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

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Abstract.

Ammonia (NH_3) is a key atmospheric precursor of fine particulate matter, and an indicator of agricultural and biomass burning emissions. In Central America, NH_3 variability remains largely unquantified. This study presents the first integrated spatiotemporal assessment of atmospheric NH_3 over Guatemala (2015–2023) using concatenated IASI A/B/C observations, combined with fire activity, land cover, and meteorology dataset. Annual NH_3 columns remained relatively stable, reflecting a persistent agricultural background with episodic enhancements driven by ~~source dominated by~~ biomass burning. Significant anomalies occurred in 2016, 2020, and 2023, with 2020 showing the highest annual and monthly NH_3. A clear seasonality is observed with maxima in April–May coincided with the regional fire season, followed by a rapid decline after rainy season. The spatial hotspots were consistently detected in northern (Petén–Quiché) and southern (Escuintla) agricultural regions. The most extreme episode in April 2020 recorded 957 active fires over ~1,486 km^2, largely within the Maya Biosphere Reserve. This episode occurred under elevated temperatures and short-term dry conditions, despite high annual precipitation, demonstrating the importance of seasonal meteorological variability. These results indicate that Guatemala's variability in NH_3 total columns reflects a stable agricultural condition with superimposed fire-driven peaks, modulated by climatic anomalies.

1 Introduction

Atmospheric ammonia (NH_3) exerts~~utilizes~~ a considerable influence on air quality and ecosystem~~logical~~ integrity through its contribution to secondary inorganic aerosol formation and its atmospheric transport~~potential for long-range~~, dispersion, and deposition under ~~transport~~ ~~and interaction with~~ prevailing meteorological conditions (Zhou et al., 2019). As a reactive nitrogen (Nr) compound, NH_3 plays a fundamental role in the global nitrogen cycle and a variety of biogeochemical processes, representing a dominant form of nitrogen present in terrestrial and atmospheric systems (Sutton et al., 2007, 2013; Whitburn et al., 2016). Despite its relatively short atmospheric lifetime ranging from several hours to a few days due to its high deposition efficiency and conversion into particulate ammonium, current surface-based monitoring approaches remain inadequate for providing accurate global emission estimates, often introducing substantial uncertainties (Dammers et al., 2016; Herrera et al., 2022). NH_3 is also a key component in atmospheric chemistry and in the coupling of nitrogen and carbon cycles within ecosystems, with broad consequences regarding climate regulation, agricultural sustainability, air quality and public health. NH_3 emissions originate from both natural and anthropogenic activities, with the latter contributing the majority of the global NH_3 burden. The agricultural sector remains the principal source, accounting for over 81% of total anthropogenic emissions globally (Van Damme et al., 2021; Wyer et al., 2022), while additional anthropogenic contributions stem from residential combustion, vehicular exhaust, industrial production, and wastewater treatment systems (Abeed et al., 2022; Dragosits et al., 2002; Sutton et al., 2007). Although agriculture particularly using fertilizers and manure remains the dominant source of atmospheric NH_3. Nonagricultural sources such as vehicular and industrial emission may be also contribute and are significantly underestimated (Chen et al., 2024; Chen and Wang, 2025; Farren et al., 2020; Gu et al., 2023; Zhou et al., 2017).

In recent decades, satellite remote sensing has significantly advanced the detection of atmospheric NH_3, leading to the development of several global NH_3 measurement datasets, notably from the Infrared Atmospheric Sounding Interferometers (IASI) instrument. At the same time~~For this study~~, global fire inventories and satellite derived products, ~~we also~~ includ~~ing~~e ~~fire-based emission datasets such as~~ the Global Fire Emissions Database (GFED) (Giglio et al., 2006, 2013; van der Werf et al., 2010, 2017), the Global Fire Assimilation System (GFAS) (Remy and Kaiser, 2014) developed by the European Centre for Medium-Range Weather Forecasts (ECMWF), and two fire products from the National Aeronautics and Space Administration (NASA), based on Fire Radiative Power (FRP) measurements, have enable the characterization of biomass burning (Fu et al., 2020; Li et al., 2020; Remy and Kaiser, 2014; Vermote et al., 2009; Wooster et al., 2003).

Central America's climate is significantly shaped by the two oceans it borders, with the vast Pacific Ocean, spanning nearly half the Earth's circumference at the equator, being especially crucial for climate regulation by El Niño brings drier conditions to Guatemala, while La Niña produces more precipitation (Bardales Espinoza et al., 2019) Guatemala's geomorphological attributes and geospatial coordinates inherently facilitate a multitude of microclimatic zones and pronounced climatic heterogeneity, the variability has been amplified in recent years by the nation's persistent susceptibility to extreme meteorological phenomena, including prolonged arid periods and intense tropical cyclones, both of which are intensified by the overarching impacts of anthropogenic climate change (Alfaro Marroquín and Gómez, 2019). Guatemala's climate deviates from the typical four-season delineation observed in the Northern Hemisphere. Instead, it is characterized by two distinct periods: the wet season, spanning from May to October, and the dry season, occurring from November to April (INSIVUMEH, 2018; Orrego León et al., 2021).

Furthermore, these climate condition directly influence and intensify of biomass burning events, particularly during dry season, Guatemala is exposed to a variety of threats, with wildfires being one of the main threats in recent decades (CONRED, 2025).

Guatemala has experienced increasing concern from fire-related activities that are strongly tied to agricultural expansion, shifting cultivation, and deforestation. These practices, often used to clear land for crops or grazing, are typically intensified during the dry months, aligning with peak fire activity (Liu et al., 2024b; Monzón-Alvarado et al., 2012). Guatemala consistently reports a high number of fire hotspots (CONRED, 2025), especially in years dominated by El Niño-induced drought conditions (Chuvieco et al., 2019; CONRED, 2025; Giglio et al., 2013). The recurrence of such fires in forested and agro-pastoral zones not only transforms land cover but also releases large quantities of reactive trace gases and aerosols, including atmospheric NH_3 into the atmosphere (Andreae, 2019; Pohl et al., 2022; Wyer et al., 2022). Despite this, the role of biomass burning as a driver of NH_3 emissions remains underexamined in Central American air quality studies.

Despite the increasing availability of satellite-based datasets for monitoring atmospheric NH_3, there remains a significant lack of regional-scale studies in Central America, particularly in Guatemala, where land use dynamics and biomass burning are likely to play an important role in shaping substantially to atmospheric NH_3 patterns. Previous research has primarily examined individual drivers, such as meteorological circulation and fire season in Central America (Corona-Núñez and Campo, 2023; Liu et al., 2024a), or continental scale assessment of NH_3 variability (Clarisse et al., 2009; Van Damme et al., 2021; Herrera et al., 2022; Luo et al., 2022; Zhu et al., 2015). However, integrated regional analysis that simultaneously consider concatenated NH_3, fire activity, land cover and meteorological variables remain limited.

This study investigates the monthly spatiotemporal dynamics of atmospheric NH_3 total column over Guatemala from 2015 to 2023, using three satellite-based observations from IASI onboard of the Meteorological Operational satellite programme (MetOp), MetOp-A, MetOp-B, and MetOp-C, in combination with land cover classification from the Environmental Systems Research Institute (ESRI), fifth-generation global reanalysis (ERA5) meteorological data, fire activity from Moderate Resolution Imaging Spectroradiometer (MODIS-FRP), and vertical profiles global reanalysis of NH_3 from Copernicus Atmosphere Monitoring Service (CAMS). The study~~research~~ aims to identify spatial hotspots and the interannual and seasonal variability in NH_3. In addition, spatial clustering using k-means algorithm is applied to partition NH_3 patterns and explore their heterogeneity, with a particular focus on land cover types and the influence of fire-pixel activity. ~~To ensure the reliability of the fire data, fire-pixels from MODIS with a confidence level ≥70% were included in the analysis.~~ A case study in 2020 further examines a period of anomalous NH_3 of the total column variability in relation to extreme fire events linked to agriculture and meteorological conditions.

