Replies to comments provided by Anonymous Referee #2
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 version 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 #2

The authors infer NOx emissions in Qatar using satellite NO2 observations and compare it with the bottom-up inventories. It is well written. The results look sound. I recommend publication after minor revision.

General comments:

Section 4.2. The divergence method used here has been proposed by existing studies, e.g., Beirle et al. (2011). I think the authors shall give the credit to those studies by clarifying that this study is an application of an existing method. How the method is different (if any) from existing studies shall be highlighted.
→ The divergence method follows Beirle et al. (2019) (not Beirle et al., (2011)). The article is mentioned but we recognize we don't emphasize enough on the importance of this first study and the differences it has with our method. Section 4.2 is modified accordingly. The following sentences are modified/added:

- "As a second step, we derive top-down NO_2 production maps with the flux-divergence method, which has originally been proposed by Beirle et al. (2019)." *(modified)*
- Through the OH concentration, we enable a variability in the chemical lifetime. This variability is not allowed in the original version of the first-divergence method by Beirle et al. (2019), which relied on heavy averaging over time to infer emissions at the scale of cities and power plants. Here, seasonal and spatial variations of lifetimes are resolved, thus limiting the errors in the estimation of the daily sink term. Although errors remain high when estimating daily emissions, averaged monthly emissions are correctly resolved above the main emitters. *(added)*

The uncertainty of using 5 percentiles as background shall be discussed.
→ The main reason why the 5^{th} percentile of external mask pixels is chosen is because we want to estimate the background using pixels that do not contain anthropogenic NO_2. The domain is quite small and most of it is polluted with emissions from either Qatar, Bahrain, Saudi Arabia, UAE and shipping/flaring emissions in the Persian Gulf. The entire domain has 1536 pixels and the external mask has 1065 pixels, so the 5^{th} percentile-threshold should correspond to the 53 lowest pixels. To

illustrate the evolution of the inferred background with respect to the percentile chosen, I compared the daily background value obtained with the 10^{th}, 15^{th} and 20^{th} percentiles, as well as the pixels involved in their calculation for year 2022 (counted as the number of times a pixel is lower than the background value during the year):

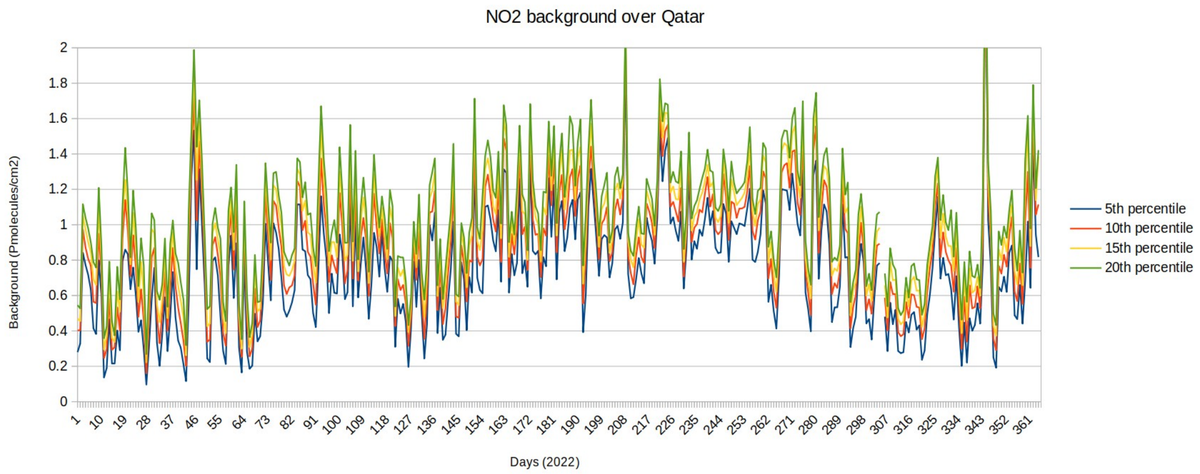

Figure AC2-1: Time series of estimated background using different percentiles of NO_2 columns in the external mask for year 2022.

