Multi-satellite sensor study on precipitation-induced emission pulses of NOx from soils in semi-arid ecosystems by J. Zörner et al.

Reply to anonymous referee #2

We would like to thank reviewer #2 for the critical and helpful feedback. Our replies as well as the changes made to the manuscript are provided below.

Blue: Reviewer comment
Black: Author's reply
Red: Modified text in manuscript

General remarks:

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(1) While I have few criticisms of the analysis itself I do have trouble understanding how this analysis significantly enhances our understanding of global soil NOx emissions. Synthesis and interpretation of the results were unsatisfying. For example, there is a confusing amount of time spent on correcting for background emissions following a pulse event. What is the purpose of this? Is it to advance modeling efforts? If so, there needs to be some direct connection of the results to modeling or at least a proposed way in which to use these results to inform modeling.

We think that our study improves the knowledge on precipitation-induced emission pulses of NO_x in many aspects:

- First unambiguous characterization of sNO_x emissions from satellite measurements only with a particular focus on pulsed emissions (no input from models or inventories) and explicit exclusion of other NO_x sources and artefacts
- First global study enabling identification of relatively small-scale areas exhibiting pulsed sNO_x emissions
- Based on the referee comments, a new subsection was added in which total nitrogen emissions from soils are calculated and put into a broader perspective (see comment #1 by referee #1). We thereby set the emissions in context by comparing pulse amounts to regional emissions. This exploits the good time resolution and spatial coverage of the satellite measurements.
- We separated the observed NO_2 VCDs into three emission categories: (i) the pulse on Day0, (ii) the enhanced emissions over 14 days following Day0 and (iii) a background which is not directly affected by the pulsing event. This information is beneficial for analogue modelling studies and has not been provided in such detail from a purely top-down approach so far.

We carefully addressed the concerns of the referee in the revised manuscript and also refer to our proposed changes to the manuscript in comment #1 by referee #1.

Change in the Abstract:
We find strong peaks of enhanced NO_2 Vertical Column Densities (VCDs) induced by the first intense precipitation after prolonged droughts in many semi-arid regions of the world, in particular in the Sahel.

Addition to line 18, page 18 in the conclusion section:
Note, however, that our method was optimized for the quantification of pulsed soil emissions from space by demanding long droughts and good viewing conditions (low cloud fractions) on the day of precipitation onset. Thus, regions showing no clear response for these strict selections might still be capable of rain-induced soil emissions.

Addition to end of the conclusion section:
With respect to the seasonal NO_x budget, we assess a contribution between 21 to 44% from these rain-induced intense pulsing events to total soil NO_x emissions in the Sahel.
In conclusion, our findings facilitate a detailed characterization and estimation of emission budgets for

intense sNO_x pulses, triggered by individual rain events, which can be directly implemented in modelling studies.

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(2) One of the unique and valuable aspects of the analysis is spatial resolution at the global scale however the authors focus much of the paper on a single event in the Sahel, a phenomenon many other papers have already focused on. The conclusion section does not even mention the global analysis except to say that it was done and confirm that semi-arid regions of the world are likely to have soil NOx pulses. The significance of these pulse emissions at the global scale should be quantified and more clearly presented in order to show their significance within the global NOx budget and how it has advanced our understanding of the global NOx budget.

We first applied our algorithm on a global scale to delineate regions which are suitable for further analyses. The subsequent results indicated that the Sahel region exhibits strongest signals from pulsed soil emissions at the start of the wet season. Therefore, we focused our investigations on this particular region. Our newly introduced budget calculation for the Sahel (see comment #1 of referee #1) shows, that the contribution of the pulsing events to total emissions in the April-May-June period is about 4-8%. Consequently, the overall contribution of such pulsing events to the total nitrogen budget on a global scale is expected to be much smaller. To address the concerns of the referee, we add further conclusions on our global study as well as the budget calculation over the Sahel to section 6. For the corresponding proposed changes to the manuscript, we refer to comment #1, and also to comment #1 by referee #1.

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(3) Also, within the Sahel analysis, it is again not clear how the results enhance our understanding of soil NOx pulses in the Sahel beyond which we already know.

In general, our investigations provide an improved quantification of rain-induced pulsing events of soil NO_x emissions and, furthermore, perform the necessary and so far missing validation work for previous space-based studies in the Sahel. We provide the first unambiguous characterization of pulsed sNO_x emissions from satellite measurements only (no input from models or inventories) and explicit exclusion of other NO_x sources and artefacts. Based on the referee comments, we added a new subsection in which total nitrogen emissions from soils in the Sahel are calculated and put into a broader perspective (see comment #1 by referee #1). Thereby, we separated the observed NO_2 VCDs into three emission categories: (i) the pulse on Day0, (ii) the enhanced emissions over 14 days following Day0 and (iii) a background which is not directly affected by the pulsing event. Such detailed information has not been provided by previous studies on pulsed emissions of sNO_x in the Sahel. Furthermore, the high resolution of our approach facilitated the separation of the pulsing signal for different land cover classes in the Sahel region.
We think that the revised manuscript conveys these statements adequately.