2 Data and Methods

2.1 Study location

The Republic of Guatemala, a Central American country situated between latitudes 13.5°N to 17.8°N and longitudes 88.2°W to 92.2°W. According to the National Institute of Statistics of Guatemala (INE, 2020), the country is administratively divided into 22 departments, which differ in terms of land use, population density, and economic activity. Guatemala encompasses a diverse range of ecological regions, topographical variations, and land use patterns. Its landscape is characterized by a complex zone of agricultural lands, forested highlands, volcanic zones, and rapidly urbanizing areas. Agriculture remains a cornerstone of the Guatemalan economy and landscape with extensive cultivation of crops such as maize, beans, coffee, sugarcane, oil palm, and bananas (FAO, 2019; Hervas, 2019; Lopez-Ridaura et al., 2019). Fertilizer application and livestock farming are particularly prevalent in rural regions. Meanwhile, increasing urbanization and industrialization, especially around Guatemala City and its metropolitan zone, have introduced additional anthropogenic activities, such as vehicular exhaust, industrial activity, and waste treatment processes.

Guatemala experiences a pronounced dry season (typically November to April) and rainy season (May to October) (Alfaro Marroquín and Gómez, 2019; Bardales Espinoza et al., 2019; INSIVUMEH, 2018; Orrego León et al., 2021), which strongly modulate fire activity, atmospheric transport conditions, and deposition processes relevant to NH_3 dispersion. Frequent wildfires, especially in the Petén department (northern area of Guatemala) and central highlands during the dry season, contribute further to the atmospheric burden of reactive nitrogen species. Topographically, Guatemala varies from sea level to 3,000 m above sea level (a.s.l) in the central plateau, and with volcanic peaks that reach 4,200 m a.s.l. (IGM, 2002). Figure 1 shows the digital elevation model (DEM) of the topographic surface in meters over Guatemala using the European Space Agency, 2024).

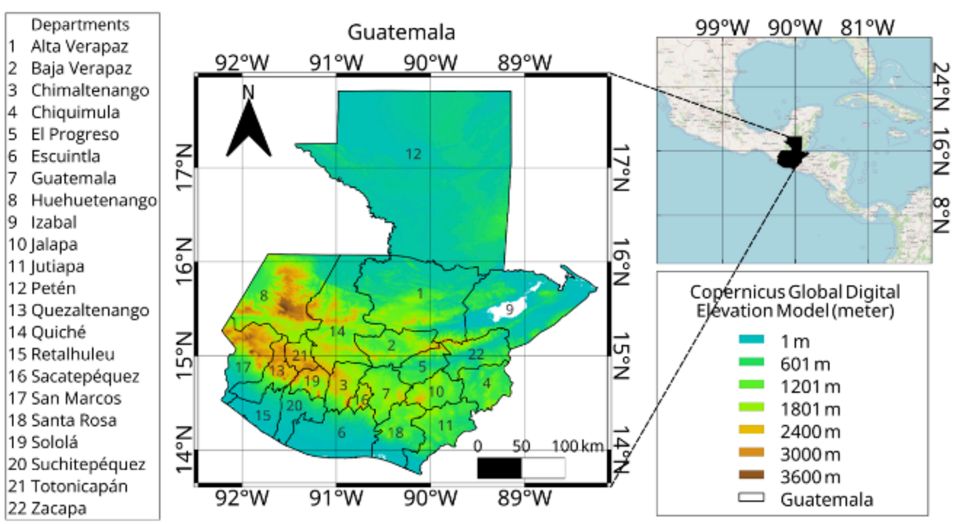


Figure 1: Departments of Guatemala and elevation (m) from Copernicus Global Digital Elevation Model.

2.2 IASI NH_3 satellite-based

This study applies a multi-step analytical framework to investigate the spatiotemporal variability of satellite-based atmospheric NH_3 over Guatemala from 2015 to 2023. The analysis is based on a temporally concatenated monthly NH_3 total column Level 3 (L3) observations, from the IASI instrument onboard the MetOp A/B/C satellites launched in 2006, 2012, and 2018, respectively (Clarisse et al., 2009, 2019; Coheur et al., 2009). The concatenation produces the dataset, which serves as the basis for all spatial distributions, time series, climatological analyses, clustering, and correlation, incorporating both morning and night observations for enhanced representativeness and discarded negative values. While IASI-B maintains the spatial resolution of sensors A and C, integrating all three sensors could improve both temporal and spatial coverage, thereby yielding more accurate and robust results. While the study period spans 108 months, the concatenated analysis incorporates a total of 228 sensor months, corresponding of IASI A (January 2015–December 2020), B (January 2015–December 2023), and C (January 2020–December 2023).

IASI works with a cross-track scanning swath approximately 2200 km wide and provides measurements with a nadir pixel diameter of about 12 km. Positioned aboard sun-synchronous polar-orbiting satellites, the instrument enables near-global coverage twice daily during both daytime and nighttime corresponding to local solar overpass times of approximately 09:30 and 21:30, respectively (Clarisse et al., 2010; Van Damme et al., 2017; Whitburn et al., 2017). The NH_3 dataset was obtained from version 4 (v4.0.0R) (L3) of the ANNI-NH_3 retrieval product (Clarisse et al., 2023), and regridded to a 0.25° × 0.25° spatial resolution. A major enhancement in this version is the incorporation of the vertical column averaging kernel (AK), which is essential for aligning satellite retrievals with chemistry-transport model simulations by mitigating the influence of the priori NH_3 vertical profiles applied during retrieval. While spatial patterns remain consistent with previous versions, total column values are approximately 15–20% higher due to improvements in the high-resolution infrared retrieval configuration (HRI). Version 4 offers improved uncertainty characterization and enhanced temporal uniformity of the dataset from 2007 to 2023 (Clarisse et al., 2023). The retrieval algorithm estimates a hyperspectral range index from IASI spectra and converts it into NH_3 total column densities using an artificial neural network (Van Damme et al., 2021; Franco et al., 2018; Whitburn et al., 2017). The uncertainty was quantified using the standard error and the relative uncertainty was derived from the distribution of the observation within of each grid cell (Text S1).

Additionally, NH_3 vertical profiles data were obtained from the ECMWF, Atmospheric Composition Reanalysis 4 (EAC4), produced by the CAMS. This global reanalysis provides NH_3 with mass fraction in the air, provided as a mass mixing ratio (kg kg^{-1}), the model is defined by 60 hybrid sigma-pressure levels. It provides a detailed representation of the atmospheric structure, particularly near the surface (~0–100 m) where most emissions occur (Inness et al., 2019). These reanalysis datasets incorporate satellite observations and model simulations to provide globally consistent, spatially and temporally resolved atmospheric composition data (Flemming et al., 2017; Inness et al., 2019). In our study, the CAMS analysis of vertical structure and latitudinal distribution of NH_3 during a specific period of interest, rather than for a quantitative comparison with satellite of total column densities.

2.3 Cluster analysis of NH_3

An unsupervised clustering approach was applied to classify NH_3 total columns field based on their statistical similarity. Clustering is a type of unsupervised machine learning that groups large datasets based on their similarity, allowing for more manageable and interpretable analyses (Ahmad and Dey, 2007; Pham et al., 2005). This analytical approach is particularly beneficial when there is limited or no prior knowledge about the underlying structure of the data (Gašparović et al., 2019). Among clustering methods, the k-means algorithm is one of the most commonly applied and reliable techniques. It partitions data into a predefined number of *k* clusters by iteratively determining central points, or centroids, for each group (Pham et al., 2005). The algorithm requires the number of clusters to be specified in advance (Ahmad and Dey, 2007; Mahata et al., 2020). K-means operates using the squared Euclidean distance as its primary metric (Spencer, 2013), which quantifies the separation between two points within a Euclidean space of any dimension (Li et al., 2022). The Euclidean distance between two points, p and q, in a j-dimensional space is mathematically expressed as $d(p,q)$.

$$d(p,q) = \sqrt{(p_1 - q_1)^2 + (p_2 - q_2)^2 + \ldots + (p_j - q_j)}^2 \tag{1}$$

The k-means algorithm divides a dataset into *k* clusters by aiming to minimize the variance within each group (Li et al., 2022). It operates on a set of input samples $X = \{x^1, \ldots, x^n\}$, where each $X^m = \{x_1^m, x_2^m, \ldots, x_j^m\}$ represents an observation composed of j variables, and $m \epsilon X = \{1, \ldots, n\}$, with n being the total number of observations. These samples are categorized into *k* clusters $(S_1, S_2, \ldots S_k)$ with the goal of minimizing the total intra-cluster variance $(S_{i=1,\ldots,k})$, as described in Equation (2):

$$\overset{argmin}{S} = \sum_{i=1}^{k} \sum_{X \in S_i} \|X - \mu_i\|^2 \tag{2}$$

The notation $\|X - \mu_i\|$ represents the squared Euclidean distance between each data point (X) and its assigned cluster centroid μ_i within a multidimensional Euclidean space (Li et al., 2022). In this study, k-means clustering was utilized to examine the spatiotemporal patterns of NH_3 throughout the specified timeframe (Anne Fouilloux, 2018; Pedregosa et al., 2011). To determine the most suitable number of clusters k, the elbow method was employed. This approach assesses the Cluster Sum of Squares (CSS) to identify the point at which the inclusion of additional clusters no longer significantly improves the model performance (Umargono et al., 2019).

