Replies to comments provided by Anonymous Referee #1
Title: Detecting nitrogen oxide emissions in Qatar and quantifying emission factors of gas-fired power plants - A four-years study
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https://egusphere.copernicus.org/preprints/2023/egusphere-2023-1024

We would like to thank the reviewers for their careful reading, that led to interesting comments and improvements of the article. Minor results will be added in the revised versions of the manuscript and the Supplementary Material.

IMPORTANT: We noticed a mistake in our estimation of power emissions in CAMS-GLOB-ANT due to a code typo. We corrected the mistake: power emissions in CAMS are now 1.81 times higher than they were in the manuscript, and the corresponding total emissions are now 1.16 times higher. The most significant change thus concerns one of the different estimations of the power plant emission factor in Section 6.3 and Table 1 which is now 1.219 t_{NOx}/GWh (previously 0.674 t_{NOx}/GWh). Results involving this inventory (lines 23, 454, 461, 463, 466, 484 and 572 in the current manuscript version) have been modified as a consequence, but the conclusions remain unchanged.

Questions provided by Anonymous Referee #1

This manuscript applies the flux divergence method to estimate NOx emissions over Qatar using TROPOMI NO2 retrievals. It represents an incremental development on the author's previous paper for emissions in Egypt. The paper is clearly written and appears to be thorough and sound. I am happy to recommend it for publication.

General Comments:

Urban emissions: as you note, Doha coincides with 5 gas power plants, making it difficult to separate emissions. However, it would be interesting to show estimated emissions of the urban and residential sectors versus the power and industrial sectors. These are readily available for EDGAR and CAMS. They would also improve the discussion of seasonal and day-of-week variability below.
→ In CAMS-GLOB-ANT, emissions from the different sectors do not show any seasonality, with the power, industry and transport sector at around 5.1, 2.8 and 8.0 kt/month respectively. On the other hand, those sectors in EDGAR show clear variations between months, especially the power sector. The following figure corresponds to Figure S4 but without stacking the emissions.

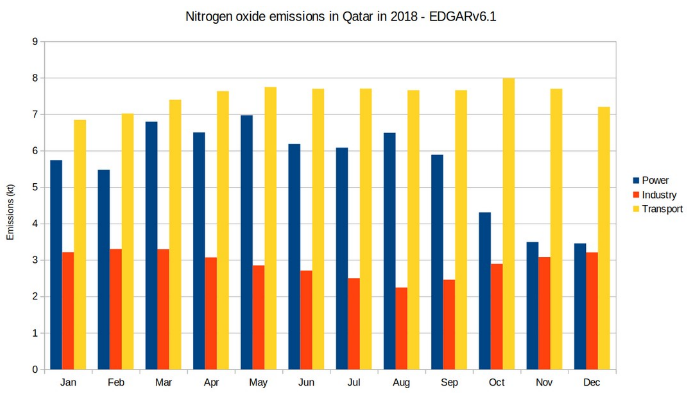

Figure AC1-1: Monthly NO_x emissions by sector for Qatar for 2018 in EDGARv6.1

The industry emissions are slightly lower during summertime; they can illustrate the lower production due to the reduced outdoor activity mentioned in Section 2. Power emissions are lower during wintertime, but the observed cycle has an amplitude much lower than what is observed in the electricity generation data. Finally, transport emissions do not vary much throughout the year. These elements are added to the revised version of the manuscript (Section 6.2). However, EDGAR and CAMS-GLOB-ANT inventories cannot be used in the discussion regarding the weekly cycle, since they both have a 1-month resolution.

Fig. 7: This makes me wonder if a coarse land-use mask is used. Work with the TROPOMI methane product found that a new high resolution water mask had to be used for coastal areas (de Foy et al., 2023). This problem is much more acute for methane than for NOx, but still it might have an effect here.

→ In the TROPOMI product, the parameter `surface_classification` in `NO2____/PRODUCT/SUPPORT_DATA/INPUT_DATA` is a combined land/water mask and surface classification data field. The water mask has been taken from Carroll et al. (2009), which has a 250 m resolution. We do not know exactly how the TROPOMI product uses this mask but the corresponding parameter does not have a coarse resolution for both versions, although there is a noticeable improvement from version 2.3.1 to version 2.4.0 according to the following figure:

