Satellite evidence of substantial rain-induced soil emissions of ammonia across the Sahel

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Abstract. Atmospheric ammonia (NH₃) is a precursor to fine particulate matter formation and contributes to nitrogen deposition, with potential implications for the health of humans and ecosystems. Agricultural soils and animal excreta are the primary source of atmospheric NH₃, but natural soils can also be an important emitter. In regions with distinct dry and wet seasons such as the Sahel, the start of the rainy season triggers a pulse of biogeochemical activity in surface soils known as the Birch effect, which is often accompanied by emissions of microbially-produced gases such as carbon dioxide and nitric oxide. Field and lab studies have sometimes, but not always, observed pulses of NH₃ after the wetting of dry soils; however, the potential regional importance of these emissions remains poorly constrained. Here we use satellite retrievals of atmospheric NH₃ using the Infrared Atmospheric Sounding Interferometer (IASI) regridded at 0.25° resolution, in combination with satellite-based observations of precipitation, surface soil moisture, and nitric dioxide concentrations, to present evidence of substantial precipitation-induced pulses of NH₃ across the Sahel at the onset of the rainy season in 2008. The highest concentrations of NH₃ occur in pulses during March and April, when biomass burning emissions estimated for the region by the Global Fire Emissions Database database are low. For the region of the Sahel spanning 10° to 16° N and 0° to 30° E, changes in NH₃ concentrations are weakly but significantly correlated with changes in soil moisture during the period from mid-March through April, when the peak NH₃ concentrations occur (r=0.28, p=0.02). The correlation is also present
when evaluated on an individual pixel-basis during April \((r=0.16, p<0.001)\). Using a simple box model, average emissions for the entire Sahel are between 2 and 6 mg NH\(_3\) m\(^{-2}\) day\(^{-1}\) during peaks of the observed pulses, depending on the assumed effective lifetime. These early season pulses are consistent with surface observations of monthly deposition, which show an uptick in NH\(_3\) deposition at the start of the rainy season for sites in the Sahel. The NH\(_3\) concentrations in April are also correlated with increasing tropospheric NO\(_2\) concentrations observed by the Ozone Monitoring Instrument \((r=0.78, p<0.0001)\), which have previously been attributed to the Birch effect. Box model results suggest that pulses occurring over a 35-day period in March and April are responsible for roughly one fifth of annual NH\(_3\) emissions from the Sahel. We conclude that precipitation early in the rainy season is responsible for substantial NH\(_3\) emissions in the Sahel, likely representing the largest instantaneous fluxes of nitrogen gas from the region during the year.

1. **Introduction**

Ammonia (NH\(_3\)) plays an important role in the atmosphere and in the nitrogen (N) cycle. In the atmosphere, NH\(_3\) is a precursor to the formation of fine particular matter (PM\(_{2.5}\)), which contributes to substantial levels of premature mortality (Lelieveld et al., 2015). NH\(_3\) can also form a substantial proportion of atmospheric N deposition (Dentener et al., 2006; Holland et al., 2005), affecting downwind ecosystems by potentially altering productivity (Thomas et al., 2009), soil pH (Tian and Niu, 2015), eutrophication status (Bergstrom and Jannson, 2006), biodiversity (Bobbink et al., 2010), and stimulating emissions of other trace gases such as nitric oxide (NO) and nitrous oxide (N\(_2\)O; e.g., Eickenscheidt et al., 2011; Pilegaard et al., 2006).

Cropland and grazed soils have long been known to be a major source of atmospheric ammonia through the volatilization of urea and ammonium (NH\(_4^+\)) based inorganic fertilizers as well as of livestock excreta (Bouwman et al., 1997). Ammonia emissions can also represent an important N flux in natural ecosystems, particularly in drylands. In deserts, soil NH\(_3\) emissions can represent over 25% of
annual nitrogen losses (McCalley and Sparks, 2008) and over 10% in a semiarid savanna (Fiona M Soper, 2016).

Soil moisture is a key control over biogeochemical cycles in drylands (Austin et al., 2004). Biogeochemical cycling in dryland soils is often characterized by pulsing dynamics related to the wetting or re-wetting of dry soils, known as the Birch effect (Birch, 1960; Birch and Friend, 1956). In environments where the distribution of annual precipitation is distinctly seasonal, soil microbial activity typically declines during the dry season, as water becomes limiting and microbes senesce or become dormant (Borken and Matzner, 2009). N may build up in soils during this period, when little biological uptake occurs, but when atmospheric N deposition continues and senesced microbial and plant material accumulates (Borken and Matzner, 2009). The onset of the rainy season can initiate a rapid increase in microbial activity (Birch and Friend, 1956; Borken and Matzner, 2009; Placella and Firestone, 2013; Placella et al., 2012), as re-awakened microbes take advantage of pools of N that accumulated or were made more bioavailable during the dry season, leading to large increases in N mineralization rates (Birch, 1958; 1960; Borken and Matzner, 2009; Dijkstra et al., 2012; Saetre and Stark, 2004; Semb and Robinson, 1969).