2.4 ESRI land cover class map

The ESRI Land Use Land Cover (LULC) 2020 dataset, released in June 2021, was developed using deep learning models trained on more than 5 billion manually labelled pixel samples derived from the European Space Agency’s Sentinel-2 satellite imagery with 10 m spatial resolution (Karra et al., 2021), enables land cover mapping at both national and local scales. According to (ESRI, 2021) these training samples were collected from 24,000 image tiles globally, each measuring 510 × 510 pixels, and reflect a wide range of land surface types. The LULC 2020 product is classified into nine classes: Water, Trees, Flooded vegetation, Crops, Built area, Bare ground, Snow/Ice, Clouds, and Rangeland (Karra et al., 2021). In this study, the analysis was restricted to classes related to Water, Trees, Flooded vegetation, Crops, Built area, and Rangeland.

2.5 Meteorological data from ERA-5

Meteorological variables used in this study were obtained from the ERA5 reanalysis (Soci et al., 2024) dataset provided by ECMWF, (Hersbach et al., 2020). Originally available at a horizontal resolution of approximately 31 km, the data were resampled to a 0.25° × 0.25° grid and both spatially and temporally to match the IASI NH_3 observation times and locations. The selected meteorological parameters were subsequently used in statistical analysis with atmospheric NH_3, these variables include 2 m air temperature (t2m), 10 m wind speed (ws), boundary layer height (BLH), relative humidity (RH, derived using 2 m air temperature and dew point temperature), and total precipitation (tp) from the monthly average reanalysis product, representing the twelve monthly precipitation values within each year, and monthly climatology for each calendar month. Pearson correlation matrix coefficient ~~were~~was calculated between monthly meteorological variables means and total column means of NH_3, including total fire counts per month, to quantify their linear relationship.

2.6 Fires

Active fire detections were obtained from MODIS Aqua/Terra Thermal Anomalies/Fire Locations product (MOD14/MYD14). Data was accessed via the Fire Information for Resource Management System (FIRMS) Near Real-Time (NRT), collection 6.1 (Giglio et al., 2021a). These data are produced by NASA´s Land, Atmosphere Near-real-time Capability for EOS (LANCE) and provide global active fire information at a nominal spatial resolution of 1 km.

MODIS fire detection recognizes thermal anomalies in individual pixels using mid-infrared radiance signals. It assigns each detected fire´s geographic location to the center of the corresponding 1 × 1 km^2 spatial resolution (Giglio et al., 2003, 2006; Justice et al., 2010).Each detection includes fire location, detection confidence, and FRP. Detection confidence, indicating the likelihood of an active fire in a pixel, is classified as low level: 0% to < 30%, nominal level: 30% to < 80%, high level: 80% to 100% (Giglio et al., 2016, 2021b, a; Hantson et al., 2013).

To reduce false detections, and ensure strong fire identification, only fire pixels with nominal to high confidence levels ≥70% were retained for analysis, in accordance with recommendations from previous studies (Giglio et al., 2016, 2021b, a; Hantson et al., 2013). Fire activity was quantified using fire counts, defined as the number of detected fire pixels, which serve as a proxy for fire occurrence and spatiotemporal variability. Monthly fire counts were aggregated for each year to characterize seasonal and interannual variability in fire activity.

FRP served as an indicator of fire intensity with energetic significance providing as an additional filtering. Moreover, it quantifies the rate of radiative energy released from combustion and is directly related to biomass consumption (Wooster et al., 2003). In this study only fire detections with FRP values ≥40 Megawatt (MW) were included, thereby excluding low-intensity or small-scale fires to ensure consistency between temporal statistics and spatial fire distribution.

FRP is derived from MODIS 4 μm radiance measurement using the methodology proposed by Wooster et al., 2003 in equation (3):

$$FRP = \frac{\sigma \times A_{pixel}}{\alpha \times \tau_4} (L_4 - L_{4b}) \tag{3}$$

A_{pixel} is the fire pixel area σ = 5.6704 × 10^{-8} Wm^{-2} K^{-4} is the Stefan–Boltzmann constant, α = 3.0 × 10^{-9} Wm^{-2} $sr^{-1}m^{-1}k^{-4}$ is the MODIS empirical constant, τ_4 is the atmospheric transmittance at 4 μm, and $L_4 - L_{4b}$ are radiances at 4 μm of the fire and background pixels, respectively (Wooster et al., 2003).

The burned analysis for this work was obtained by MODIS MCD64A1 Version 6.1 product, which combines observations from both Terra and Aqua platforms to produce a monthly global dataset gridded at 500 m that provides per-pixel burned-area and quality information (Giglio et al., 2018). The MCD64A1 MODIS burned area product integrates surface reflectance data with active fire detections to identify burned pixels based on temporal changes in a burn-sensitive vegetation index derived from shortwave infrared bands (bands 5 and 7) and spatial texture metrics (Dong et al., 2013; Freeborn et al., 2011; Giglio et al., 2003, 2021b; Justice et al., 2010). For each pixel, the product provides the estimated burn date as the ordinal day of the year, as well as quality assurance layers and uncertainty metrics. Pixels identified as unburned, water, or missing data are assigned to distinct flag values (Giglio et al., 2016).

3 Results

3.1 ~~Spatiotemporal~~Annual and seasonal variability of atmospheric NH_3

Fig. 2 shows the annual variability of NH_3 total columns over Guatemala from the period 2015 to 2023, while the corresponding anomalies relative to long-term are presented in Fig. S1. The respective boxplots show the distribution of monthly NH_3 values within each year. The annual medians of NH_3 remained ~~reveal a NH~~~~3~~ relative stable, ranging from ~~with a minimum of~~ 3~~2~~.95~~0~~ × 10^{15} molecules cm^{-2} in 2021 to ~~and a maximum of~~ 4~~2~~.66~~33~~ × 10^{15}~~6~~ molecules cm^{-2} in 2020 (Table S1). ~~While the median values show an increase of NH~~~~3~~ ~~notable during 2020 (4.66 × 10~~~~15~~ ~~molecules cm~~~~−2~~~~) and 2023 (4.33 × 10~~~~15~~ ~~molecules cm~~~~−2~~~~).~~ In contrast~~Consistently~~, the standard deviation varied considerably between years, reaching a peak in 2020 of 5.83 × 10^{15} molecules cm^{-2} ~~.~~ following by 2016 with 5.26 × 10^{15} molecules cm^{-2} and 2023 with 2.88 × 10^{15} molecules cm^{-2}.

The spatial distribution of NH_3~~,~~ exhibited a consistent area-wide pattern characterized by elevated values in specific areas, and the corresponding annual anomalies relative to the long-term (Fig. S2). Frequently~~Persistent~~ hotspots are observed in the northern (Petén), north-central (Quiché, Alta Verapaz, and Izabal), and along the southern coastal department of Escuintla. Conversely, lower annual mean NH_3 dominate in the central midlands, including the departments of Totonicapán, Sololá, Chimaltenango, Sacatepéquez, Guatemala, Jalapa, and Jutiapa. Interannual variability in hotspot intensity is evident, with particularly high values over Petén, Alta Verapaz and Quiché in 2016 and more widespread increase~~ds~~ NH_3 across Petén, Quiché, Alta Verapaz, Izabal and Escuintla in 2020. Notably, 2018 presented ~~even in years with~~ lower annual mean~~s such as 2018, increased~~ NH_3 across Guatemala, however, the main spatial distribution of the main hotspots ~~total column~~ were still evident ~~in~~ (Petén, Alta Verapaz, Izabal and Escuintla) showing frequent spatial patterns despite lower annual columns values.

