EGUSPHERE-2025-5668 | Research article

Seasonal and interannual variability of atmospheric ammonia over Guatemala driven by land use, biomass burning, and meteorological circulation

Christian Saravia et al. (2025)

Response to Editor

Public justification (visible to the public if the article is accepted and published):
I have carefully reviewed the response to referee document and the updated manuscript and SI. The manuscript has substantially improved and many of the comments have been addressed. However, major revisions are required before it is suitable for publication.
Line numbers refer to the track changes version of the manuscript.
Major comments:

We sincerely thank the editor for the careful evaluation on our revised manuscript, and we appreciate the positive assessment that most of the previous comments have been substantially improved and addressed. In this revised manuscript we considered all the comments and suggestions, we improved the interpretation, structure and clarity. Specially in the Discussion section to connect the results between the interpretation.

1) The structure of the manuscript sections requires further attention and the discussion sections 4.1 and 4.2 are currently underdeveloped. While many of the ideas put forth in sections 4.1 and 4.2 are interesting and I think are likely supported by the data, a more thorough and quantitative analysis needs to be completed and discussed in these sections to support the findings. Some of the supporting points are already in the manuscript, but it is challenging for the reader to connect the conclusions to the points because of how the manuscript is structured. In particular, in section 3, so much time is spent on land use, meteorology, etc. and these results are not connected to NH3 until multiple pages later (in Sect 4) that the reader is left wondering how these results advance the ideas of the manuscript.

We thank the editor for this constructive suggestion. We agree that the previous structure and organization presented difficulties to connect the different dataset with the interpretation of the NH_3 variability. In the revised manuscript we have reorganized the discussion section and strengthened the quantitative interpretation throughout the document. (i) The discussion section was restructured and focus on the main drivers of atmospheric NH_3: (L490-L683)

- Section 4.1 we have focus on the persistent agricultural sources of NH_3 background. (L499-540).
- Section 4.2 biomass burning and meteorological controls on seasonal and interannual NH_3 variability. (L552-L602).
- Section 4.3 April 2020 extreme episode as an illustrative case study, previously case study (3.5) to improving the logical flow of the manuscript on how the agricultural source, biomass burning and meteorological condition interact during extreme event. (L604-L647).
- Section 4.4 the robustness and implications of the concatenated satellite observations. (L649-L683).

(ii) following the recommendations the relevant evidence from the land cover, fire observations, and meteorological dataset is now discussed together with the NH_3 observations instead of being separated by pages. (iii) we have included additional quantitative analysis to support the discussion section to better interpretation.

I recommend changing the structure of the manuscript such that the current Sect. 3.1 remains the result section and then discussion is grouped by agriculture, biomass burning, etc. with the relevant supporting datasets shown in the appropriate section. This will allow the reader to more easily connect the results (currently in various subsections of section 3) to the interpretation (currently in various subsections of section 4).

We thank the editor for this recommendation, in the revised manuscript we have reorganized accordingly. The Result section now focuses on presenting the observation, while the discussion section is organized around the mechanisms controlling atmospheric NH_3.

For Sect. 4.1 and 4.2, I am not yet convinced that the conclusions regarding agricultural sources and biomass burning have been adequately supported by the analysis. Some more quantitative metrics showing the relationship between fire and NH3 would be beneficial. Additionally, it seems that the argument is that crop land is the main agricultural source, not rangeland (otherwise the land use argument doesn't hold since clusters with high rangeland have low NH3). Is this idea supported by prior work? Does the timing correspond with known cropland agricultural practices in the regions?

We thank the editor for this valuable suggestion. Section 4.1 and 4.2 have been revised and provide the quantitative that support the interpretation. Additionally, although rangeland is abundant throughout Guatemala, its relative high proportion in the low NH_3 cluster, indicates that rangeland alone cannot explain the observed NH_3 distribution. Instead, the larger proportion of cropland in the highest NH_3 cluster suggest that cropland related to agricultural activities are strong associated with elevated NH_3. (L500-L604).