Specific comments

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(4) On page 3 line 19, it is stated that soil NOx pulses are only enhanced for 1-3 days post precipitation, however other studies have shown pulses to last much longer, up to 25 days. (See Oikawa et al. Unusually high soil nitrogen oxide emissions influence air quality in a high temperature agricultural region, Nature Communications 2015)

We refer in this context to the peak emissions of the pulsing event of sNO_x which typically occur on the scale of 1-3 days (Kim et al. 2012). We updated the corresponding sentence accordingly. Oikawa et al. (2015), however, show that the release of soil NO_x after irrigation peaks approximately seven days after the initial (controlled) wetting and then gradually decreases until the emission rate goes back to background values. This behaviour is different to the one we investigate in our paper and previous space-based studies. As our detailed analysis over specific regions shows, such a delayed pulsing signal cannot be observed using our approach in the Sahel (Fig. 5), South Africa or Australia (Fig. 13). To address this issue also in our manuscript, we also added a remark to section 5.1.

Change in the introduction section:

The main objective of this study is to quantify precipitation-induced short-term enhancements in soil emissions of NO_x, which typically show peak emissions on the scale of 1-3 days (Kim et al., 2012), from space-based instruments in semi-arid regions in the world.

Addition to section 5.1

Peak emissions of sNO_x pulses typically occur on the scale of 1–3 days (Kim et al., 2012) in accordance to our results for the Sahel, South Africa and Australia showing peak emissions shortly after the first re-wetting. Some studies, on the other hand, measure peak emissions several days after the first re-wetting of the soil, *e.g.* seven days as observed in field by Oikawa et al. (2015). Our algorithm does not specifically distinguish between such cases by taking average time series after the first precipitation event. Single pixels within the regions we investigated may exhibit peak emissions several days after the initial precipitation which would, however, not be resolved by our analysis.

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(5) Pg 6 line 17, Authors state only minor effects resulting from uncertainty in precipitation events across 3 data products. However it would be preferable to quantify that uncertainty or at least state the maximum and average amount of deviation there is across the data products for different regions. Appendix A shows only 1 example.

The average deviations among the three used products (TMPA/TRMM, CMORPH, PERSIANN) are provided for the Sahel, South Africa and Australia as differently grey shaded areas in Fig. 5 and Fig. 10. For a further quantitative assessment of the deviations among the three used products (TMPA/TRMM, CMORPH, PERSIANN) for different regions we refer to literature (Ebert et al., 2007; Novella and Thiaw, 2010; Romilly and Gebremichael, 2011; Liu et al., 2012; Pipunic et al., 2013; Pfeifroth et al. 2016; and references therein).
As appendix A shows, our algorithm does not significantly depend on the choice of precipitation product as *trigger* for the Sahel. Furthermore, we added two maps as appendix E which show enhanced NO_2 VCDs for the global study similar to Fig. 3d but for precipitation from CMORPH and PERSIANN products as trigger for the 2 mm threshold. The map based on CMORPH data compares well with our presented TRMM world map in Fig. 3d. The global analysis based on precipitation estimates from the PERSIANN product shows the same spatial patterns, but the general enhancement is lower over the Sahel and higher over South Africa. Although the product choice has some influence on our retrieved signals, this does not affect the observed global spatial patterns. Furthermore, the impact on our budget calculation for the Sahel is also low, as differences are partly reduced by the respective background subtraction and subsequent sNO_x fluxes are of similar magnitude (see appendix E3).

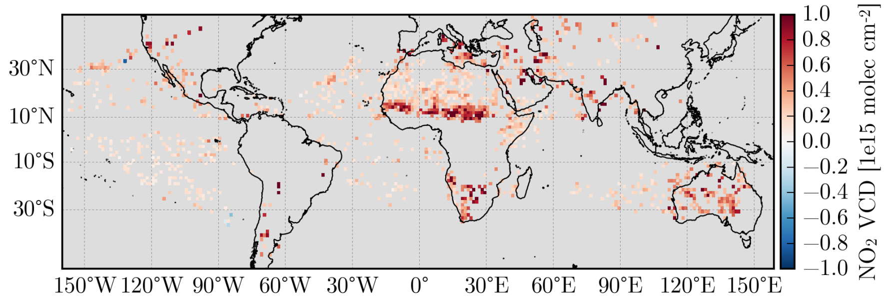
Change in line 13, page 6, section 2.3:

Inter-comparison studies show good agreement with ground based precipitation observations for these data products (e.g. Ebert et al., 2007; Novella and Thiaw, 2010; Romilly and Gebremichael, 2011; Liu et al., 2012; Pipunic et al., 2013; Pfeifroth et al. 2016; and references therein) which is, however, variable for different geographic regions, surface types and rain intensities. In our study, we apply each precipitation product individually to differentiate between days with or without rain fall. From the comparison of the corresponding results we find that the uncertainties and differences among the precipitation data sets have only minor effects on the obtained results (see Appendix A, E).