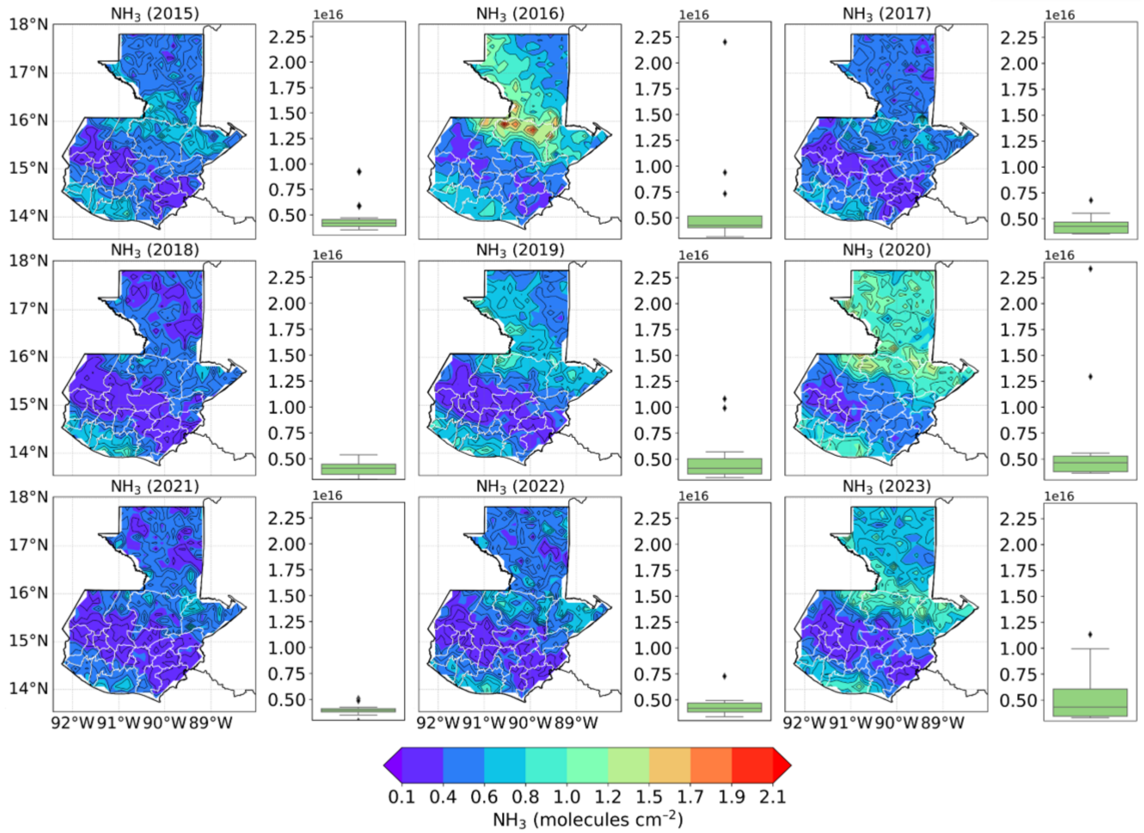


Figure 2: Annual means area-wide and boxplot distribution of monthly NH_3 total columns within each year ($\times 10^{16}$ molecules cm^{-2}) over Guatemala (2015–2023) from concatenated IASI A, B and C.

The monthly climatology variability of NH_3 total columns is illustrated by boxplots in Fig. 3, showing a distinct seasonal pattern. Monthly medians were lowest in winter,~~A~~ ~~remained relatively~~reaching a minimum in February (~~low from January to March ranging from~~ 3.52×10^{15} molecules cm^{-2}~~-~~) while January and March also exhibited relative low median values (4.25×10^{15} molecules cm^{-2} and 4.00×10^{15} molecules cm^{-2}), before increasing in ~~minimum of 2.90 × 10^15 molecules cm^-2 observed in March. A substantial increase occurred in~~ the month of April~~, with a median of~~ with 7.34×10^{15} molecules cm^{-2}, ~~followed~~ and remaining elevated ~~by~~in May~~ with a median of~~ with 7.27×10^{15} molecules cm^{-2} (Table S2). These months exhibit the largest standard deviation, that shows greatest variability with high NH_3~~, reflected by a prominent outlier~~. The values started decreasing thereafter in the month of June with a median of 4.83×10^{15} molecules cm^{-2}. From July through December, the median stabilizes, ranging between 3.58×10^{15} molecules cm^{-2} (August) to 4.18×10^{15} molecules cm^{-2} (November).

The spatial distribution of monthly climatology mean NH_3 displays the distinct seasonal pattern across Guatemala. From January to March, NH_3 remain generally low over most of the country, with only limited area exhibiting elevated columns

(Escuintla). A substantial increase in both the total column values and spatial coverage of NH_3 is observed in April, with widespread elevated areas particularly in the northern (Petén), north-central (Quiché, Alta Verapaz, and Izabal), and southern coastal area (Retalhuleu, Suchitepéquez, and Escuintla). Specific defined areas with highest values primarily in the departments of Quiché, Alta Verapaz and Escuintla is observed in the month of May. Subsequently, a sharp decline in NH_3 is evident across the country from June through December. During these months, the spatial distribution of NH_3 is characterized by few hotspots and generally uniform low values in the central midlands (Totonicapán, Sololá, Chimaltenango, Sacatepéquez, Guatemala, Jalapa, and Jutiapa).

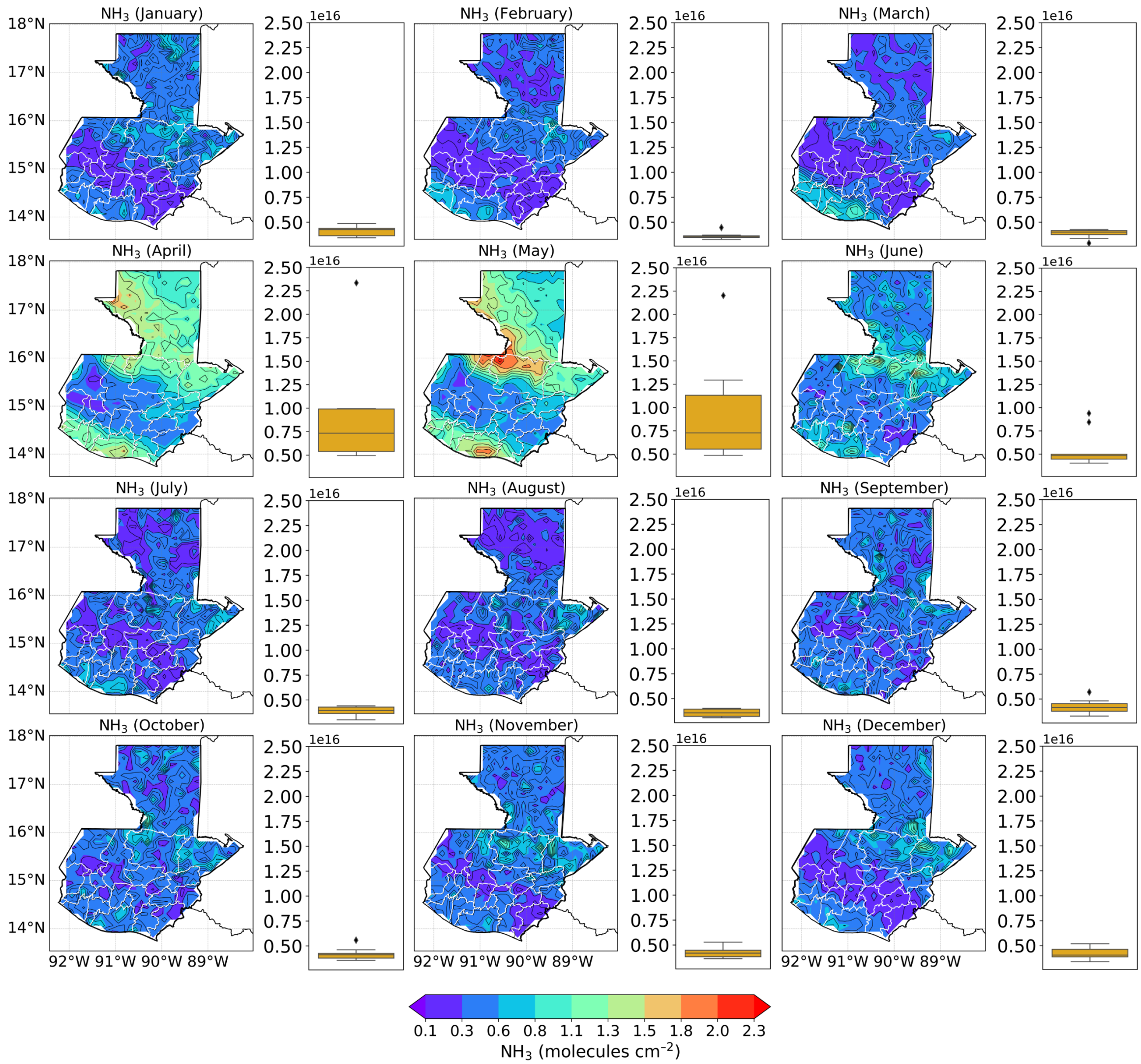


Figure 3: Monthly climatology area-wide and boxplot distribution of NH_3 total column for each calendar month ($\times 10^{16}$ molecules cm^{-2}) over Guatemala (2015–2023) from concatenated IASI A, B and C.

