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Supplement of

Changes in biomass burning, wetland extent, or agriculture drive atmospheric NH₃ trends in select African regions

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Introduction

The supporting information contains four main categories of supporting information. First, Figures S1-S5, S7, S11, and S20 represent additional continental-scale figures supporting analysis in the main text of the document. Figure S6 provides supporting analysis of trends in West Africa. Text S1 and Figures S8-S10 and S12 provides supporting analysis of trends in South Sudan, including the potential effects of conflict in South Sudan. Figures S13-S18 provide supporting analysis of trends in the Lake Victoria region. Figure S19, Table S1, and Text S2 provide supporting analysis of national-scale relationships. Collection, generation, processing, and analysis of data are described either in the main document or in the relevant supplementary text section.
Figure S1. Trend in atmospheric NH$_3$ VCDs from IASI for the period 2008 through 2018 where trends meet the significance threshold of (a) $p=0.05$ or (b) $p=0.20$. 
**Figure S2.** Change in mean monthly atmospheric OMI NO$_2$ VCDs for the period 2008 through 2018.
Figure S3. Change in mean monthly atmospheric MODIS burned area for the period 2008 through 2018.
Figure S4. Change in mean monthly atmospheric CO VCDs for the period 2008 through 2018.
Figure S5. Change in mean monthly atmospheric NH$_3$ VCDs for the period 2008 through 2018 where the relationship is significant at $p=0.05$. Grid cells where mean annual NH$_3$ VCDs for the entire period are under $5\times10^{15}$ molecules cm$^{-2}$ are not displayed.

Figure S6. Correlation coefficient for the relationship between mean annual CO and NH$_3$ VCDs (a), changes in NH$_3$ VCDs (b) and changes in CO VCDs (c) over 2008 through 2018 in West Africa where the relationship is significant at $p=0.05$. Grid cells where mean annual NH$_3$ VCDs for the entire period are under $5\times10^{15}$ molecules cm$^{-2}$ are not displayed.
Figure S7. Correlation coefficient for the relationship between mean annual CO and NH$_3$ VCDs over 2008 through 2018 where the relationship is significant at P=0.05. Regions where mean annual NH$_3$ VCDs for the entire period are under 5x10$^{15}$ molecules cm$^{-2}$ are screened out.
Figure S8. Mean monthly atmospheric NH$_3$ VCDs over South Sudan; mean is for the period 2008 through 2018.
Text S1. South Sudan conflict
In 2013, a civil conflict emerged in South Sudan that was ultimately responsible for the displacement of millions of people (Global Internal Displacement Monitoring Centre, 2020; World Bank, 2019) and the disruption of livestock migration patterns (Idris, 2018). These disruptions could be expected to lead to a decrease in \( \text{NH}_3 \) VCDs if they result in lower rates of fertilizer use and a decrease in livestock and livestock-related emissions. Although there are some spatial correspondences between the location of conflict events and changes in \( \text{NH}_3 \) VCDs (Fig. S7), the change in \( \text{NH}_3 \) VCDs appears already to have been underway years in advance of the onset of conflict (Fig. S6, Fig. S8), suggesting that other factors are responsible for the interannual variation. Displacement spiked in 2014, the year that \( \text{NH}_3 \) VCDs were at their lowest values. It is possible that this displacement and the associated conflict contributed to the low \( \text{NH}_3 \) values, but 2014 was the year of the largest Sudd extent during February through May, which would also be expected to reduce \( \text{NH}_3 \) emissions. The number of refugees and internally displaced people increased substantially from 2013 through 2017, a period during which the dry season flooded extent of the Sudd decreased, and \( \text{NH}_3 \) VCDs increased (Fig. S8). Maps of trends and annual mean \( \text{NH}_3 \) VCDs over the IASI lifetime reveal that most interannual variability occurs over the Sudd (Fig. S7, S10). The strong spatial relationship between the Sudd and interannual \( \text{NH}_3 \) variability suggests that Sudd flooded extent is likely the main factor responsible for the interannual variation in \( \text{NH}_3 \) VCDs during this period, and the overall trend we observe for 2008 through 2017.
Figure S9. Kernel density estimate of conflict events (left) and change in NH$_3$ concentrations (right) between 2008 and 2018. Conflict data are from the Armed Conflict Location and Event Project (Raleigh et al., 2010; acleddata.com), and includes both violent and non-violent events.
Figure S10. Mean annual NH3 VCDs (a) and mean annual refugees and internally displaced people (b) in South Sudan over the 2008-2018 period for years where data are available.
Figure S11. Change in mean annual tropospheric NO$_2$ VCDs over Africa, 2008 through 2018.
Figure S12. Mean annual atmospheric NH$_3$ VCDs over South Sudan for 2008 through 2018. The Sudd is highlighted in the black box.
Figure S13. Mean annual atmospheric NH$_3$ VCDs over the Lake Victoria region for 2008 through 2018.
Figure S14. Cropped area in the Lake Victoria region for 2008 through 2018.
Figure S15. Change in mean monthly atmospheric NH$_3$ VCDs for the period 2008 through 2018.
Figure S16. Total annual burned area in the Lake Victoria region for 2008 through 2018.
**Figure S17.** Mean annual (a) and mean monthly (b) NH$_3$ VCDs over Lake Victoria and the surrounding land area, 2008-2018.