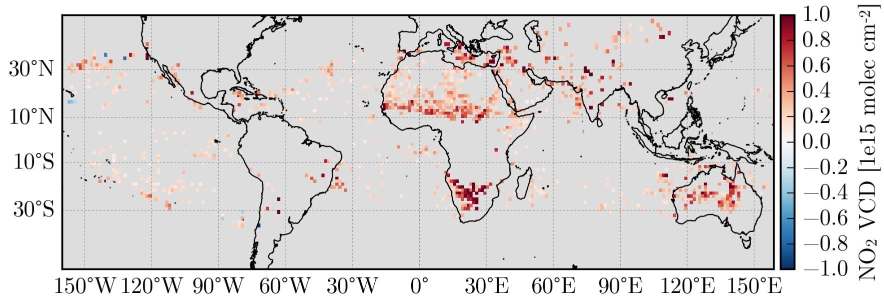
Appendix E: Impact of a-priori precipitation product

In this section, the impact of the precipitation product on the derived soil NO_x emissions is investigated. Figures **E1** and **E2** depict the NO_2 enhancement on Day0 as in Fig. 3d, but based on CMORPH and PERSIANN data, respectively. While the absolute values differ for the Sahel, the final emission estimates for pulsed emissions are quite similar (see Table **E3**), as the choice of the precipitation data affects the background correction as well.

E1 CMORPH



E2 PERSIANN



E3 Derived Fluxes

	TRMM	CMORPH	PERSIANN
∅ Day0 enhanc. [ngNm^{-2}s^{-1}]	**6.95**	7.75	6.62
max. Day0 enhanc. [ngNm^{-2}s^{-1}]	**64.61**	64.61	64.61
Day1-14 enhanc. [ngNm^{-2}s^{-1}]	**3.39**	3.07	2.42
Background (soil) [ngNm^{-2}s^{-1}]	**2.75**	3.39	4.36
Background (total) [ngNm^{-2}s^{-1}]	**14.54**	15.18	16.15

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(6) Pg.7 line 20. Please provide at least a discussion of the error associated with land cover data sets.

We added remarks on data quality of the GlobCover data set to the paragraph.

The product is publicly available via `http://due.esrin.esa.int/page_globcover.php` and comprises 22 land cover classes defined with the United Nations (UN) Land Cover Classification System (LCCS) with an overall accuracy across all classes of 58% (Arino et al., 2007; Bontemps et al., 2011). The data is down-scaled using a most-common-value approach to identify dominant land cover types and to match the resolution of the other data sets. Thus, misclassifications might occur particularly over heterogeneous terrain and transition zones, while classification over homogeneous terrain is expected to be robust.

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(7) Line 19 Pg 11–The authors refer to error caused by AMF several times however never indicate any quantification of that error, or suggest references that have investigated error in data products such as in OMI. After filtering for cloud cover, for example, what amount of error is expected to remain?

A general quantification of the error introduced by the AMF is difficult since it is dominated by the uncertainties in assumed trace gas profiles, aerosol and cloud conditions (Boersma et al., 2004). We added the following sentence at the end of section 2.2 to provide a brief remark on the uncertainty for the VCD products:

Addition to the end of section 2.2:

Uncertainties of tropospheric NO_2 VCDs result mainly from uncertainties of the stratospheric correction (about $2 * 10^{14}$ $molec\ cm^{-2}$) and tropospheric AMFs (about 35-60%) (Boersma et al., 2004).

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(8) On pgs 14-15 there is a large discussion of whether enhanced VCD's are the result of precipitation on Day 0 vs precipitation generally being enhanced following that first rain event, aka seasonal changes. For example, the authors state "However, it still needs to be clarified whether the enhanced NO2 VCDs after Day0 are induced by the initial precipitation on Day0 or by continuous precipitation during the following days." But it is not clear to the reader why this distinction is important.

Our study focuses on the quantification of the emission pulse of the first rain of the wet season. Thus, a differentiation between emissions originating from the initial pulse and emissions from other rain events has to be conducted. We also refer to our answer to question #1 of the referee which further describes the need for a separation. We changed the sentence, highlighted by the referee, to:

As our focus is on the quantification of the emission pulse triggered by the first rain of the wet season, it still needs to be clarified whether the enhanced NO_2 VCDs after Day0 are induced by the initial precipitation on Day0 or by continuous precipitation during the following days.