3.2 ~~L~~Spatial ~~and cover classification driven by~~ NH_3 and associated ~~cluster k-means~~land cover

The spatial distribution of NH_3 in Guatemala, based on the overall ~~annual~~ mean for the period 2015–2023, reveals several ~~six~~ distinct hotspots areas, most notably in the southern coast ~~area 1~~ (Escuintla), central-northern~~2~~ (Alta Verapaz and Quiché and Izabal), and northern (Petén) ~~and Izabal), 3 (Alta Verapaz), 4 (Quiché and Alta Verapaz), 5 (Southwest of Petén) and 6 (Northwestern Petén)~~ (Fig. 4a). Among these, the most prominent hotspot is observed in the central-northern area~~area 4~~, which exhibits the highest ~~annual~~ mean ~~of~~ NH_3 total column during the study period.

The k-means clustering partitions the country into three emission zones (Fig. 4b), each with distinct land cover profiles when integrated with ESRI data (Fig. 4c). Cluster 1 with smallest area (~28,254 km^2) (red) associated to the highest NH_3, is located in the northern (Petén), central-north (Quiché, Alta Verapaz, Izabal), and southern regions (Escuintla, Suchitepéquez, Retalhuleu and San Marcos) is dominated by extensive tree cover (53.2%; 15,024.6 km^2), together with rangeland (24.5%; 6934.2 km^2) and cropland (16.7%; 4710.8 km^2) ~~and rangeland (24.5%; 6934.2 km^2)~~, ~~. Tree cover remains extensive (53.2%; 15,024.6 km^2),~~ while built-up areas are limited to ~~(~~3.4%~~;~~ (948.6 km^2) as shown in Fig. 4d. The complete land cover distribution across clusters is provided in Table 1.

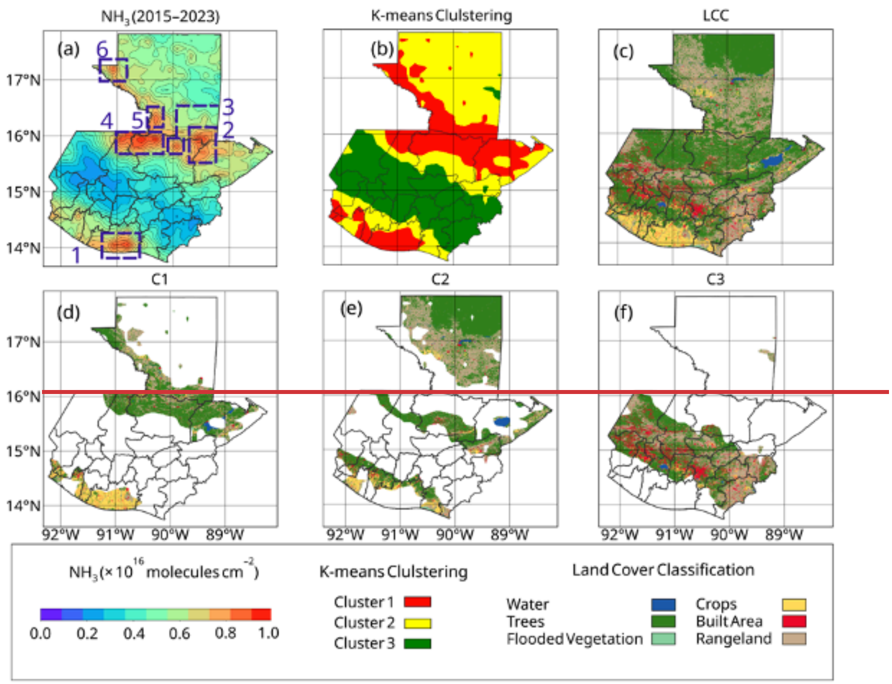
Cluster 2 with a largest extend area around 45,662 km^2 (yellow) represents moderate zones forming a transition around Cluster 1 and extending into northern (Petén), ~~central~~ north-central (Huehuetenango, Quiché, Alta Verapaz, Santa Rosa, Izabal), and south (Quetzaltenango, Escuintla, Suchitepéquez, Retalhuleu, Santa Rosa, Jutiapa and San Marcos) (Fig. 4e). It is dominated by tree cover (58.9%; 26,891.6 km^2) and rangeland (30.3%; 13,844.6 km^2), with a comparatively small share of cropland (6.0%; 2724.7 km^2). Built-up areas account for 2.8% (1261.8 km^2), slightly larger in absolute terms than in Cluster 1.

The intermediate extent area Cluster 3 with ~34,640 km^2 (green), associated with the lowest NH_3, covers the central region with departments of Huehuetenango, San Marcos, Totonicapán, Sololá, Chimaltenango, Sacatepéquez, Guatemala, El Progreso, Jalapa, Chiquimula and Jutiapa. This cluster is characterized by high rangeland cover (34.3%; 11,893.3 km^2) and substantial tree cover (47.1%; 16,298.9 km^2), while cropland is minimal (3.1%; 1088.6 km^2) (Fig. 4f). Notably, built-up areas occupy the largest proportion across clusters (14.8%; 5137.1 km^2).

Table 1: Land cover composition of percentage and area for the different cluster in Guatemala.

	Cluster 1		**Cluster 2**		**Cluster 3**	
LCC	**Percentage %**	**Area km^2**	**Percentage %**	**Area km^2**	**Percentage %**	**Area km^2**
Water	1.94	548.97	1.78	812.44	0.64	221.61
Trees	53.16	15,024.57	58.89	26,891.61	47.05	16,298.85

Flooded Veg.	0.31	86.77	0.28	127.16	0	0.63
Crops	16.67	4710.8	5.97	2724.67	3.14	1088.56
Built Areas	3.36	948.62	2.76	1261.81	14.83	5137.06
Rangeland	24.53	6934.19	30.32	13,844.63	34.33	11,893.31



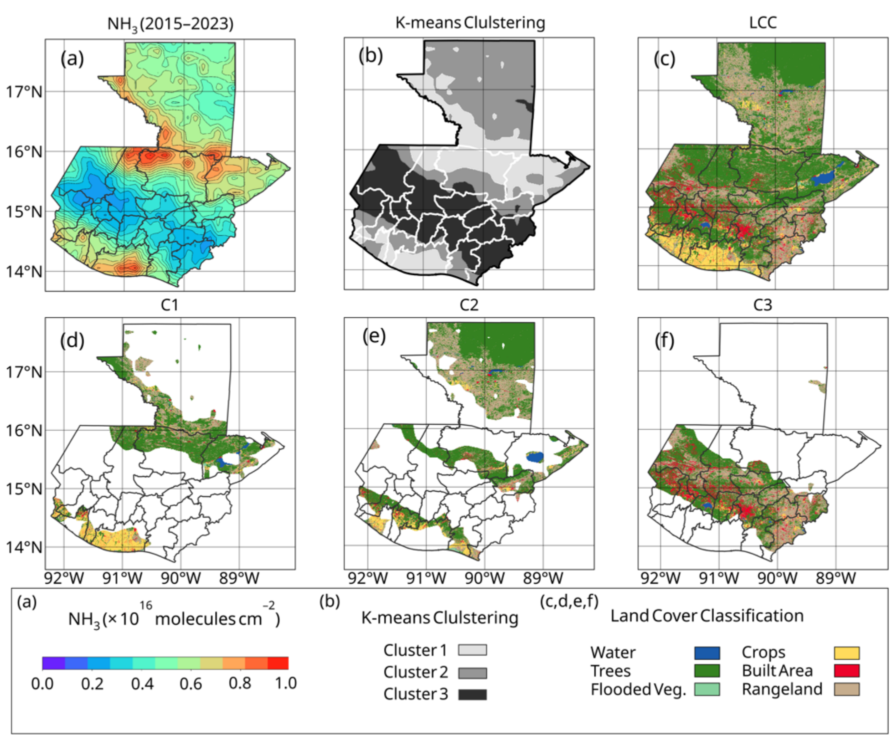


Figure 4: (a) Concatenated NH_3 total column (× 10^{16} molecules cm^{-2}) (2015–2023), (b) k-means cluster analysis with Cluster 1 (black~~red~~ color), Cluster 2 (gray~~yellow~~ color) and Cluster 3 (light gray~~green~~ color). (c) ESRI Land Use Land Cover across

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.