The abrupt change in water potential also represents a stress to microbes, prompting a flush of labile N solutes released by microbes to maintain turgor pressure (Kieft et al., 1987). This increase in microbial activity is accompanied by pulsed emissions of trace gases such as carbon dioxide (CO$_2$; Emmerich, 2003; Huxman et al., 2004; Saetre and Stark, 2004) and NO (e.g., Anderson and Levine, 1986; Davidson, 1992), which can be an important component of annual emissions (Davidson, 1992; Jaegle et al., 2004). As the availability of NH$_4^+$ is a major control over NH$_3$ volatilization (Nelson, 1982; Schlesinger and Peterjohn, 1991), a flush of N mineralization would be expected to trigger an NH$_3$ emission pulse as well. A few studies have documented pulse dynamics in emissions of NH$_3$ in laboratory or field settings (Delon et al., 2017; McCalley and Sparks, 2008; Schlesinger and Peterjohn, 1991; Soper et al., 2016). In arid and semi-arid ecosystems, soil NH$_3$ emissions have been observed to increase by ~15% to 630% (Schlesinger and Peterjohn, 1991), though there are few studies outside
desert ecosystems (Kim et al., 2012), and an increase in NH$_3$ emissions following wetting is not always observed (e.g., Yahdjian and Sala, 2010). The potential importance of these pulse emissions of NH$_3$ at landscape or regional scales remains poorly constrained.

In addition to NH$_4^+$ availability, soil pH is a key environmental control over NH$_3$ production in soils (Dawson, 1977; Nelson, 1982). Since NH$_3$ is typically produced through the deprotonation of NH$_4^+$, NH$_3$ emissions would be expected to be higher in relatively alkaline soils, or in soil with alkaline microsites. Globally, soils tend to shift from alkaline to acidic when mean annual precipitation exceeds mean annual evapotranspiration (Slessarev et al., 2016), so soils in drier biomes such as deserts and grasslands tend to be alkaline (though there are exceptions to this pattern), creating conditions favourable to NH$_3$ volatilization. For example, the combination of pH and ammonium concentrations in soils from a semi-arid ecosystem in Senegal have been shown to create conditions favorable to the emission of NH$_3$ (Delon et al., 2017).

Given the importance of rainfall seasonality, soil pH, and N availability in contributing to NH$_3$ emission pulses, soils in the Sahel may be an important source of NH$_3$ to the atmosphere during the onset of the rainy season. As such, the Sahel is a good region to focus on in determining whether Birch effect NH$_3$ pulsing is an important process at broad regional scales. The Sahel is a grassland environment representing a transition between desert and productive savannas. It is characterized by a unimodal rainfall seasonality, with mean annual precipitation typically ranging between 100 and 600 mm yr$^{-1}$. Seasonal variation in rainfall is broadly determined by movement of the Intertropical Convergence Zone (ITCZ). Migration of the ITCZ north of the equator in the first half of the calendar year is accompanied by the onset of the rainy season and West African Monsoon, with the first substantial rain events occurring in April. The southward retreat of the ITCZ marks the dry season starting in October or November. The onset of the rainy season is accompanied by rapid mineralization of nitrogen following the wetting of dry soils in East Africa (Semb and Robinson, 1969), and soil NH$_3$ emission have been shown to be higher at a site in northern Senegal following a rain event (Delon et al., 2017). Recent maps of African soils based on surface reflectance suggest that soils across the Sahel
tend to have pHs largely near neutral, but can be higher than 9 in some areas (Vågen et al., 2016). The combination of seasonal rainfall variability and soils with neutral or alkaline pHs suggests that Sahelian soils may be an important source of NH$_3$ at the onset of the rainy season. Although the Sahel has regions of relatively dense cropland, it is characterized by lower levels of fertilizer inputs (FAO, accessed 2018) and smaller loads of atmospheric N deposition (Dentener et al., 2006; Galy-Lacaux and Delon, 2014; Laouali et al., 2012), though deposition can be elevated at the Sahel’s southern boundary) than other parts of the world. However, it has moderately high livestock densities (Robinson et al., 2014), potentially providing sites of abundant available N for the production of NH$_3$.

Earlier work using total column observations from the GOME instrument presented evidence of high atmospheric concentrations of nitrogen dioxide (NO$_2$) over the Sahel in the early rainy season of 2000, which appeared to broadly correspond to rainfall events in the region (Jaeglé et al., 2004). These early growing season increases in tropospheric NO$_2$ concentrations could not be attributed to lightning or to biomass burning, leaving soil emissions the presumed source. Soils emit NO through a variety of biotic and abiotic mechanisms; in the atmosphere, NO rapidly interconverts to NO$_2$, and the two gases are collectively referred to as NO$_x$. Inverse modeling subsequently suggested that soil emissions of NO across sub-Saharan Africa were of the same magnitude as emissions from biomass burning, which previously had been thought to be the dominant NO$_x$ source in the region.

At regional scales, the processes controlling intra-annual variability in emissions, and the magnitude of emission responses to these controls, are not well constrained. Atmospheric models often rely on static emissions inventories of NH$_3$ that lack intra-annual variability or detailed environmental controls over emissions from soils (e.g., Bouwman et al., 1997; European Commission, Joint Research Center (JRC)/Netherlands Environmental Agency (PBL), 2011; Lamarque et al., 2010), particularly for natural ecosystems (e.g., Paulot and Jacob, 2014). Fire emission inventories are generally created using data on burned area, fuel load, combustion completeness, and emission factors that translate total carbon or dry matter emissions into trace gas or aerosol emissions into account, producing daily emissions estimates at 0.25° resolution (e.g., van der Werf et al., 2017). Inventories of NH$_3$ emissions from
natural soils tend to rely on a global estimate for the year 1990 (Bouwman et al., 1997) and agricultural emission inventories with sub-annual temporal resolution tend not to consider environmental controls other than temperature and wind speed (e.g., Paulot and Jacob, 2014).

