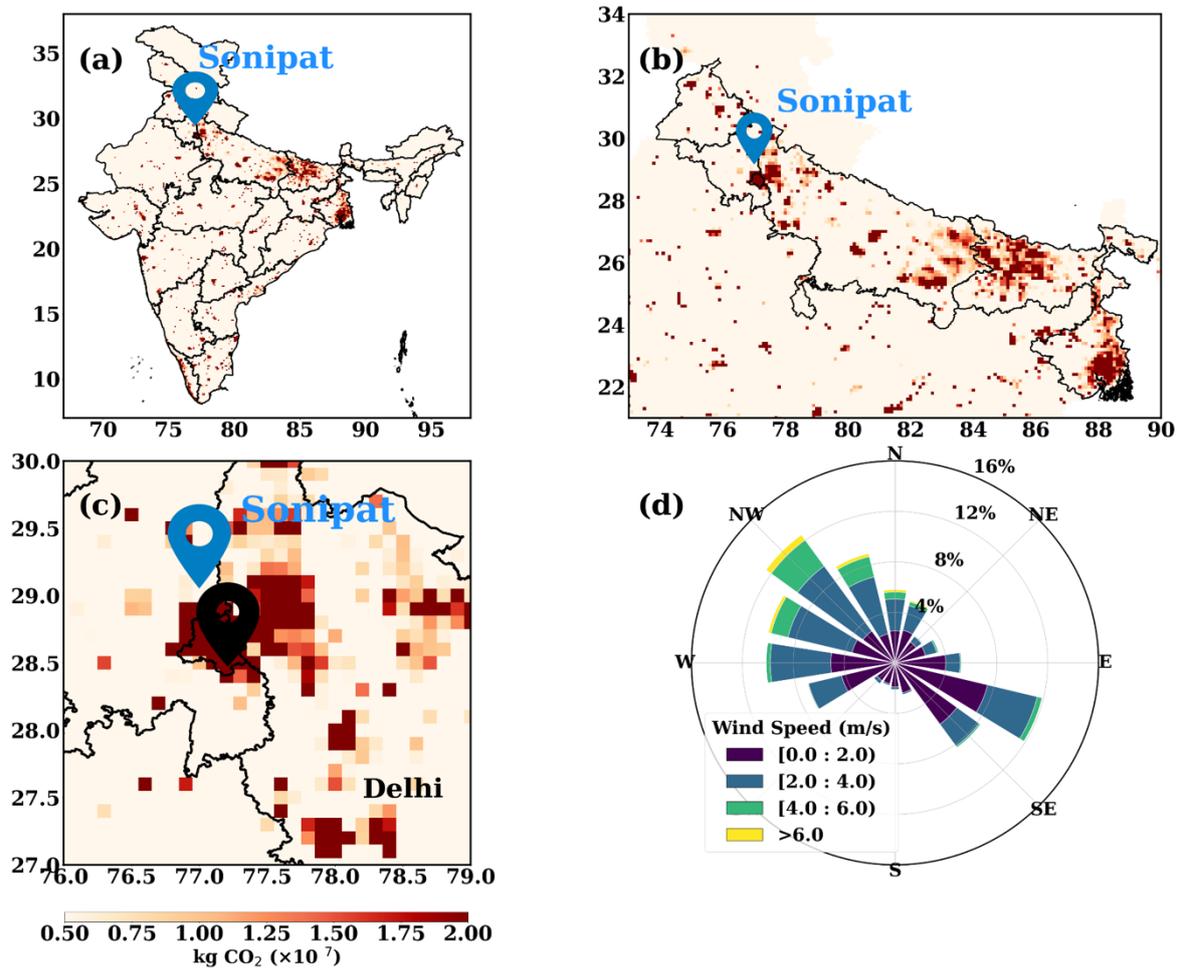
Figure 2: Anthropogenic CO_2 emissions over (a) India (b) Indo-Gangetic Plain and (c) Sonipat/Delhi are derived from the EDGAR emission inventory for 2021. (d) Annually averaged wind patterns over Sonipat for February 2023 – January 2024.