**Figure S18.** Masks used in time series analysis of NH3 over Lake Victoria (a) and over the surrounding land surface (b).
**Text S2. Additional national-scale relationships**

**Temperature:** Mean temperature changes are small—less than 0.015% yr⁻¹ with standard errors that bracket zero; the values are too small to appear on Figure S19. Although they are nearly significantly different among bins at p=0.11, they do not exhibit a relationship with NH₃ at the country scale in our binned analysis: the annual rate of warming is lowest in the middle bin (0.006 C yr⁻¹) and roughly equal in the bottom and top bins (0.013 C yr⁻¹ and 0.017 C yr⁻¹, respectively).

**NO₂:** NO₂ exhibits marginal increases in each bin, which appear to decrease across bins, but these differences are not significant (Fig. S19; p=0.55). It remains possible that changes in NO₂ emissions may influence NH₃ trends by decreasing the lifetime of NH₃ in the atmosphere, which would be evident as a negative correlation between the two species. In examining spatial relationships between the two gases there is a lot of noise (Fig. S20), but in Nigeria, South Sudan, the Nile Region, and the North African coast, we observe positive correlations, suggestive that changes in NH₃ VCDs in those regions are not the result of reactions with NO₂. Instead, the fact that trends of both gases have the same sign is consistent with changes in emissions being responsible for the trends.

**SO₂:** As with NO₂, SO₂ may be expected to decrease the lifetime of NH₃. However, in our binned analysis, SO₂ did not vary among bins (Fig. S19; p=0.98). In addition, NH₃ and SO₂ may vary increase in parallel, suggesting that chemistry involving SO₂ does not make an important contribution to the observed NH₃ trends. Outside of South Africa, variation in SO₂ emissions in sub-Saharan Africa are largely related to volcanic emissions. During the period of our analyses, emissions from volcanoes in eastern Democratic Republic of Congo and Eritrea play particularly important roles in interannual SO₂ variability. A 2011 eruption in Eritrea results in an overall decline in SO₂ concentrations in the region in our analysis. In South Africa, SO₂ emissions from an array of coal fired power plants in the highveld have declined over the period of our analyses. However, the variation in SO₂ VCDs is not spatially related to variation in NH₃ VCDs, which are also small in the continental context. Note that we exclude Lesotho from these analyses, which experienced a 1000% rate of increase in SO₂ VCDs from 2005 to 2018; including Lesotho results in a very high mean rate of SO₂ increase in the middle bin.
Figure S19. Annual percentage changes in national mean annual Tropical Livestock Units, crop area, crop yield, fertilizer N use, burned area, CO VCDs, NH$_3$ VCDs, SO$_2$ VCDs, NO$_2$ VCDs, and CO$_2$ emissions for African countries with low, medium, or high rates of NH$_3$ VCD change for the period 2008-2018. Error bars represent the standard error of the mean. See Table S1 for the list of countries in each bin.
Figure S20. Correlation between mean annual NH$_3$ and NO$_2$ VCDs over Africa for the period 2008 through 2018. Pixels where mean annual NH$_3$ VCDs are below 5 x 10$^{15}$ molecules cm$^{-2}$ for all years are masked.
Table S1. List of countries in Low, Medium, and High bins in Figure 8.

| Low bin       | Medium Bin       | High Bin       |
|---------------|------------------|----------------|
| Algeria       | Central African  | Angola         |
| Republic      |                  |                |
| Botswana      | Chad             | Benin          |
| Djibouti      | Cote d’Ivoire    | Burkina Faso   |
| Eritrea       | Guinea           | Burundi        |
| Ethiopia      | Kenya            | Cameroon       |
| Gambia        | Lesotho          | Congo          |
| Guinea-Bissau | Liberia          | DRC            |
| Libya         | Mali             | Egypt          |
| Madagascar    | Mauritania       | Equatorial Guinea |
| Namibia       | Morocco          | Gabon          |
| Niger         | Mozambique       | Ghana          |
| Somalia       | Senegal          | Malawi         |
| South Africa  | Sierra Leone     | Nigeria        |
| South Sudan   | Sudan            | Rwanda          |
| Former Sudan  | Tunisia          | Tanzania        |
| Eswatini      | Uganda           | Togo           |
| Western Sahara| Zimbabwe         | Zambia         |

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