Here we use satellite retrievals of atmospheric NH$_3$ concentrations (Whitburn et al., 2016) over Africa to evaluate whether the onset of the rainy season causes pulsed emissions of NH$_3$ over the Sahel, focusing on the year 2008, and evaluate its environmental drivers. We compare the seasonal pattern in atmospheric NH$_3$ concentrations observed by satellite to monthly surface NH$_3$ deposition measured at 7 sites in north equatorial Africa. We also use a simple box model to calculate surface fluxes based on retrieved atmospheric concentrations, and compare modeled surface fluxes to NH$_3$ emissions from biomass burning as quantified in the Global Fire Emissions Database 4s (GFED4s; van der Werf et al., 2017). Finally, we also make comparisons to modeled surface fluxes of NO$_x$ derived from NO$_2$ observations made by the Ozone Monitoring Instrument (OMI; Krotkov, accessed 2018).

2. Methods

2.1 Satellite products

The Infrared Atmospheric Sounding Interferometer (IASI-A), launched aboard the European Space Agency’s MetOp-A in 2006, obtains retrievals of atmospheric NH$_3$ at a global distribution and bi-daily resolution. IASI-A is a polar-orbiting instrument in a sun-synchronous orbit (9:30 Local Solar Time equator crossing, descending node), providing two observations daily; here we use morning observations, when the thermal contrast is more favorable for retrievals (Clarisse et al., 2009; Van Damme et al., 2014). IASI-A provides a horizontal resolution of 12 km over a swath width of about 2,200 km. The retrieval product used follows the approach implemented by Whitburn et al. (2016), in which total columns of NH$_3$ are obtained by calculating a dimensionless spectral index (HRI), which is then converted into a NH$_3$ total column through the use of a neural network. The neural network uses a range of variables such as temperature and water vapor profiles to represent the state of the atmosphere as best as possible to produce the matching NH$_3$ total column for that atmospheric state. Retrievals with
errors above 100% were excluded from the analysis, though exceptions were made for low concentrations, which tend to have a higher error, when the following condition was met:

\[
\text{Retrieval error} \times \text{total column NH}_3 \times 0.01 < 5 \times 10^{15}
\]  \hspace{1cm} (1)

where the retrieval error is a percentage and the total column NH$_3$ is a concentration in molecules cm$^{-2}$. In addition, only retrievals that were at least 75% cloud-free were used. We regridded the Level-2 IASI NH$_3$ product to 0.25° × 0.25° resolution to match the resolution of soil moisture and other data used in the analysis. The IASI product has been validated using ground-based Fourier transform infrared (FTIR) observations of NH$_3$ total columns, with robust correlations at sites with high NH$_3$ concentrations, but lower at sites where atmospheric concentrations approach IASI’s detection limits (Dammers et al., 2017). Compared to the FTIR observations the IASI total columns are biased low by ~30% which varies per region depending on the local concentrations.

We used the Tropical Rainfall Measuring Mission (TRMM) daily precipitation product (3B42), which is based on a combination of TRMM observations, geo-synchronous infrared observations, and rain gauge observations (Huffman et al., 2007). Independent rain gauge observations from West Africa have been used to validate the product, with no indication of bias in the product (Nicholson et al., 2003).

We used the European Space Agency’s Climate Change Initiative (ESA-CCI) 30-year daily soil moisture product gridded at 0.25° × 0.25° resolution (Dorigo et al., 2017; Gruber et al., 2017; Liu et al., 2012). The product is based on both passive and active microwave sensors, and has been validated globally (Dorigo et al., 2014) and in East Africa (McNally et al., 2016). Although the product exhibited moderate correlation with ground observations globally, it provides relatively high correlations ($r \sim 0.7$) for West African sites when seasonality is included in the analysis (Dorigo et al., 2014).
We also used the publicly available level 3 tropospheric NO$_2$ concentrations product from OMI, a nadir-viewing spectrometer measuring solar backscatter in the UV-visible range aboard NASA’s Aura satellite (Krotkov et al., 2017). The product is cloud-screened, including only pixels with less than 30% cloud cover, and presented in at 0.25° × 0.25° resolution. The OMI product relies on air mass factors calculated with the assistance of an atmospheric chemical transport model, and is sensitive to model representations of emission, chemistry and transport data. These are generally poorly constrained for regions not commonly analyzed in chemical transport models such as sub-Saharan Africa (McLinden et al., 2014). Additional bias may be introduced due to the reliance on nearly cloud-free pixels, where greater sunlight may induce higher photochemical rates. For example, the current product is biased roughly 30% low over the Canadian oil sands (McLinden et al., 2014). Level 2 OMI-NO$_2$ product has been validated against in situ and surface-based observations showing good agreement (Lamsal et al., 2014). In statistical analyses, soil moisture, precipitation, and NO$_2$ data were masked to match pixels for which NH$_3$ retrievals were also available.