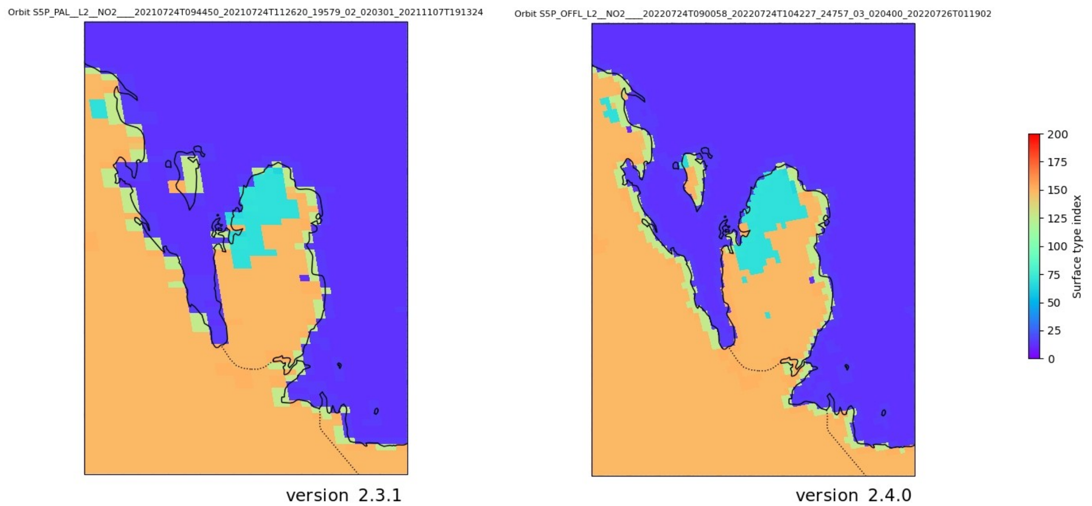

Figure AC1-2: Example of the use for the land/water mask used in the TROPOMI L2 NO2 product for versions 2.3.1 (left, 2021/07/24) and 2.4.0 (right, 2022/07/24).

Fig. 8: I wonder if you could show boxplots here to get a sense of the difference as a function of the variability. I think you did a sum of the flux divergence over the whole of Qatar? What happens if you look at different areas? I would expect a stronger weekday effect over residential area, and a weaker one over power plants and industrial facilities. As a check, I think it would be good to show the weekly cycle in VCD as well as in flux divergence.

→ We prefer not to use boxplots here to focus on highlighting the absence of significant differences between years. Indeed, the week-end effect is stronger over residential areas and weaker over power plants. The figure below displays the weekly cycle of NO_2 VCDs, OH concentrations and NO_x emissions over the whole country, the Ras Laffan power plants and the urban area of Doha for the 2019-2022 period (at around 13:30 LT). It will be added in the revised Supplementary Material. OH concentrations do not vary much within the week (in the CAMS product, we do not know if a weekly variation was introduced in the calculation of OH), so the observed trend is mainly due to the observed VCDs in the calculation of emissions.

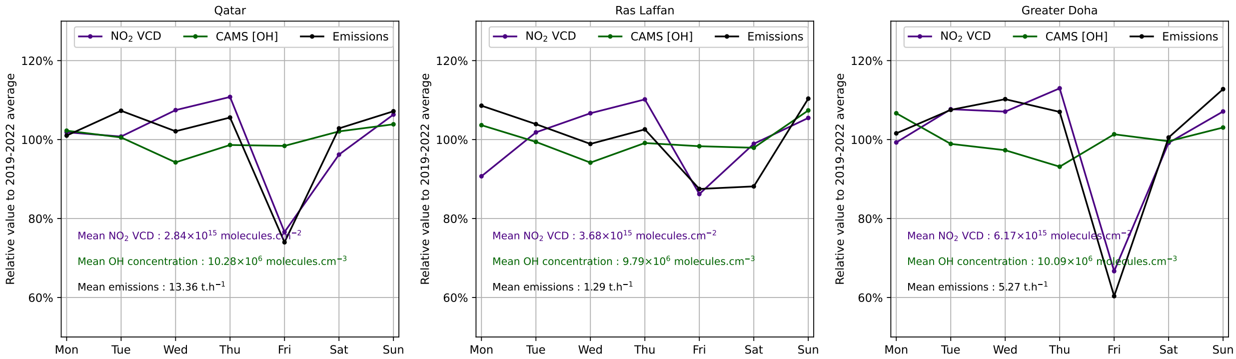

Figure AC1-3: Mean weekly profiles for NO_2 tropospheric vertical columns, OH concentration and NO_x emissions for the entire country (left), the Ras Laffan power plants in the north (middle), and the Greater Doha area (right). 2019-2022 averages are given and represented by the 100% line on the y-axis.

Note that the 4-year average is calculated without accounting for values lower than the 5^{th} percentile or higher than the 95^{th} percentile (as explained in Section 5.4), and that the re-scaling using the load curve is not used. Moreover, the power plant emissions are calculated summing emissions of the 6 pixels that are the closest to the power plants. For those three reasons, the mean values shown on this figure do not correspond exactly to those of Figures 10, 12 and 13.

Fig. 10: Maybe in SI you could show the monthly variation, or at least put color bars over the summer months to help see the annual cycle. In the text you say there is no seasonal signal in the VCD. I think it would be good to show the cycle in VCD as well as flux divergence side by side (as for the weekly cycle). Given the large seasonal cycle in electricity cycle, a lack of cycle in the TROPOMI results suggests that something else is going on. For example transport and industrial emission may be stable throughout the year.