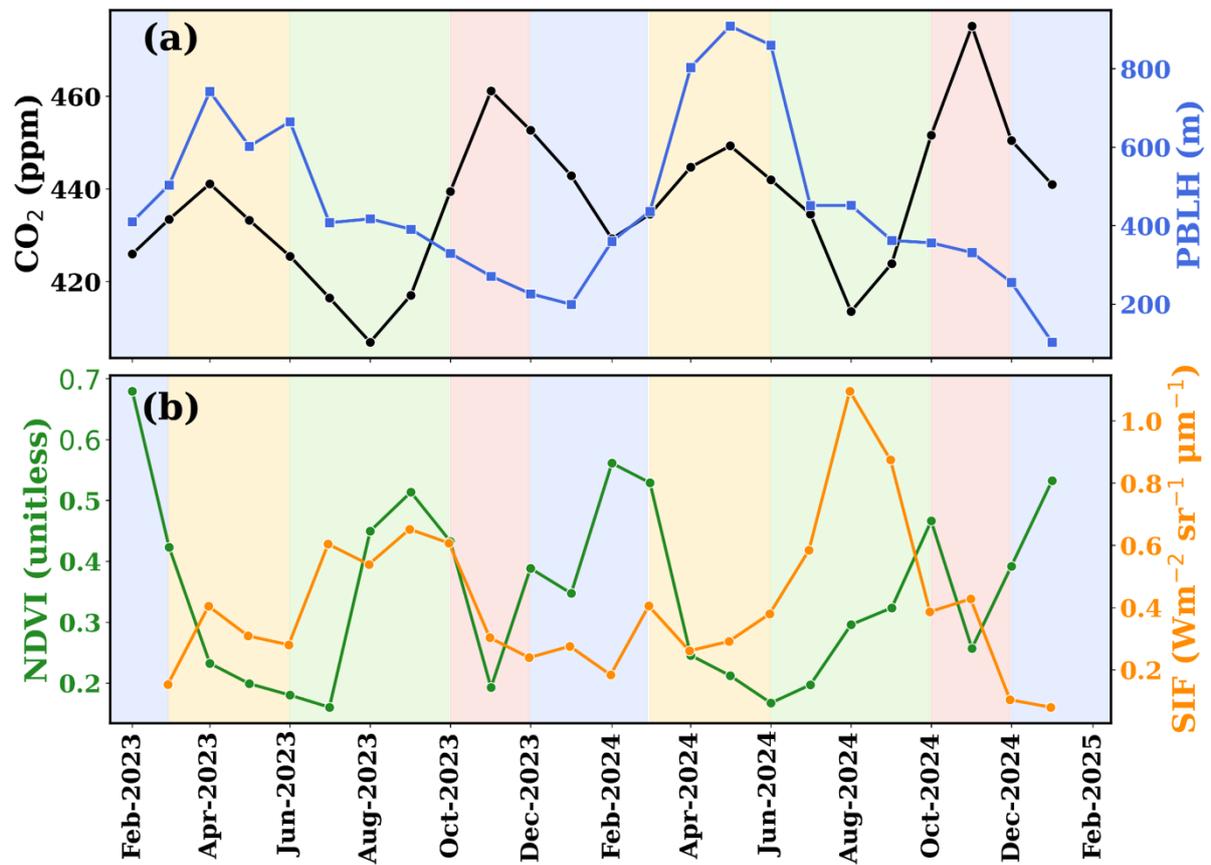
Figure 3: (a) Monthly variations of atmospheric CO_2 mole fraction (black) and PBLH (blue) and (b) NDVI (green) and SIF (olive green) over the Sonipat monitoring station during the study period.