2.2 Surface flux calculations

A range of possible surface fluxes of NH$_3$ and NO$_2$ from our focal study region in the Sahel, ranging from $10^\circ$ to $16^\circ$N and from $0^\circ$E to $30^\circ$E, were calculated from IASI total column NH$_3$ concentrations and OMI-NO$_2$ tropospheric concentrations using a simple box model (Jacob, 1999). The specific region was selected as representative of the Sahel, and to allow for direct comparisons to earlier work examining NO$_2$ emissions from the region (Jaeglé et al., 2004). Daily mean gridded concentrations of retrievals for each gas were averaged across the focal region with units of molecules cm$^{-2}$. The mean total column concentrations of gas $x$ were converted to a mean surface density for the region in units of kg m$^{-2}$ for each day, using the following equation:

$$M_{x,t} = \frac{(TC_{x,t} \times MM_x \times 10)}{N_a}$$

(2)

where $M_{x,t}$ is the mean surface density of gas $x$ for day $t$, $TC_{x,t}$ is the average of retrieved total columns of gas $x$ in units of molecules cm$^{-2}$ for day $t$, $MM_x$ is the molar mass of gas $x$, and $N_a$ is Avogadro’s
number. The dividend on the right hand of the equation is multiplied by 10 to convert the mean surface density to units of kg m\(^{-2}\). This mean surface density was then used in the box model to calculate a mean surface flux for each day, assuming first order losses of gas \(x\):

\[
E_{x,t}(mol) = (M_{x,t} - M_{x,t-1})/\left(\tau_x (1 - e^{-d/\tau_x})\right)
\]

where \(E_{x,t}\) is the surface flux on day \(t\) in units of kg m\(^{-2}\) day\(^{-1}\), \(d\) is the time between subsequent observations (one day in this study), and \(\tau_x\) is the effective lifetime of a molecule of gas \(x\), including both reactive and transport losses. As both the effective lifetime and the surface flux are unknowns in the equation, we use a range of plausible lifetimes for each gas to calculate a range of surface fluxes. For \(\text{NH}_3\), we use lifetimes of 6, 12, 24, and 36 hours (Dentener and Crutzen, 1994; Whitburn et al., 2015); for \(\text{NO}_2\), we use lifetimes of 6, 12, and 24 hours (Beirle et al., 2011; de Foy et al., 2015; Jena et al., 2014). The values were selected to reflect the possible range of lifetimes throughout the year, including periods of elevated wet deposition during the rainy season.

2.3 Emissions inventory

GFED4s (van der Werf et al., 2017) provides monthly fire emissions at 0.25° resolution based on satellite-derived burned area (Giglio et al., 2013; Randerson et al., 2012) and a modified version of the Carnegie-Ames-Stanford-Approach (CASA) biogeochemical model (Potter et al., 1993). Daily emissions are calculated using data on the fraction of monthly emissions emitted on each date.

Uncertainty in GFED fire emissions stems from uncertainty in burned area, fuel consumption, and emission factors but is poorly constrained. According to van der Werf et al. (2017) a 1\(\sigma\) of about 50% for fire carbon emissions is reasonable for continental scale estimates. This may also be a best-guess estimate for fire \(\text{NH}_3\) emissions in our study region; while the uncertainty in \(\text{NH}_3\) emission factors is large because few fires have been sampled and adds to the total uncertainty, burned area and fuel consumption in savannas is in general better constrained than in other biomes.
2.4 Statistical analyses

Pearson product moment correlation analyses were conducted using pearsonr from the scipy.stats package in Python v3.6.3.

3. Results and Discussion

The wetting of dry soils has been known to stimulate biogeochemical cycling since at least the 1950s. Its role in creating large pulsed emissions of trace gases such as CO$_2$ and NO$_2$ has been demonstrated at laboratory (e.g., Birch and Friend, 1956), field (e.g., Davidson, 1992), and regional scales through satellite observations (Jaeglé et al., 2004) and observation networks (Adon et al., 2010).

Evidence for its importance to emissions of NH$_3$ has been limited to a few laboratory and field studies, with sometimes contrasting results, and its importance at landscape or regional scales is not well constrained. Here we present evidence that the Birch effect is an important driver of NH$_3$ emissions at regional scales, and likely responsible for the periods of the highest atmospheric NH$_3$ concentrations over the Sahel region in Africa.

3.1 Seasonal variability in NH$_3$ concentrations over Africa

Atmospheric NH$_3$ concentrations in 2008 exhibited broad seasonality that appears to correspond to seasonal precipitation patterns across the continent (Figure 1). In January, mean monthly concentrations are highest across a latitudinal band from roughly 5° N to 10° N, broadly corresponding to the region of highest biomass burning emissions (Figure 1). In April, higher cumulative monthly precipitation across the southern Sahel coincides with increased mean monthly NH$_3$ concentrations in the focal region (the red box in figure 1b); fire emissions are generally absent across the Sahel and much of the rest of the continent in April, with some emissions occurring along coastal West Africa. By August, during the middle of the West African Monsoon, hotspots of ammonia concentrations are generally absent from the continent, though concentrations are slightly elevated in central southern Africa, where emissions from biomass burning are also elevated (Figure 1).
3.2 Evidence for precipitation-induced emissions of NH₃ in the Sahel