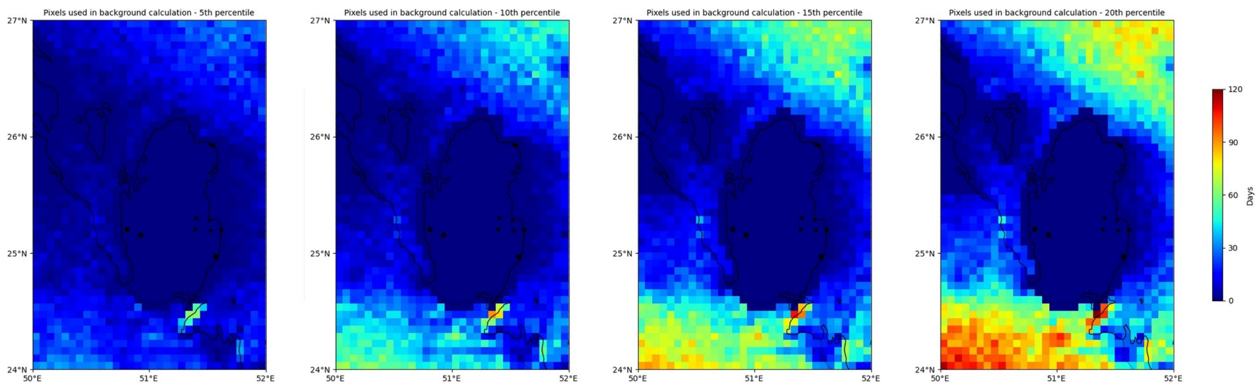

Figure AC2-2: Frequency map of NO_2 columns below a given percentile (from left to right: 5^{th}, 10^{th}, 15^{th} and 20^{th} percentile) used in the estimation of the background for year 2022.

Using a background defined as a higher percentile involves pixels that are increasingly close to the main emitters. On average, the difference between the 5^{th} percentile and percentiles 10, 15 and 20 are $0.13\pm0.04\times10^{15}$ molecules/cm^2, $0.22\pm0.06\times10^{15}$ molecules/cm^2, $0.31\pm0.08\times10^{15}$ molecules/cm^2, which is small compared to the total tropospheric VCDs which is often above 4.0×10^{15} molecules/cm^2 for the Ras Laffan power plants and 4.0×10^{15} molecules/cm^2 for Greater Doha. In terms of NO_x emissions, using the 20^{th} percentile instead of the 5^{th}, the size of the internal mask, and a mean lifetime of 4.3 hours (average 2019-2022 over the domain), would result in an average lowering of the inferred emissions of ~0.6 kt/month, i.e. about 6% of the average monthly emissions for 2019-2022.

Section 6.1. I understand the correlation between emissions and generation data is relatively low for monthly data. How is the correlation compared with that between bottom-up estimates and generation data? The comparison could help explain the inconsistency between TROPOMI-derived emissions and generation data.

→ NO_x emissions estimates from EDGAR and CAMS-GLOB-ANT do not correlate with electricity generation data. Electricity generation is shown to be highly variable, whereas the variability in total emissions from these two inventories is very low in comparison. If considered only the power emissions, EDGAR has some variability, but it is lower than that observed in electricity generation and the profile is slightly different. The following table shows the correlation coefficient (R^2) between electricity generation data and bottom-up total and power emissions, with TROPOMI-derived emissions as comparison.

Dataset compared with monthly power generation 2019-2022	R^2
Total emissions – TROPOMI (2019-2022)	0.400
Total emissions – TROPOMI – only more than 18 days in average (2019-2022)	0.657
Total emissions – EDGARv6.1 (2018)	0.062
Power emissions – EDGARv6.1 (2018)	0.117
Total emissions – CAMS-GLOB-ANT_v5.3 (2019-2022)	0.001
Power emissions – CAMS-GLOB-ANT_v5.3 (2019-2022)	0.137

Table AC2-1: Correlation coefficient of the comparison between inferred or inventory total or power NO_x emissions and electricity generation data.

The absence of correlation between electricity generation and NO_x emissions in inventories are briefly mentioned in the revised version of the manuscript (Section 6.2).

Specific comments:

Line 13. Regularly updated.

→ Done.

Line 19. No dash in under-estimated.