2) The Case Study section (3.5 currently) should go later in the manuscript after the general discussion of the overarching trends since it is analysis of a specific event rather than general trends.

Thank you for the suggestion. In the revised manuscript the result section 3.5, has been shifted to discussion section (4.3). (L604-L648).

3) Please add some discussion about how variation in elevation could impact the NH3 results. Given the similarities between elevation and patterns in the NH3 column, the reader who may be an expert in NH3 but not necessarily satellite measurements need to be convinced the elevation is not introducing an artifact into the column.

We thank the editor to point this out. In the revised manuscript we have added this point to the discussion in the section 4.4, where we mention the influence of topography on satellite NH_3 retrievals. To support this discussion the observation density map Fig. S9 demonstrate that the areas of high elevation are not associated with lower NH_3 because of reduce satellite sampling. With this the western areas exhibit the highest observation densities while maintain relatively low

NH_3, so the observed spatial patterns reflect differences in total column sources rather than elevation related to retrieval artifacts. (L649-L683).

4) The conclusions section needs to be revised to follow the ACP guidelines (https://www.atmospheric-chemistry-and-physics.net/policies/guidelines_for_authors.html). In particular, please pay attention to the points about caveats and limitations and make sure to clearly discuss the implications for our understanding of the atmosphere rather than for the specific location.

We thank the editor for this important suggestion. We have adapted the conclusion to better align with the ACP standards. We now include (i) the concise summary of the principal quantitative findings, (ii) a synthesis of the process controlling NH_3 variability, (iii) the broader scientific context and advances provided by this study relative to previous work, (iv) a discussion of the main limitation associated with satellite observations and the need for future research, and (v) an expanded discussion of the implications of our findings for understanding the dynamics of atmospheric NH_3, biomass burning, and meteorological controls in tropical regions, rather than focusing solely on Guatemala. (L684-L735).

Minor points

1) Sect 3.1 This section needs to be carefully checked for accuracy and clarity. For instance: Lines 472-476: Please revise these introductory sentences to be accurate and clear. The sentence "The medians reveal…" is inaccurate as the numbers reported in the sentence are min and max values, not medians. Additionally, I am not sure if it makes scientific sense to report the min and the max. I suggest reporting the median values for the years. The following two sentence "While the median values…" is incomplete and the last sentence "Consistently, the…" is unclear. I believe the main point of this paragraph is to say that 2020 had the highest median NH3 while 2021 had the lowest median, but that there was substantial intra-annual variability, as represented by the standard deviation. Finally, medians are discussed in words, but the figure shows means. It can be useful to discuss medians to show that extreme events are not responsible for the pattern in the means. I suggest adding additional discussion on these ideas.

We thank the editor for this observation, we agree that the paragraph in sec. 3.1 mixed annual means, medians and minimum and maximum values, which reduce consistent clarity. The section has been revised eliminating the minimum and maximum values, therefore the revised paragraph shows the annual and monthly median values, and the standard deviation to show the intra annual variability observed during the years 2016, 2020 and 2023. (L240-L247).

2) Lines 969-971: What is the evidence that agricultural sources dominate the stability and not something else? This idea needs to be further supported and developed.

We thank the editor for this valuable comment. We agree that the section did not provide sufficient evidence to support the interpretation of the persistent agricultural activities dominated the background NH_3 values. In the revised manuscript, we have extended the discussion to justify the interpretation using evidence from our own results rather than relying only on previous studies. We have now explained (i) the annual median NH_3 values that keep relatively stable throughout the study period, where the interannual differences are mainly driven

by increased in maximum values and also added the standard deviation during the years with enhanced fire activity. (ii) The hotspots of NH_3 persist spatially across the years, including years with relatively low annual NH_3, and (iii) the land cover analysis shows that the highest NH_3 cluster 1 is spatially associated with agricultural landscapes characterized by cropland and rangeland. Together, with these observations suggest that continuous agricultural activities maintain the background NH_3, while the biomass burning primarily contributes to short-term enhancement, specifically during the dry season.(L499-L548).