For our focal region of the Sahel (defined above and outlined in red in Figure 1), mean atmospheric NH₃ concentrations exhibit two distinct peaks in late March and April (Figure 2a, highlighted in light and dark pink, respectively), which represent the highest concentrations observed in 2008. The peak in April, during which atmospheric NH₃ concentrations over the Sahel are elevated relative to other parts of north equatorial Africa (Figure 3a), occurs during the first period of sustained rainfall in the focal region, and corresponds to a peak in soil moisture, suggesting a possible causal relationship between changes in soil moisture and atmospheric NH₃ concentrations (Figure 2b and section 3.2.1 below). The late March peak occurs at the same time as an apparent modest increase in mean soil moisture (Fig 2b), but also as a possible modest increase mean fire emissions (Fig 2a) across the Sahel. Overall, however, the seasonality in IASI-retrieved atmospheric NH₃ concentrations exhibits a marked difference from the seasonality in GFED4s NH₃ emissions from fires, which start increasing in September and peak in November (Fig 2a and section 3.2.2 below).

3.2.1 Soil moisture controls over early growing season atmospheric NH₃ concentrations

Multiple lines of evidence support a causal relationship between changes in soil moisture and atmospheric NH₃ concentrations across the Sahel. Foremost are the significant correlations between ESA-CCI’s soil moisture product and the IASI total column during the onset of the rainy season. Specifically, for the period from February 23 to May 1, 2008, there is a significant correlation between mean atmospheric NH₃ concentrations of all pixels with acceptable retrievals in the Sahel focal region and mean soil moisture across the same set of pixels (r=0.28, P=0.02; Figure 4a). This correlation integrates all pixels across the Sahel, and thus excludes any sub-regional spatial structure in the data. To examine whether a relationship between soil moisture and NH₃ concentrations is also present at a finer spatial scale, we conducted a correlation between the two variables for each pixel for which both variables were present during April, and again found a significant positive linear correlation (r=0.16, p<0.001; Figure 4b). Maps of 3-day averages for precipitation, soil moisture, and total column NH₃ concentration over the southern Sahel at 0.25° resolution illustrate the changes in each variable that
occur during the development of the April emissions peak (Figure 5). Between April 13 and April 27, precipitation events in the southern half of the focal region (left-hand column) appear to be accompanied by steady increases in soil moisture (middle column) and total column NH$_3$ (right-hand column).

Although the explanatory power of the correlations between ESA-CCI’s soil moisture product and the IASI total column NH$_3$ concentrations is relatively low, it demonstrates a broad regional correlation between NH$_3$ concentrations and changes in soil moisture at the onset of the rainy season – a relationship that is strong enough to be observed at the scale of the Sahel. To provide some context for the statistical result, earlier work finding that rainfall is responsible for large emissions of NO$_2$ in the same region did not include any statistical analysis in support of its findings (Jaegle et al., 2004), and studies using satellite observations to infer environmental controls interpret correlation coefficients on the order of 0.25 to be evidence of a strong effect (e.g., Andela et al., 2017).

3.2.2 Minimal contribution of fire emissions to early growing season pulses

We can further exclude biomass burning as the source of the observed pulses of atmospheric NH$_3$. Biomass burning occurs in the Sahel with a well-known seasonality as based on several independent satellite fire metrics such as burned area and active fire detections (Duncan, 2003; Giglio et al., 2006). In general, burning in the Sahel occurs in the second half of the year, and few emissions are expected at the onset of the rainy season (Figure 1, 2). A comparison between our box model estimates of NH$_3$ flux and emissions from the GFED4s inventory strongly supports the hypothesis that biomass burning does not play an important role in NH$_3$ emissions during March or April, and further suggests that biomass burning may represent a relatively unimportant regional source of NH$_3$ during most of the year (Figure 6). The modelled total surface flux based on IASI observations varies depending on the effective lifetime used by up to a factor of roughly 4, with seasonal patterns mirroring the patterns in atmospheric concentration, and the largest emissions occurring during the pulses in March and April (Figure 6). In contrast, fire emissions of NH$_3$ from GFED4s are
concentrated in the second half of the year, and are negligible during March and April, suggesting that they do not contribute to the early growing-season emission pulses.

The importance of a source of NH$_3$ other than biomass burning in equatorial North Africa was suggested earlier for 0 to 10° N, a region immediately south of the Sahel and of the southern boundary of our focal region in Figures 1 and 2 (Van Damme et al., 2015; Whitburn et al., 2015). Whitburn et al. observe a one to two-month lag between peak fire radiative power and IASI-NH$_3$ that differs from the pattern of IASI carbon monoxide (CO) concentrations, suggesting that fire emissions can explain only some of the atmospheric NH$_3$ present. They speculate that soils may be the source of NH$_3$ emissions following the fire season, perhaps resulting from an increase in volatilization caused by increasing soil temperatures and pH, though the paper is focused on evaluating fire emissions and they do not test this hypothesis (Whitburn et al., 2015). Van Damme et al. speculate that the emissions are agricultural in nature (Van Damme et al., 2015). IASI-NH$_3$ concentrations in the other regions examined (southern Africa, Southeast Asia, and central South America) generally track fire activity, or are thought to be due to anthropogenic emissions (Whitburn et al., 2015). Although we have focused on the Sahel, it seems possible that the seasonality of rainfall in environments further south, between 0 and 10° N, could partly explain the elevated emissions observed there following the end of the fire season.