3.3 ~~Fires~~Meteorology

Figure 5 illustrates the annual variability and monthly climatology of meteorological variables over Guatemala derived from ~~monthly scales over Guatemala from~~ ERA5 reanalysis. Fig. 5 (a,c), exhibits the BLH and precipitation, respectively. The BLH shows fluctuations with the highest median recorded in 2019 (524 m).~~,~~ ~~in~~ contrasted ~~to~~by the lowest median observed in 2017 (415 m) which also ~~demonstrated~~recorded the minimum value (305 m) (Table S6). Although the annual medians varied moderately, the ~~highest~~peak monthly BLH values detected during 2020 (791 m) indicate~~d a large~~ high intra annual variability during that year. At the monthly scale, April shows the highest BLH (median 671 m), while~~and~~ the lowest occurred ~~during~~ in October (median 348 m). Furthermore, the distribution of the twelve-monthly total precipitation values within each year ~~indicates~~ shows that the median monthly precipitation was highest ~~were~~ in 2020 (164 mm) and 2022 (142 mm), while the lowest median monthly occurred in 2019 (89 mm). The maximum monthly precipitation values exceeded 840 mm in 2017, 2021, and 2022, reaching an overall maximum of~~inged~~ 1283 mm in 2022. The monthly climatology~~yical~~ indicates that precipitation increased rapidly from~~the month of~~ May onward, with median monthly precipitation increasing from 49 mm in April to 135 mm in May, peaking in ~~the month of~~ June (269 mm), before remained~~ing~~ elevated through October.~~,~~ Subsequently,~~and then~~ precipitation declined~~ing~~ during the dry season, with the lowest median climatological precipitation occurred in ~~during the month of~~ February (28 mm).

Fig. 5 (b,e) presents the air temperature and relative humidity. The ~~warmest~~highest annual median temperature occurred during the ~~year~~ 2023 (22.8°C), whereas the maximum ~~temperature~~ was detected in~~during~~ 2020 (27.9°C). The ~~coldest~~lowest temperature was recorded in~~during~~ 2018 at~~with~~ 20.2°C. Additionally, the warmest month is May (median 26.4°C) and the coldest is January (21.9°C). Relative humidity showed the highest annual median ~~observed during~~in 2016 (81%), while the lowest annual median ~~year was~~occurred in 2019 (76%).~~, t~~The minimum ~~year~~value was detected~~ was~~ in 2020 with 63%, which also featured~~this also showed~~ the largest relative humidity values. The years 2017 and 2022 exhibited the maximum values with 87%. ~~The m~~Monthly medians indicated that the lowest relative humidity occurs in April (71%) and the highest in October (84%).

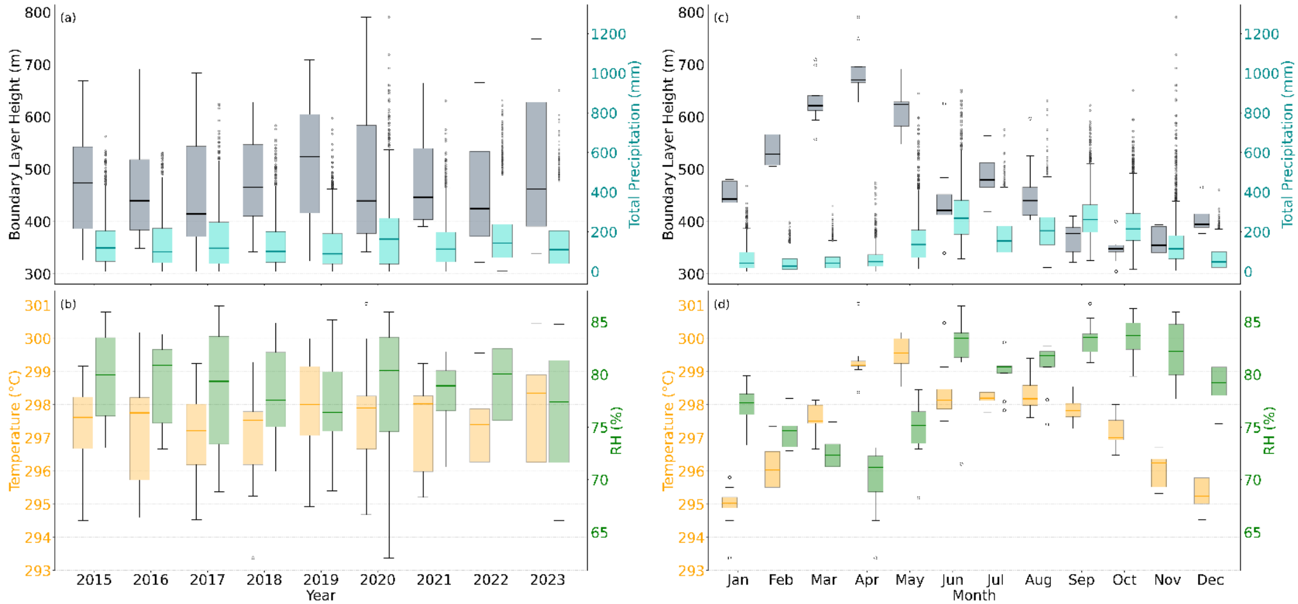
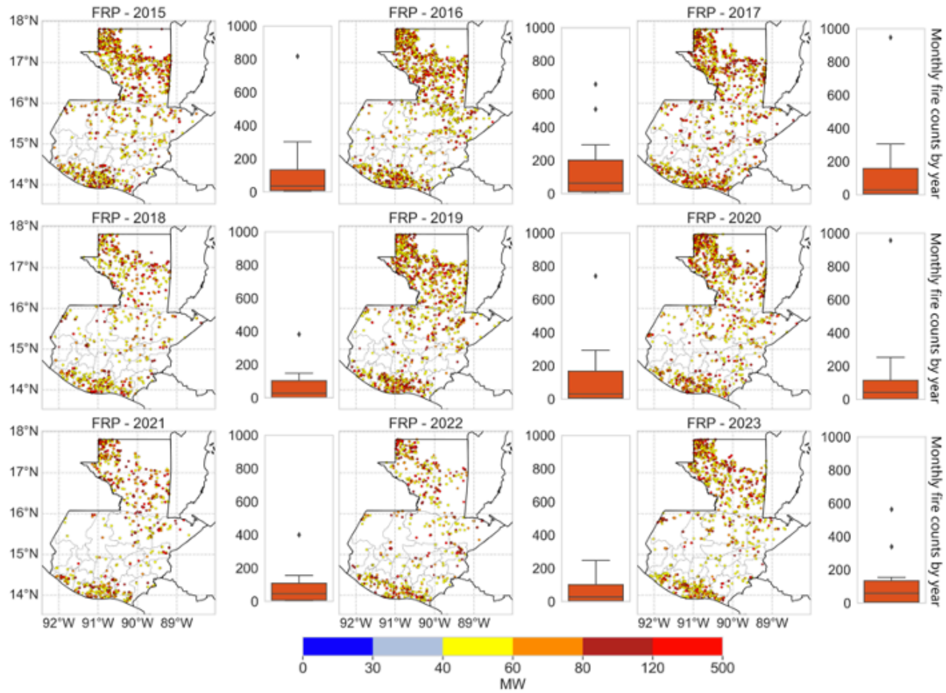


Figure 5: Annual distribution of monthly ERA5 meteorological variables and monthly climatology over Guatemala (2015–2023). Annual boxplots represent the distribution of the twelve monthly values within each year, (a) boundary layer height (m) (gray) and total precipitation (mm) (turquoise). (b) relative humidity (RH %) (green) and temperature (°C) (yellow). Monthly climatology boxplots represent the distribution of each calendar month across all study years. (c) boundary layer height (m) and total precipitation (mm). (d) temperature (°C), and relative humidity (RH, %).