3) Ensure that all SI figures are referenced and are referenced in order. I may have missed it, but, for instance, I did not see a reference to Figure S1.

We thank the editor for this observation. Supplementary Figures (Fig. S1,S2) are now properly cited in the section 3.1. (L241 and L250).

Technical

Line 11: Please add the word "and" in between "matter" and "an."

Thank you. Adapted as suggested. (L11).

Line 15: "a persistent agricultural source dominated by biomass burning" appears contradictory unless the biomass burning is really agricultural burning. Or perhaps a word is missing and variations are dominated by biomass burning? Please revise this sentence.

We thank the editor for the constructive suggestion. We agree that the wording was contradictory because the persistent agricultural sources were itself dominated by biomass burning. In the revised manuscript we have rewrite the text, stated that the relative stable annual NH_3 reflect a persistent agricultural background. (L14-L15)

Line 16: Change "seasonal" to "seasonality."

Thanks. Corrected as suggested. (L16).

Line 24-25: Change "utilizes" to "exerts" or something equivalent to that. It is also unclear what is meant by "interaction with prevailing meteorological conditions." Please revise this sentence to be clearer.

Thanks. Adapted as suggested. (L25-L27).

Lines 75-79: "For this study…" This sentence does not belong at this point in the introduction and should be moved to the last paragraph of the introduction or to the methods.

Thanks. Adapted as suggested. (L43-50).

Lines 119-120: “To ensure the reliability…” This sentence belongs in the methods rather than the introduction.

Thanks. Adapted as suggested. (L87-L92).

Lines 473-475: This sentence is inaccurate as written and needs to be corrected. The numbers provided are the min and the max of Table 1, not the median values.

We thank the editor for this observation, in the revised manuscript we have corrected the values to mention only the medians. (L240-247).

Line 557: I am not sure I agree with the term “persistent” since in some years (e.g., 2018) the Petén region is quite low. Perhaps “frequent” would be a better term. Alta Verapaz also appears to be frequently high and I wonder why it isn’t called out.

We thank the editor for this observation. We agree with the editor and have changed the word to “frequent”. Alta Verapaz it included in the north-central areas. (L251).

Line 562: “…increased NH3 columns…” increased relative to what? The values in the regions are still low compared to the values in that same region in other years. Please clarify.

Thank you for pointing this out. We agree that the phrase was ambiguous, it didn’t specify the reference for comparison. In the revised manuscript we have clarified it, although 2018 exhibit lower annual mean of NH_3 than 2016 and 2020, the hotspot areas remained spatially consistent. (L255-L257).

Line 569: Why is it important to report the global minimum (observed in March)? It creates a misleading representation of the data since the other months are discussed in terms of medians and February rather than March has the lowest median.

Thank you for the comment. In the revised manuscript the analysis focus on the central tendency and seasonal variability of the monthly distribution, we have removed the global minimum and report the monthly medians. (L259-L265).

Line 679: I believe the word “annual” should be deleted and it should just read “the overall mean for the period…”

Thanks. Corrected as suggested. (L288).

Lines 679 -682: How were these areas determined? By visual inspection? What was the criteria? What governs the shape of area 3 and why are 4 and 5 separate? The determination of these areas needs to be discussed further. Alternatively, this could be removed as it does not add much beyond what the k-means clustering analysis provides.

We thank the editor for this value comment. We agree that the boxes were redundant. We have removed the boxes (1–6) from the Fig. 4a and revised the text in the section 3.2 for the k-means clustering to characterize the spatial distribution of NH_3 and the relationship with land cover class, avoiding ambiguity with the visual defined areas. (L288-L292).