### 3.2.3 Co-emission of NH$_3$ and NO$_2$

The peak in NH$_3$ concentrations in April occurs at the same time as a peak in NO$_2$ concentrations (though unlike NH$_3$, the April peak does not represent the highest annual atmospheric concentration of NO$_2$). For the entire month of April, total column NH$_3$ concentrations and tropospheric NO$_2$ concentrations are strongly correlated ($r=0.78$, $p<0.0001$). The simultaneous increase in atmospheric NO$_2$ and NH$_3$ concentrations provides additional, indirect support for a soil source of NH$_3$ (Figure 2, 6). In addition to abundant field- and laboratory evidence that previously dry soils emit large pulses of NO following wetting (Davidson, 1992; Davidson et al., 1991; Dick et al., 2001; Meixner et al., 1997), Jaegle et al. (2004) showed that this soil NO pulse is responsible for the highest
concentrations of atmospheric NO\textsubscript{2} over the same region we focused on. As with the seasonal pattern in NH\textsubscript{3} concentrations, seasonal variation in OMI-NO\textsubscript{2} tropospheric concentrations does not match that of the GFED4s NO\textsubscript{2} emissions from fires (Figure 6). We believe that the simplest explanation for our box model results showing the strong correlation between tropospheric NO\textsubscript{2} and total column NH\textsubscript{3} concentrations in April is that the two pulses are the result of soil emissions triggered by the same environmental change—in this case, an increase in soil moisture following an extended dry period.

Like NH\textsubscript{3}, concentrations of NO\textsubscript{2} also exhibit a peak in mid-March, but the peak lags a week behind the NH\textsubscript{3} peak (Figure 2). Although NO emissions from soils can peak within hours after wetting (Davidson, 1992), in a laboratory setting using soils from the Mojave Desert, an NO pulse lagged 1 to 2 days behind an NH\textsubscript{3} pulse following experimental wetting (McCalley and Sparks, 2008). The authors argue that this lag may be related to competition for NH\textsubscript{4}\textsuperscript{+} between NH\textsubscript{3} volatilization and nitrification, with volatilization generally outcompeting nitrification during the initial period following wetting. An alternative or additional contributing factor to the lag may be related to the population dynamics of nitrifying bacteria. Although the transcriptional response of nitrifiers to wetting can be very rapid (Placella and Firestone, 2013), at a population level nitrifiers are generally slow-growing (Robertson and Groffman, 2007), suggesting that populations in resource-limited environments may not be able to immediately take advantage of sudden large increases in resource availability. For example, NO emission responses to inorganic N inputs—which arguably provides a similar immediate release from a resource limitation as wetting of dry soils for nitrifiers, particularly in relation to the presumed increase in NH\textsubscript{4}\textsuperscript{+} concentrations caused by wetting—exhibited pulse responses that lagged roughly a week behind fertilizer additions in Kenya (Hickman et al., 2017). In the case of the Sahel, nitrifier populations may not be able to recover quickly from the extended dry conditions in March, and the lagged emission response of NO could be explained by the slow population-level response to the flush of mineralized N that follows wetting.

The March NO pulse is also smaller than the April NO pulse, and smaller than the April NH\textsubscript{3} pulse. Field studies have observed larger pulses following the second rainfall of the season (Meixner et
The initial increase in soil moisture during March was modest (Figure 2), so it seems possible that soils dried out quickly, before populations of nitrifying bacteria grew large enough to trigger an NO pulse of the magnitude that occurs in April. Increased competition for available NH$_4^+$ by nitrifying bacteria in April may have limited the NH$_3$ pulse.

Although earlier researchers have hypothesized that NH$_3$ volatilization and nitrification cannot co-occur in the same soils (Praveen-Kumar and Aggarwal, 1998), the few field and lab studies measuring soil emissions of both gases following wetting observe positive fluxes of each (McCalley and Sparks, 2008; Schlesinger and Peterjohn, 1991; Soper et al., 2016), with NH$_3$ dominating emissions from desert soils (McCalley and Sparks, 2008; Schlesinger and Peterjohn, 1991) and NO$_2$ dominating from grassland soils (Soper et al., 2016). We expect that even were the two processes mutually exclusive at the scale of a soil core or chamber, heterogeneity in soil properties at the pixel or regional scale can explain our observations of coinciding pulses of NO and NH$_3$.

3.3 Magnitude and importance of soil NH$_3$ emission pulses

During the early growing season, atmospheric concentrations of NH$_3$ are roughly an order of magnitude higher than NO$_2$ (figure 2). It is important to note that NH$_3$ retrievals generally have a higher error, and that our screening process may introduce a potential bias in that we permit retrievals with higher uncertainty if they are low concentrations; we also retain observations of negative concentrations. From this perspective, our concentration and emission estimates can be considered conservative.