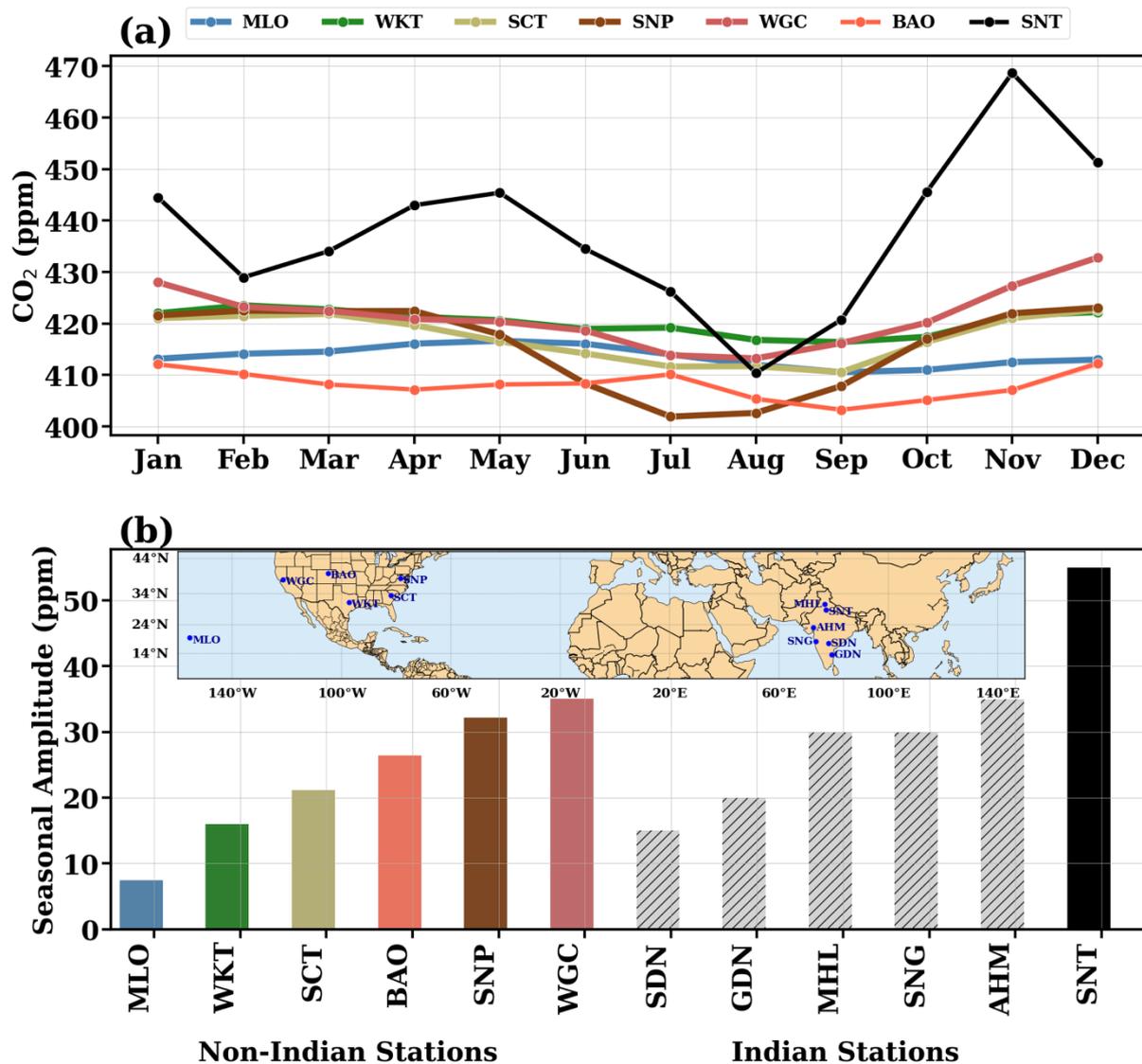
Figure 7: (a) Comparison of the seasonal variability of atmospheric CO_2 over Sonipat monitoring station with various locations in the same latitudinal band. (b) Comparison of the seasonal amplitude between Indian (coloured bars) and international monitoring stations (grey bars). Indian stations include Shadnagar (SDN), Sinhagad (SNG), Ahmedabad (AHM), Mohali (MHL), Gadanki (GDN), and Sonipat (SNT). International stations include Mauna Loa (MLO), South Carolina (SCT), Shenandoah National Park (SNP), Walnut Grove, (WGC), Moody (WKT) and Boulder (BAO). For all international stations except BAO, the five-year average (2018 - 2022) has been chosen for the seasonality. For BAO, 2011 – 2016 has been used. The monthly average of the entire study period (February 2023 – January 2025) has been used for this comparison.