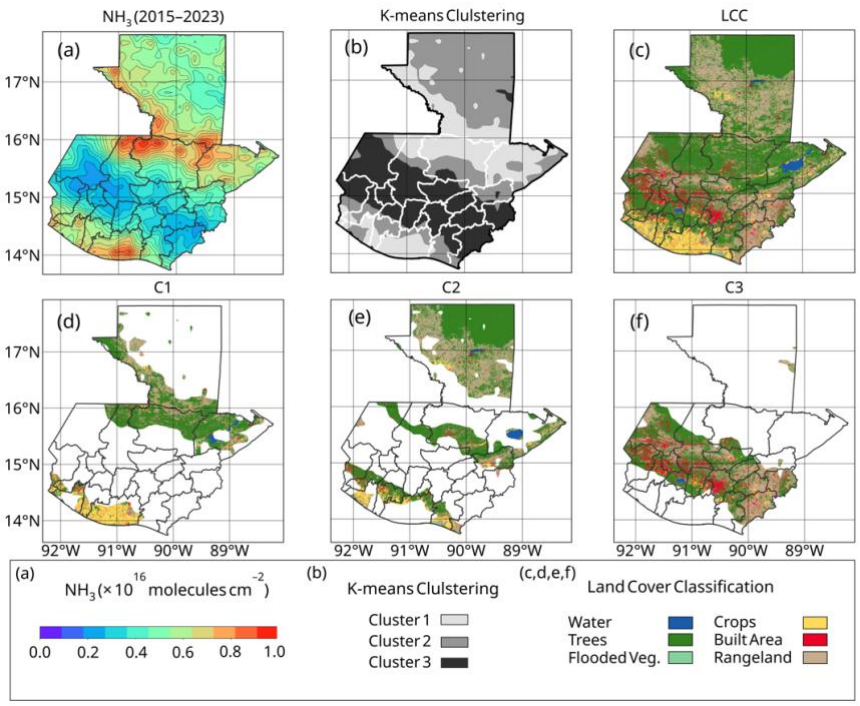

Figure 4: (a) Concatenated NH_3 total column ($\times 10^{16}$ molecules cm^{-2}) (2015–2023), (b) k-means cluster analysis with Cluster 1 (black color), Cluster 2 (gray color) and Cluster 3 (light gray color). (c) ESRI Land Use Land Cover across Guatemala, categorized into three clusters based on k-means combined with land cover types: water, trees, flooded vegetation, crops, built area, and rangeland, (d) C1 related to cluster 1, (e) C2 to cluster 2, and (f) C3 to cluster 3.

Line 704-706: It is inaccurate to say cluster 1 is dominated by range and crop when forest is >50%.

Thanks, we agreed that the previous text was inaccurate. We have changed the text to mention that the dominant area is tree cover. (L297).

Lines 846-847: Please reword to make the meaning clearer.

Thanks. We have changed the wording to make it more clear. (L328-330).

Line 946: There is a word missing after "widespread."

Thanks. Corrected we have moved the previous section 3.5 to the Discussion section "4.3 April 2020 extreme episode associated with biomass burning and meteorological conditions on NH_3" and we have modified the text to describe and interpreted the extreme episode associated with NH_3. (L638-L643).

Figure 4: I recommend changing the colors in panel b to be color blind friendly and different from the colors used in other panels.

Thank you. We agree and have changed the colors. (L319).

Figure 7 and associated text (around line 848 or so): Please double check the units and scale for

precipitation. The values do not align with those discussed in the text.

Thank you. We have recalculated the ERA5 precipitation data using monthly averages and have modified the text and figures accordingly. Please see Fig. 5 and Fig. S4, Table S6 and the discussion and conclusion sections (L325-L346).