Because the magnitude of mean surface fluxes depends on the effective lifetime used in the box model, comparisons between the modeled fluxes of NO$_2$ and NH$_3$ are not straightforward. In general, however, our modelled emissions suggest that NH$_3$ is probably emitted at substantially higher rates than NO during pulse events, possibly by a factor of ten or more (figure 6). This result is unexpected, given earlier observations that NH$_3$ tends to be the dominant source in highly alkaline desert soils (pH 9-11;
McCalley and Sparks, 2008), whereas emissions from grassland soils with a more neutral pH, as might be expected in the Sahel, were dominated by NO, by roughly a factor of 10:1 (Soper et al., 2016). This pulse produces NH$_3$ concentrations comparable in magnitude to the peak concentrations over many of the Earth’s major biomass burning regions (Whitburn et al., 2015). Indeed, NH$_3$ emissions during the date range February 29-March 16 and April 12-May 1, which cover the two emission peaks during that period, represented about one fifth of annual NH$_3$ emissions from our focal region in the Sahel (annual emissions of ~0.4 to 2 Tg N, and total pulse emissions of ~0.1 to 0.5 Tg N, depending on the effective lifetime assumed). It is important to note that in addition to uncertainty associated with the NH$_3$ retrievals, additional sources of bias and uncertainty—such as the use of an effective lifetime rather than explicitly accounting for deposition fluxes and chemistry, uncertainty in the value and variability in that lifetime, and biases in both the IASI and OMI retrievals—limit our ability to quantitatively constrain the surface NH$_3$ or NO fluxes, or to make strict quantitative comparisons between them.

This substantial pulse of NH$_3$, and the co-occurrence of a pulse of NO$_x$, could be an important source of PM$_{2.5}$ in the region during the first half of the year. Secondary inorganic aerosols such as ammonium sulfate are formed in reactions involving NH$_3$, and ammonium nitrate aerosol formation requires both gaseous NH$_3$ and NO$_x$. In the Sahel, combustion sources of NO$_x$ are relatively small in March and April (Fig. 6), making soil NO emissions potentially more important in the formation of PM$_{2.5}$.

### 3.4 Comparison to surface observations

The INDAAF network (International Network to Study Deposition and Atmospheric Chemistry in Africa, http://www.indaaf.obs-mip.fr) provides monthly surface NH$_3$ deposition rates between 1998 to 2016 for seven sites in north equatorial Africa, both in and outside the Sahel. The work of Adon et al. (2010) presents an analysis of annual and seasonal variability of surface gases concentrations (NO$_2$, HNO$_3$, O$_3$, SO$_2$, and NH$_3$) from the long-term monitoring INDAAF stations over the period 2000-2007. The two sites in the Sahel (Figure 3c (Banizoumbou, Niger) and 3f (Katibougou, Mali)) exhibit broadly similar seasonal patterns, with NH$_3$ concentration increases starting in April (or March in the 2008 case
of Katibougou, Mali (Figure 3f)), but this seasonal pattern is generally absent in sites outside the Sahel (Figure 3b, 3d, 3e, 3g, and 3h). These seasonal patterns are broadly consistent with the pulsing dynamics observed by IASI in the Sahel, and the absence of pulsing outside the Sahel (Figure 3).

An evaluation of seasonal patterns in the network found that emission patterns differ between wet savannah and dry savannah: dry season emissions tend to be higher in wet savannah, where biomass burning dominates annual emissions (Adon et al., 2010). In dry savannah ecosystems, emissions are higher during the wet season, and are likely enhanced by the volatilization of N inputs from agro-pastoralism in the region, leading to high total N deposition fluxes (Adon et al., 2010). It is conceivable that regional differences in soil pH (Vågen et al., 2016) could also result in different rates of soil NH$_3$ emissions. In addition, higher leaf area index in wet savannas and forest could result in more interception of NH$_3$, reducing soil contributions to atmospheric concentrations during the wet season.

### 3.5 Later growing season NH$_3$ emissions

After the early season pulses, NH$_3$ concentrations and fluxes remain fairly elevated (figure 2, 6); during this period, NO$_2$ concentrations and fluxes increase, becoming comparable in magnitude to NH$_3$ (figure 2,6). This pattern is consistent with earlier studies describing elevated concentrations of these gases in or near our focal study region for several months following the end of the biomass burning season (Jaeglé et al., 2004; Whitburn et al., 2015). Jaegle et al. attribute these elevated concentrations to the wetting of dry soils, and Whitburn et al. to the possible acidification of soils. An additional explanation is that these emissions may be associated with agricultural activity. The mean start of the cropping season ranges from May to August in the focal region, based on NDVI-based observations of plant phenology (Vrieling et al., 2011), suggesting that the bulk of elevated NO$_2$ and NH$_3$ emissions in the region occur after planting, and well into the rainy season. Elevated emissions could be associated with soil disturbance from tillage (e.g., Yang et al., 2015) or from the use of fertilizer inputs, which have been argued to be higher than generally acknowledged in the scientific and development literature.
(Cobo et al., 2010; Sheahan and Barrett, 2017), though N additions in Sahelian countries such as Niger tend to be very low, even for farmers who use fertilizer (Masso et al., 2017; Sheahan and Barrett, 2017).

### 3.6 Possible sources of error and bias

It is worth noting that the morning overpass time used in this analysis is likely to cause a further underestimation of daily NH$_3$ concentrations, as emissions would be expected to follow diurnal temperature variation and be higher in the afternoon (Van Damme et al., 2015). A more sophisticated inverse modelling approach could provide firmer insight into the magnitude of emissions, as well as provide some insight into the magnitude of specific NH$_3$ sources. Our analysis is subject to several additional sources of uncertainty: increased cloud cover during the rainy season tends to result in fewer observations than during the dry season, so our regional means are based on different numbers of observations at different times of year.

