Responses to referee 2:

We would like to thank the referee for the useful comments and constructive suggestions. In the following, we address the referee's comments and describe corresponding changes we have made to the manuscript. The referee's comments are listed in *italics*, followed by our response in blue. New/modified text in the manuscript is in **bold**.

This manuscript applies the flux divergence method to numerous cities on 3 continents in order to identify the changes in emissions over the 3 years impacted by COVID-19 lockdowns. The method includes refinements on the handling of terrain and lifetime that were reported in a prior publication. A clustering algorithm was applied to show that cities in North America, Europe and Asia had very different annual variability in NOx emissions over the last 4 years.

I believe that the method is sound and the results are valuable. The paper is clear and well written. I am happy to recommend it for publication.

We appreciate the positive feedback from the referee. Strictly speaking, the method in this work does not calculate flux divergence. Therefore, it is more accurate to refer to the method as the "directional derivative" method. The newly added Appendix B compares this work and previous works applying the flux divergence method in details.

My impression is that the height scale and the lifetime are at least partly numerical tuning parameters that have a loose connection with a physical interpretation. This would explain the particularly large values: the beta values are the inverse of the parameters, so large values suggest smaller than expected impact of the corresponding terms in the equations. I wonder if the question of the parameters would merit some more discussion and caveats in the analysis.

Thanks for this comment. We expand the discussion about this in the second last paragraph in the conclusions and discussion section:

"In this study we fit scale heights at monthly resolution and fit chemical lifetimes for each climatological month to strike a balance between the quality of the fitting results and temporal resolution. However, we assume spatially homogeneous scale heights and chemical lifetimes within each subregion. Considering that the fitting is conducted over cleaner locations where free tropospheric NO_2 subcolumn is expected to take a larger fraction of the tropospheric column, the fitted scale heights and chemical lifetimes are likely overestimated for urban areas. Additionally, the NO_x chemical lifetime is highly nonlinear with respect to NO_x concentration (Valin et al., 2013; Laughner and Cohen, 2019). Therefore, although some aspects of the fitted results are consistent with the expected spatial and temporal variation of PBL height and NO_x chemical lifetime, we caution that the inverses of scale heights and chemical lifetimes are fundamentally linear fitting parameters and suggest against over-interpreting the results. Future investigations might be helpful to achieve higher spatial granularity and/or considering the dependencies of scale height and chemical lifetime on the column amount."

My other impression is that for each site the time series is robust in a relative sense. However, I think there are probably larger uncertainties in the absolute emission values of one city compared to another and of absolute estimates of emissions in the winter compared with the summer. Because the purpose of the paper is to look at lockdown-induced variability, I don't think this is a major problem. However, I do think it should be discussed to prevent over-interpreting the data. A more detailed comparison of emission totals by city with published emission inventories is beyond the scope of this study, but would be interesting in the future.

We add the following sentences to last paragraph in the conclusion to be cautious about the absolute emission data:

"The main focus of this work is the relative emission changes for each city in the pre- and post-COVID-19 years. The absolute emission values of one city compared to another and absolute estimates of emissions month-by-month would be subject to larger uncertainties than the relative values, given the assumptions and simplifications discussed above. We expect future evaluations of spatiotemporal variations of derived emissions against known emission rates of point sources and bottom-up emission inventories."

References

Laughner, J. L. and Cohen, R. C.: Direct observation of changing NOx lifetime in North American cities, Science, 366, 723 LP – 727, https://doi.org/10.1126/science.aax6832, 2019.

Valin, L. C., Russell, A. R., and Cohen, R. C.: Variations of OH radical in an urban plume inferred from NO_2 column measurements, Geophysical Research Letters, 40, 1856–1860, https://doi.org/10.1002/grl.50267, 2013.