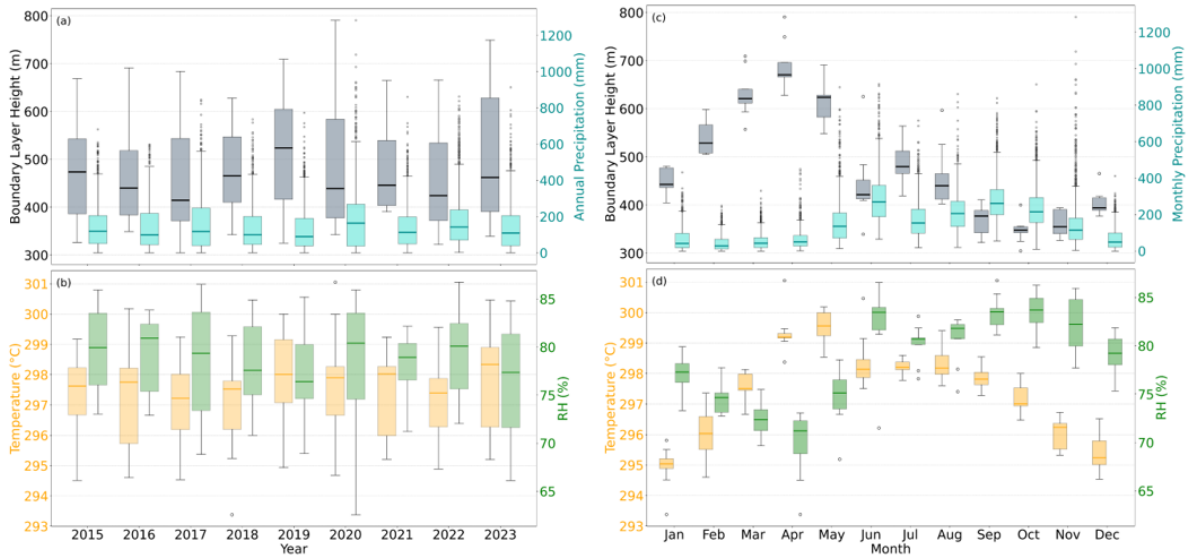

Figure 5: Annual and monthly climatology boxplot distribution of ERA5 meteorological variables over Guatemala (2015–2023). Annual variability is shown (a) boundary layer height (m) (gray) and annual precipitation (mm) (turquoise). (b) relative humidity (RH %) (green) and temperature (°C) (yellow). Monthly climatology (c) boundary layer height (m) and monthly precipitation (mm). (d) temperature (°C), and relative humidity (RH, %).

Figure S5: Since the matrix is symmetric across the diagonal, it is only necessary to show either the lower or the upper triangle since showing both is repetitive. This figure also contains many of the useful quantitative comparisons and should be moved to the main text.

Thanks. Adapted as suggested (L600).

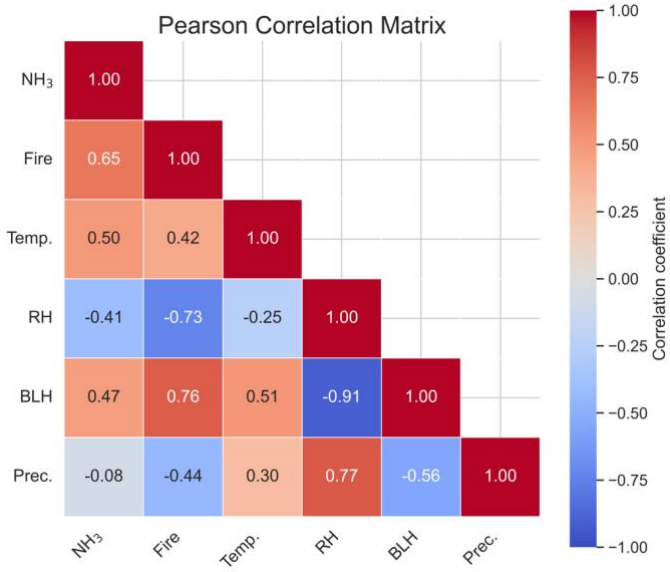

Figure 8: Pearson correlation matrix of NH_3 and different variables over Guatemala (2015–2023): Fire, temperature (Temp,°C), relative humidity (RH, %), boundary layer height (BLH, m), total precipitation (Prec, mm).

Additional private note (visible to authors and reviewers only):
Thank you for your patience in my delayed handling of the manuscript. I have been on vacation.