Although the explanatory power of the linear relationship between soil moisture and emissions in the early part of the rainy season is relatively low, this would be expected in part as we would expect the relationship to be complex and to vary over time. Multiple studies have shown that rewetting of dry soils results in lower emission pulses for the same level of water addition (Davidson, 1992; Davidson et al., 1991), including of NH$_3$ emissions (Soper et al., 2016). It also seems plausible that there are threshold effects in which an initial increase in soil moisture may simply need to be large enough to activate dormant microbial communities and/or cause a flush of labile microbial N to trigger an emissions pulse, such that the pulse response might best be described with a piecewise function. Asynchrony between plant and microbial activity during soil wet up and dry down (Collins et al., 2008), and different activation thresholds for microbial and plant responses to precipitation (Dijkstra et al., 2012) may also play a role in determining the amount of available NH$_4^+$ for volatilization at different times in the early rainy season.

### 3.7 Conclusion
Satellite measurements of trace gases—although not without their limitations—provide a powerful tool for understanding global and regional atmospheric composition, and for gaining insights into the controls over nitrogen cycling and trace gas emissions, particularly for regions where other types of measurements are scarce. With daily observed and observation-based data available for multiple environmental variables including precipitation, soil moisture, biomass burning emissions, and tropospheric NO\textsubscript{2} concentrations, it is possible to evaluate specific mechanisms behind the seasonality of trace gas emissions. In an evaluation of the Sahel during 2008, we find that NH\textsubscript{3} concentrations are elevated during March and April, a period when biomass burning emissions are absent, but when tropospheric NO\textsubscript{2} concentrations exhibit similar temporal dynamics. We further find that the increase in NH\textsubscript{3} concentrations are positively correlated to changes in soil moisture at the start of the rainy season. Using a simple box model, we estimate that average emissions for the entire Sahel are between 2 and 6 mg NH\textsubscript{3} m\textsuperscript{-2} day\textsuperscript{-1} during peaks of the observed pulses, though note that these estimates are subject to substantial bias and uncertainty. We conclude that the Birch effect is an important and geographically broad driver of NH\textsubscript{3} emissions, and am important component of the N cycle in the Sahel.

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Figure 1. Seasonality of precipitation and NH₃ emissions in Africa during 2008. Monthly TRMM precipitation (a), IASI-NH₃ concentrations (b), and GFED4s NH₃ emissions (c) over Africa in January, April, and August, 2008. TRMM precipitation is presented in mm month⁻¹, IASI-NH₃ concentrations in 10¹⁶ molecules cm⁻², and GFED4s NH₃ emissions in mg m⁻² month⁻¹.
Figure 2: Early growing season NH$_3$ pulses temporally associated with changes in soil moisture and with NO$_2$ pulses over the focal study region in the Sahel during 2008. Top panel: Daily atmospheric NH$_3$ concentrations from IASI and NH$_3$ biomass burning emissions from GFED4s. Middle panel: ESA-CCI soil moisture and TRMM precipitation. Bottom panel: atmospheric NO$_2$ concentrations from OMI. Putative soil emission pulses in March and April are highlighted in bright and dark pink, respectively. GFED4s emissions were converted from a mass-based to molecule-based flux to allow comparison with the IASI retrievals; note the different scales for the left and right y axes of the top panel.
Figure 3. NH$_3$ pulsing over the Sahel in April, and geographic variation in the seasonality of surface NH$_3$ concentrations over north equatorial Africa. (a) Observations by IASI during April 25 to April 28, 2008 reveal elevated mean atmospheric NH$_3$ concentrations specifically over the Sahel region (b-h).

Monthly NH$_3$ gas concentrations from sites in the INDAAF network; black lines represent the multi-year mean and standard error for each site, and red dots represent the 2008 value. Data are presented for Agoufou, Mali (b), Banizoumbou, Niger (c), Bomassa, Congo (d), Djougou, Benin (e), Katibougou, Mali (f), Lamto, Côte d’Ivoire (g), and Zoetele, Cameroon (h).
Figure 4. Correlations between soil moisture and atmospheric NH3 concentrations observed by IASI over the focal study region in the Sahel during the start of the rainy season in 2008. Top panel: 5-day running mean of daily NH3 concentrations and daily soil moisture for the focal study region from mid-February through the end of April, 2008. Bottom panel: scatterplot of soil moisture versus atmospheric NH3 concentration for each 0.25° pixel in the study region during April, 2008. In both panels, soil moisture data are included only for those 0.25° grid cells where NH3 observations are available for the same day.
Figure 5. Maps of changing precipitation, soil moisture, and atmospheric NH$_3$ concentrations for the focal region of the Sahel during the second half of April, 2008. 3-day averages from April 13 through April 27 are presented for precipitation from TRMM (left column), soil moisture from ESA-CCI (middle column) and atmospheric NH$_3$ concentrations for acceptable retrievals from IASI (right column).
Figure 6. Comparison of daily total surface fluxes and biomass burning emissions of a) NH$_3$-N and b) NO$_2$-N for the focal study region in the Sahel during 2008. Total surface fluxes are estimated from IASI NH$_3$ and OMI NO$_2$ observations using a simple box model and assuming effective lifetimes of 12, 24, or 36 hours for NH$_3$ and of 6, 12, or 24 hours for NO$_2$. Fire emissions are taken from the GFED4s database. Note the difference in scales, and that shorter effective lifetimes result in higher modeled emissions.