Authors’ Responses to the Editor and Referees:

We are grateful to the Editor for giving us the opportunity to address the comments from Referee #2. We thank Referee #2 (**R02**) for reviewing our revised manuscript and providing helpful comments. We have addressed all these comments and incorporated the associated modifications into the manuscript.

The Editor’s and R02's comments are given in regular black font, our responses are given in regular blue font, and the changes in the revised version are given in *blue italic font*.

EC/ RC: Editor/R02 Comments

AR: Authors’ Response

EC: Dear Authors, All reviewers agree that the revised version is much improved over the original submission. However, one of the reviewers (referee #2) have raised 4 good questions that I would like you to address. I believe that all of these can be addressed with a simple sentence or two. These are all minor updates but will add to the value of the work and make this a robust study. Kindly address these comments and then the manuscript can be accepted for publication. Thank you.

AR: We agree. Our responses to R02’s comments are listed below, indicating the modifications in the second (now-)revised manuscript.

Response to Referee 2 comments

RC:

The authors have made substantial efforts to address the comments from the previous review, resulting in a manuscript that shows improvement compared to the earlier version, particularly with additional discussions on aspects related to seasonality and the diurnal cycle. However, before accepting this manuscript, I still have a few concerns that should be addressed during the revision process.

AR: Thank you for carefully reviewing our manuscript and appreciating the importance of work. Please see our responses to the referee's concerns below.

RC: In general, the mismatches between observations and the model are influenced by emissions, encompassing both biospheric and anthropogenic sources, and uncertainties stemming from transport errors. How do you discern the variations in observations-model disparities under different environmental conditions? For instance, Mohali is influenced by anthropogenic sources, while Nainital, being a high-altitude background site, is influenced by biospheric emissions. Is there a transport-related role in the observational and model mismatches observed in Nainital? Understanding whether the errors or mismatches in the model are linked to emissions or transport is crucial.

AR: Thank you for this comment. We acknowledge that model-data mismatches are mainly due to the incorrect transport and flux variations in the model (see Sect. 6.6). Decoupling model uncertainty solely due to transport and prior (input) fluxes is challenging while evaluating the model with observations, especially when both components (transport and flux variations) contribute considerably to atmospheric CO_2 variations. It should be noted that both Nainital and Mohali observations have significant contributions from transport, as explained in the manuscript (see Sect. 5.1), in addition to flux variability. In the Sect. 6.4, we discussed these influences by showing the contribution of different components to the total CO_2 concentration. By improving the transport (STILT model driven by fine–scale meteorology), we minimised modelling errors (see Sect. 5.2) compared to reanalysis products. Further, we reported significant differences (up to 8 ppm variability) in the Mohali CO_2 simulation related to the choice of the emission inventory in the STILT model (Sect. 6.4). We revised the manuscript to clarify this vital point:

L55-57: "*The model-observation mismatch in atmospheric CO_2 concentrations emerges due to the combined effect of uncertainties in the transport processes and the improper representation of CO_2 flux variability.*"

L442-445: *"Observations from all these four sites show strong seasonal variations in CO_2 concentrations (see Sect. 5.1), contributed by biospheric flux variations and transport mechanisms. Along with the seasonal variations, these observations (except Nainital) are also characterised by strong small-scale variability associated with local flux variations and mesoscale transport processes."*

L566-569: *"... STILT simulations is particularly relevant to assess the readiness of our models to utilise these measurements in the carbon assimilation system. Though it benefits the inverse modelling community, this study is not designed to entirely decouple the uncertainties solely due to inadequate transport and improper representation of flux variations in the model."*

L598-599: *"By improving fine–scale transport in the model, STILT simulations agree better with the observed seasonal and diurnal variations than the global reanalysis products."*

RC: In line 370: The authors have emphasized that the sharp decline in CO_2 concentrations is attributed to the uptake by Rabi crops. However, in certain instances, the authors underscore the insufficient representation of biospheric fluxes, particularly related to crops. Clarification on this statement would be beneficial.

AR: We indicated that the biosphere model could not adequately capture crop uptake, resulting in an overestimation of atmospheric CO_2 simulations. The text has been revised for clarity as follows:

L332-334: *"The observed decline is likely due to the increased biospheric uptake by Rabi crops during this period, which may be misrepresented in the biospheric model. This is further examined in detail in Sect. 6.5."*

RC: The authors suggest an insufficient representation of biospheric fluxes in the model. It raises curiosity about what alternative biospheric fluxes might address this issue, considering that the VPRM biospheric fluxes have already been incorporated into the regional models.

AR: As the referee indicated, the VPRM model is being widely used to represent biospheric CO_2 fluxes across the world. The model benefits from a network of long–term eddy-covariance flux observations for parameter optimisation, which is currently lacking in the Indian region. The availability of additional CO_2 flux observations or the incorporation of additional satellite observations (e.g. Solar Induced Fluorescence) may improve the model's performance.

The text is revised to include these points:

L558-560: *"Note that the VPRM model used in the present study lacks parameter optimisation against eddy-covariance flux observations across India. The availability of eddy-covariance flux observations representing various biomes in India is expected to improve the model performance.*

L606-609: *"In addition to using eddy-covariance flux observations in India, utilising additional satellite observations such as Solar Induced Fluorescence in the VPRM model can likely improve the prior representation of biospheric CO_2 uptake and release across Indian biomes (e.g., Ravi et al., 2023). Further, an improved (inverse) estimate of fluxes can be achieved by utilising atmospheric CO_2 observations through carbon data assimilation."*

RC: Another crucial aspect to consider when simulating the model for the entire year is the significant role that the Planetary Boundary Layer (PBL) plays in the variability of observations. Was this considered in the design of the model experiments, such as incorporating a proper PBL scheme?

AR: Yes. In this study, the STILT model utilised the modified Richardson number to calculate the PBL height (see Sect. 2) by using meteorological fields from the WRF model. The WRF-simulated meteorological variables are compared well with observations (e.g., Mathew et al., 2024). Evaluating the performance of STILT CO_2 simulations with respect to the changes in PBL simulations requires additional modelling set-ups/analysis along with the availability of PBL observations, which is not addressed in this study.

The text is modified as follows:

L57-59: "*The accurate representation of the planetary boundary layer (PBL) height is also crucial for the simulation of tracer distribution in the boundary layer and its dynamics (e.g., Gerbig et al., 2008).*"

L131-132: "These WRF meteorological simulations (temperature, moisture and wind) are compared reasonably well ($R^2 > 0.75$*) with observations (Mathew et al., 2024).*

References

- Gerbig, C., Körner, S., and Lin, J. C.: Vertical mixing in atmospheric tracer transport models: error characterization and propagation, Atmospheric Chemistry and Physics, 8, 591–602, https://doi.org/10.5194/acp-8-591-2008, 2008.
- Mathew, T. A., Ravi, A., Pillai, D., Saradambal, L., Kumar, J. S., Gopalakrishnan, M. M., and Thilakan, V.: Evaluating the meteorological transport model ensemble for accounting uncertainties in carbon flux estimation over India, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2023-2334, 2024.