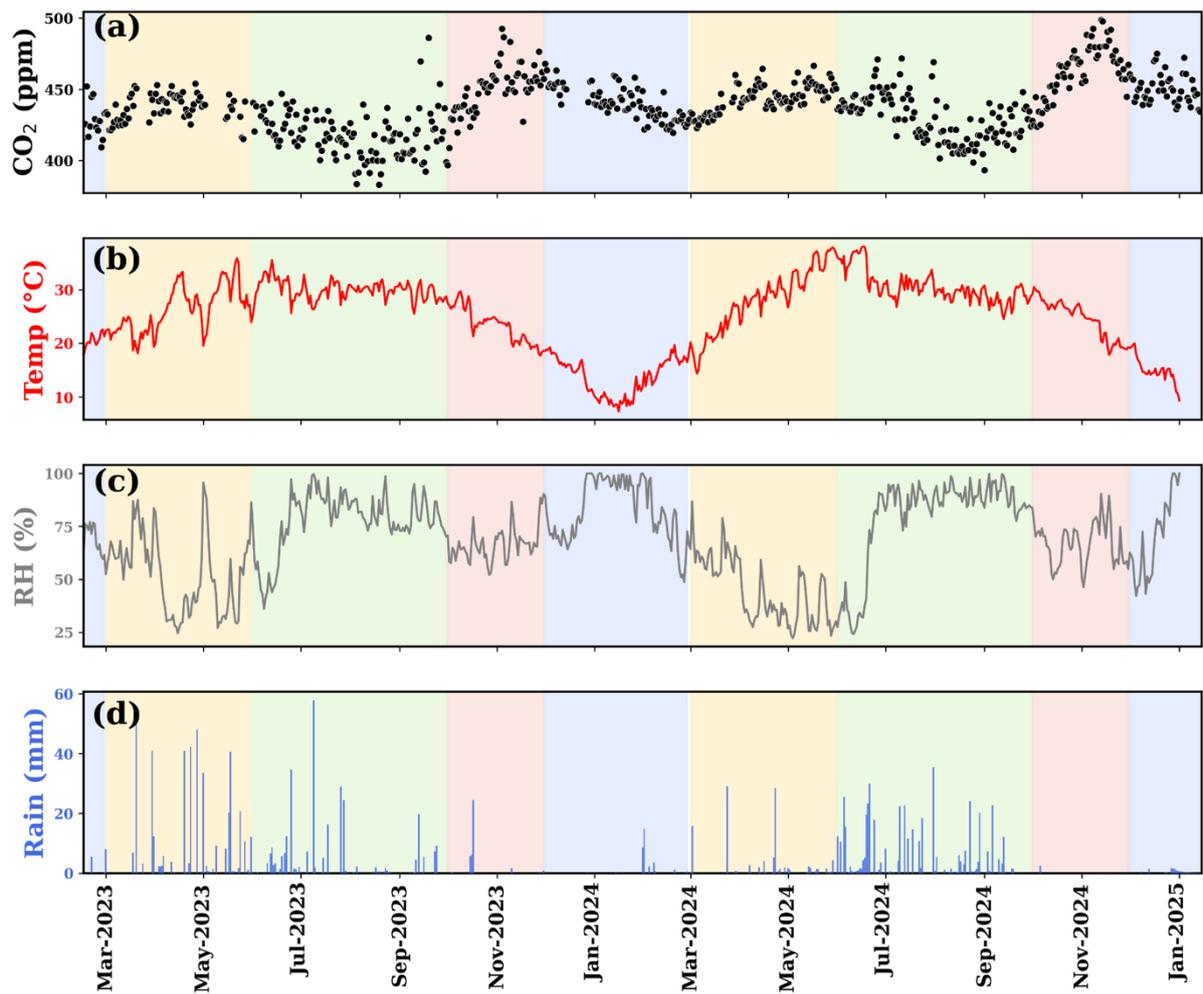
Figure S2: Daily variation in atmospheric carbon dioxide concentrations (a) and meteorological parameters (air temperature, relative humidity and rain) over Sonipat (b-d) during the study period. All measurements have been made using the Automatic Weather Station (AWS) in Sonipat.