→ We corrected the spelling (and "over-estimated" as well) but it seems like both spellings are correct, depending on the dictionary. There might be a subtlety we do not get.

Line 65. The sentence is too long to read.

→ The sentence "Because the incomplete combustion of hydrocarbons produces NO_x, the exploitation of such oil and gas resources is a source of air pollution: as a consequence, the transport sector is a source of emissions, as well as the power sector, which is dominated in Qatar by gas power plants." has been replaced by "The exploitation of such oil and gas resources is a source of air pollution, due to NO_x emissions during the incomplete combustion of hydrocarbons. The power sector, which is dominated by gas power plants, as well as the transport sector, are thus important contributors to the NO_x levels throughout the country."

Line 169. Covered?

→ The sentence has been slightly changed: "In satellite retrievals, the NO_2 signal from a sparsely populated area or a small industrial facility may be difficult to identify due to high noise levels or natural emissions."

Is there any specific reason for choosing 30 km/h as the criteria to remove high-wind speed days?

→ The 30 km/h value has been chosen as a threshold because it corresponds to the minimal value for the wind module to reach the closest high emitters of Qatar. Manama and the cement plants in the east (angle ~ -75°) are separated by ~ 110 km. Manama and the Ras Laffan power plants (angle ~ -15°) are separated by ~ 105 km. The average lifetime value calculated from CAMS OH in the area between the two countries is about 3.5 hours. The corresponding value for minimal wind module is therefore ~ 105 km / 3.5 h ≈ 30 km/h, which is why we have chosen this value as a threshold.

It should be noted that a further analysis has been conducted after reading this comment. Indeed, the lifetime in the concerned regions vary. On average during the 2019-2022 period, it reaches 5.2 hours during winter months (DJF). During wintertime, a plume originating from Manama could thus theoretically reach the power plants in Ras Laffan with a module of ~ 100 km / 5.2 h ≈ 21 km/h, which is under the 30 km/h threshold. However, three points must be made:

- This situation should not appear frequently throughout the year: the MAM, JJA and SON periods have average lifetimes of about 3.1, 2.1 and 3.2 h, which is too low to correspond to a wind module lower than 30 km/h.
- In practice, an analysis of the wind in the region shows that the wind angle during wintertime rarely corresponds to the Manama – Ras Laffan direction, but often corresponds to direction between Manama and the cement plants in the west of Qatar (Figure 2 is actually an example of this) which is unfortunately rarely observed by TROPOMI (at least before version 2.4.0).
- Unrealistic negative emissions frequently appear on maps in the region between Bahrain and the west of Qatar, which might indicate an underestimation of the sink term through an overestimation of the lifetime.

After using lower values at 25 and 20 km/h, we observed that discarded days went from 169 to 240 and 309 respectively. About half of the additional discarded days correspond to days between December and March included, for which 4.25 additional days are discarded on average. Lowering the threshold generally leads to a decrease in emissions. On average, this does not impact the value of main emissions, since the absolute change in total NO_x emissions with a threshold of 20 km/h is about -2.6% on average in 2019-2022, and about -6.0% on average for months between December and March included. Months for which the absolute change is higher than 10% are January 2019 (-10.7%, 3 additional discarded days), December 2019 (-20.1%, 7 additional discarded days), February 2021 (-14.2%, 7 additional discarded days) and December 2022 (-10.7%, 3 additional discarded days). These large diminutions are mostly explained by the fact that the additional discarded days included days for which pixels above the cement plants and Doha were visible, increasing thus the number of pixels which are never observed within a month.

With such comparisons, it can be concluded that lowering the threshold below 30 km/h in order to avoid overestimating emissions through to the inclusion of pollution from Bahrain would only be appropriate for the winter months. For these months, although a threshold of 20 or 25 km/h would be more appropriate, the impact on total emissions is marginal and only lead to a slight reduction in emissions. The months for which the reduction in NO_x emissions is significant are months for which the lowering of the threshold leads to the omission of highly emissive areas due to the discarding of some TROPOMI images in the average, which means that the reduction in total emissions is not due to the effect that the threshold lowering was intended to avoid. Most of this discussion is added in the revised Supplementary Material.