→ Colors have been added to Figure 10 to visualise the annual cycle in NO_x emissions (green: MAM; red: JJA; yellow: SON; blue: DJF). Concerning the VCD cycle, it could be considered inconsistent to put on a same graph emissions based on pixel sums within a mask and VCD columns when the extent of NO_2 plumes can go multiple kilometres beyond the mask limits, as shown on Figure 2. However, it is possible to calculate the mean VCD value over different hotspots, using only the closest pixels (where NO_2 is maximum) inside the mask. Doing so, we obtain the following figure for the mean VCD over the Ras Laffan power plants (6 pixels), the cement plants in the west (4 pixels) and the Greater Doha area (15 pixels):

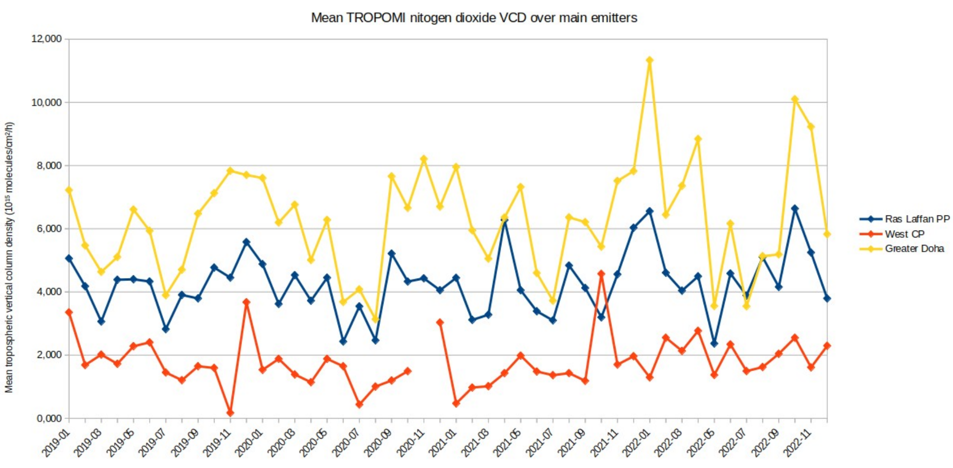

Figure AC1-4: Time series for mean NO_2 tropospheric VCDs above Ras Laffan power plants in the north, cement plants in the west, and the greater Doha area in the east.

Emissions from the cement plants in the west and from the gas power plants in the north do not show any particular seasonality. It is not the case for the greater Doha area, with lower VCD values during summer than during fall and winter. This cycle is in phase opposition to that of NO_x emissions shown on Figure 10, because the emissions cycle reflects more OH concentration variations (i.e. lifetime variations) than the NO_2 column budget. There is a non-linear relationship between OH and NO_2: following Valin et al. (2011), NO_2 levels over the main emitters in Qatar (higher than 2.0×10^{15} molecules/cm^2) are such that a linear increase in NO_2 levels is linked to an exponential decrease in OH concentrations. This relationship, which highlights a dominance of the OH variation with respect to the NO_2 variation in the high-NO_2 regime, might explain why the calculated emissions cycle is in phase opposition to that of the TROPOMI NO_2 VCDs. These elements are now mentioned in the revised version of the manuscript (Section 5.5).

Getting actual emission totals from the flux divergence method involves uncertainties, especially due to lifetime as you note. It would be interesting to see how your method compares to the values reported in the global catalog (Beirle et al., 2021). It would also be interesting to see how your evaluation of TROPOMI and EDGAR sources compares with that reported for large point sources and urban areas in South Asia (de Foy et al., 2022).
→ The Ras Laffan power plants are absent in the first version of the catalog by Beirle et al. (2021). However, they are present in the improved version of the catalog which has been published a few days ago (Beirle et al., 2023), with emissions estimated at 1.81±0.37 t_{NOx}/h, which is very close to our value of 1.86 t_{NOx}/h estimated in Section 6.1. If we compare of TROPOMI-derived NO_x emissions to those of de Foy et al. (2022), we observe that our results are notably higher: in South Asia, isolated gas power plants are Rohini and Faridabad near Delhi and Sheikhupura near Lahore, and the corresponding estimated emissions are 2.7, 4.4 and 5.4 times lower than those of the Ras Laffan complex, with capacities 2.3, 4.8 and 14.9 times lower, suggesting similar fuel efficiencies for Ras Laffan, Rohini and Faridabad and a lower efficiency for Sheikhupura compared to that of Ras Laffan. The two articles are mentioned in the revised version of the manuscript (Section 6.1).

Minor Comments:

Fig. 12: I think you are plotting one point per month, with total NOx emissions and Electricity generation over the whole of Qatar? I think the explanation could be clearer to help the casual reader.
→ The label of the Figure has been changed to "Comparison between monthly TROPOMI-derived NO_x emissions for the entire Qatar territory and corresponding electricity generation according to Planning and Statistics Authority reports. [...]"

Line 311: replace "estimaed" with "estimated".
→ Done.

References:

Beirle, S., Borger, C., Dörner, S., Li, A., Hu, Z., Liu, F., ... & Wagner, T. (2019). Pinpointing nitrogen oxide emissions from space. *Science advances*, *5*(11), eaax9800.

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Carroll, M. L., Townshend, J. R., DiMiceli, C. M., Noojipady, P., & Sohlberg, R. A. (2009). A new global raster water mask at 250 m resolution. *International Journal of Digital Earth*, *2*(4), 291-308.

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