~~In order to connect the previously described NH_3 patterns Fig. 5 shows the annual distribution of active fires in Guatemala during the study period. The fire activity shows a marked interannual variability. The area-wide total annual fire counts peaked in 2016 (1779 fires), and 2017 (1783), while the minimum was observed in 2022 (807) (Table S4). Fire frequency declined substantially in 2018, reflecting a reduction in both annual counts and monthly extremes. Fire activity increased again in 2019 (median 32) and in 2023 (median 58). The year 2020 is characterized by increased temporal variability, including with the highest single month fire count with 957 fires. Fire occurrences increase slightly in 2021 (median 30) and reached their lowest in 2022 (median 19), before recovering in 2023 (median 59).~~

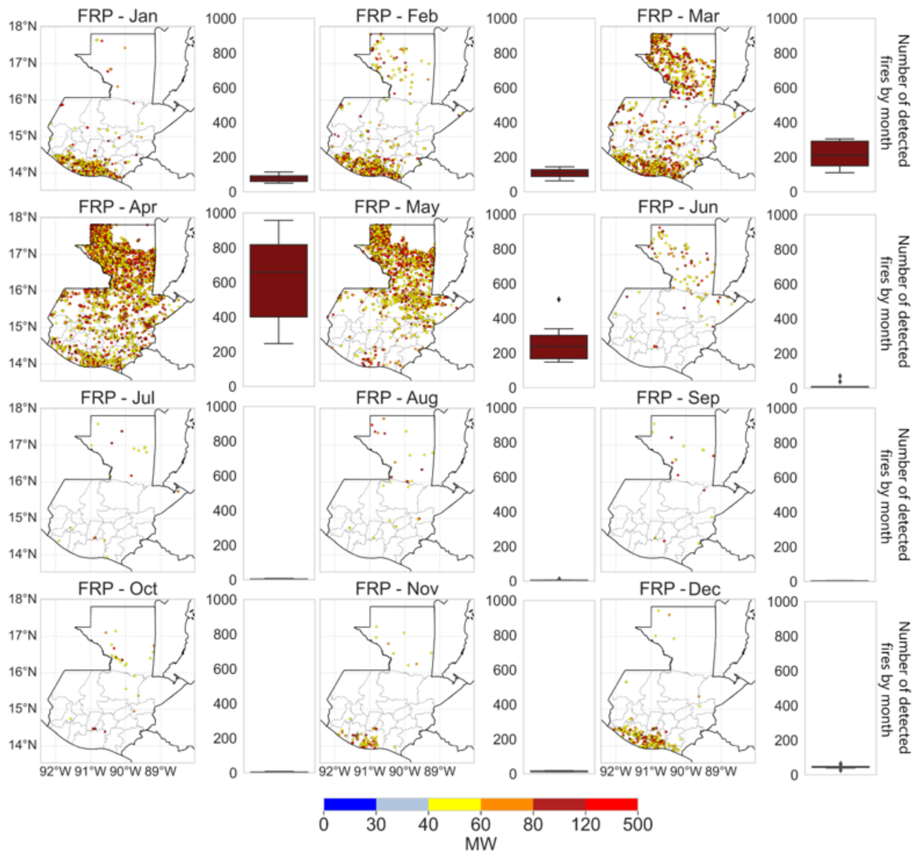
~~The spatial distribution of detected fires is consistent with the temporal variability in fire counts, showing pronounced interannual differences in both fire occurrence and spatial heterogeneity. Years with elevated fire occurrence (2016, 2017, 2019, 2020, and 2023), showed widespread spatial extents of fires detections, with recurrent hotspots concentrated primarily in the northern (Petén) and along the southern area (Escuintla, Suchitepéquez, Retalhuleu, and Santa Rosa). In contrast, years of reduced fire activity, including 2018, 2021 and 2022, showed decreased detections, and reduce spatial confined distribution of fires.~~



~~**Figure 5: Annual distribution of monthly fire counts over Guatemala (2015–2023), MODIS fire detection filtered by nominal confidence level ≥70% and FRP ≥40 MW, the boxplots represent the area-wide monthly fire count for each year.**~~

~~The monthly climatology of fire activity in Guatemala (Fig. 6). The boxplots show a clear seasonal pattern in detected fires. Fire activity is relatively low at the starting of the year, with median of 78 in January, and 105 in February (Table S5). A substantial rise occurs in March (median 211), while April marks the peak with a maximum of 957. Consequently, the month of May demonstrated a decrease of number of fires (median 238). Moreover, an observed sharply declining in June (median 15), and the lowest fire activity occurs in September (median 3). Finally, slight increase is observed at the end of the year in December (median of 46).~~

~~The spatial distribution of FRP across Guatemala also confirms this seasonal pattern and shows the shifts in fire location and intensity. During the early months of the year, fire activity is concentrated mainly along the southern areas (Escuintla, Suchitepéquez, Retalhuleu, and Santa Rosa). As the fire season advances, the activity shifts northward with central-north (Huehuetenango, Quiché, Alta Verapaz, Santa Rosa, Izabal), and northern (Petén). In November and December, the fire remerged in the southern coast (Escuintla, Suchitepéquez, and Retalhuleu).~~



~~**Figure 6: Monthly climatology of detected fires over Guatemala (2015–2023), MODIS fire detection filtered by nominal confidence level ≥70% and FRP ≥40 MW, the boxplots represent the area-wide distribution of number of detected fires for each month across all years.**~~

3.4 ~~Meteorology~~Fires activity and biomass burning patterns

In order to connect the previously described NH_3 patterns with biomass-burning, Fig. 6~~5~~ combines~~ shows~~ the annual spatial distribution of MODIS active fires detection with the distribution of monthly fire counts in Guatemala during the study period. The fire activity ~~shows~~reveals a marked interannual variability. The highest monthly fire count occurred in 2023 (median 59), followed by 2016 (median 50), where the lowest was observed in 2022 (median 19), (Table S4). Fire activity was also relatively low in 2018 (median 28) and 2021 (median 30.5) respectively. Although 2020 had a relatively low median monthly fire count (median 26) it exhibited the largest monthly variability (standard deviation 272) and included the highest monthly fire count during the study period (957). In contrast 2016 and 2017 showed the highest total annual fire counts (1779, 1783), while 2022 had the lowest total (807).

~~The area-wide total annual fire counts peaked in 2016 (1779 fires), and 2017 (1783), while the minimum was observed in 2022 (807) (Table S4). Fire frequency declined substantially in 2018, reflecting a reduction in both annual counts and monthly extremes. Fire activity increased again in 2019 (median 32) and in 2023 (median 58). The year 2020 is characterized by increased temporal variability, including with the highest single month fire count with 957 fires. Fire occurrences increase slightly in 2021 (median 30) and reached their lowest in 2022 (median 19), before recovering in 2023 (median 59).~~

The spatial distribution of detected fires ~~is~~ corresponds~~nsistent~~ with the temporal variability in fire counts, showing pronounced interannual differences in both fire occurrence and spatial heterogeneity. Years with elevated fire occurrence (2016, 2017, 2019, 2020, and 2023), showed widespread spatial extents of fire~~s~~ detections, with recurrent hotspots concentrated primarily in the northern (Petén) and along the southern area (Escuintla, Suchitepéquez, Retalhuleu, and Santa Rosa). In contrast, years of reduced fire activity, including 2018, 2021 and 2022, showed decreased detections, and reduce spatial confined distribution of fires.

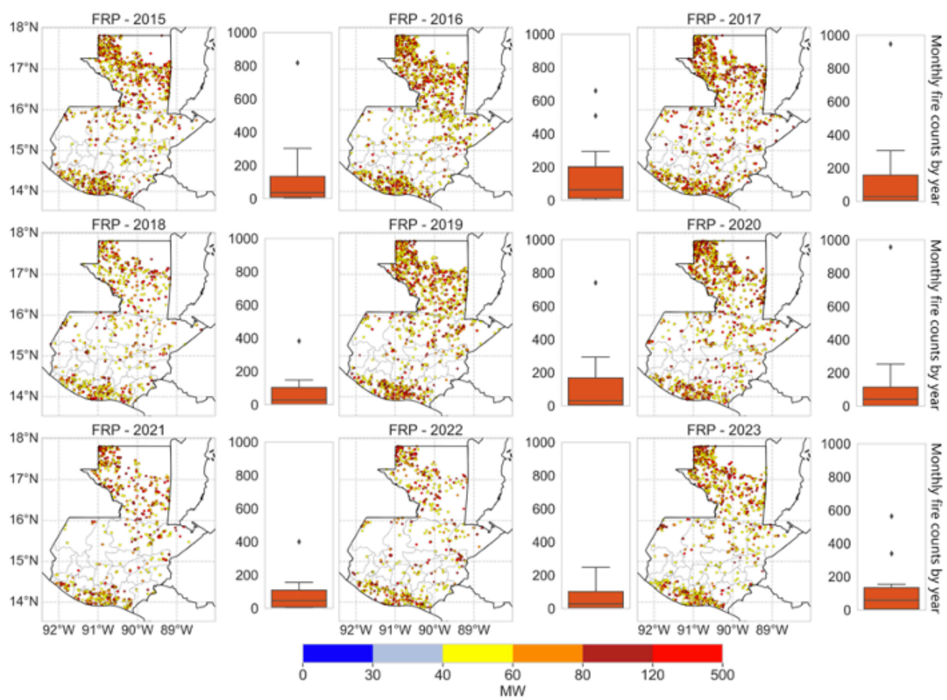


Figure 6~~5~~: Annual spatial distribution of MODIS active-fire detection and distribution of monthly fire counts over Guatemala (2015–2023), Maps show detected~~ODIS~~ fire locations colored according to FRP (MW),~~detection~~ filtered by nominal confidence level ≥70% and FRP ≥40 MW, the boxplots represent the distribution area-wide of monthly fire count within~~for~~ each year.

The monthly climatology of fire activity in Guatemala is illustrated in ~~(~~Fig. 7~~6~~~~)~~. The boxplots show a clear seasonal pattern in detected fires. Fire activity is relatively low at the ~~startingstart~~ beginning of the year, with a median of 78 in January, and 105 in February (Table S5). A substantial rise occurs in March (median 211), while April exhibited the highest fire activity (median 659) detected fires and~~marks the peak with~~ a maximum of 957. Consequently, the month of May demonstrated a decrease of ~~number~~in the number of fires (median 238). Moreover, an observed ~~sharply declining~~sharp decline in June (median 15), and the lowest fire activity occurs in September (median 3). Finally, slight increase is observed at the end of the year in December (median ~~of~~ 46).

The spatial distribution of FRP across Guatemala also confirms this seasonal pattern and shows the shifts in fire location and intensity. During the early months of the year, fire activity is concentrated mainly along the southern areas (Escuintla, Suchitepéquez, Retalhuleu, and Santa Rosa). As the fire season advances, the activity shifts northward with central-north (Huehuetenango, Quiché, Alta Verapaz, Santa Rosa, Izabal), and northern (Petén). In November and December, the fire remerged in the southern coast (Escuintla, Suchitepéquez, and Retalhuleu).

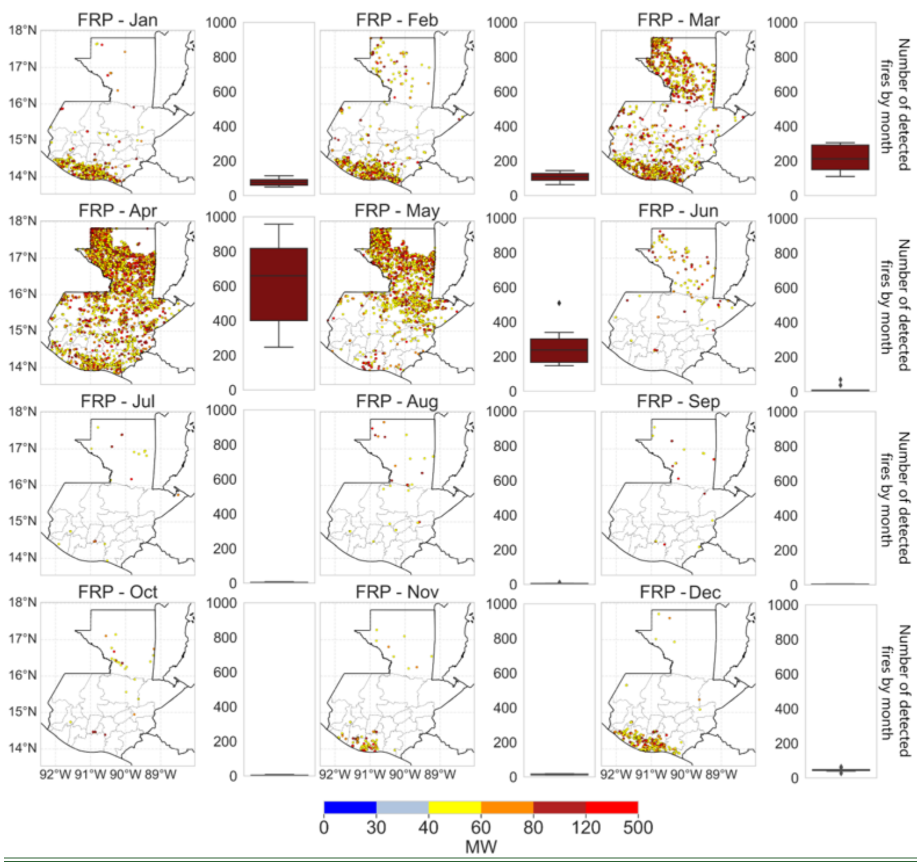
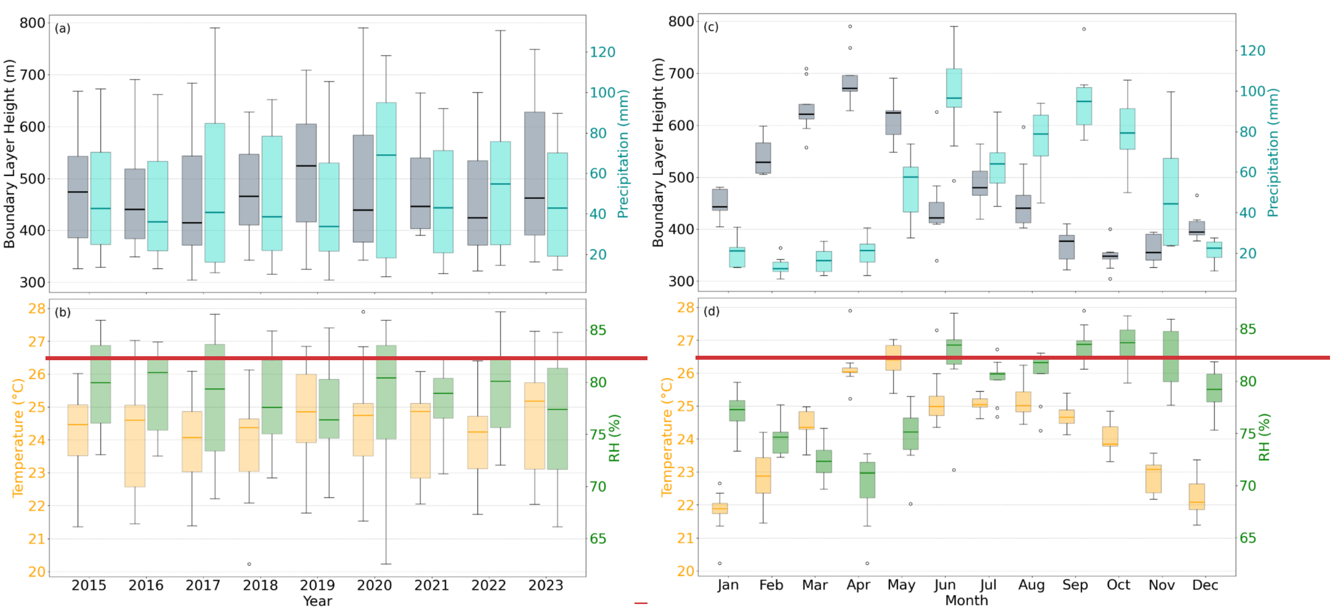


Figure 7~~6~~: Monthly climatology of MODIS active-fire detection and distribution of~~ed~~ fires count over Guatemala (2015–2023). Maps show~~ODIS~~ detected fire location for each calendar month, colored according to FRP (MW), fire detection were~~detection~~ filtered by nominal confidence level >70% and FRP >40 MW, the boxplots represent the distribution area-wide ~~distribution~~ of fire counts ~~number of detected fires~~ for each calendar month across all years.

~~Figure 7 illustrates the annual variability and monthly climatology of meteorological variables derived from monthly scales over Guatemala from ERA5 reanalysis. Fig. 7 (a,c), exhibit the BLH and precipitation. The BLH shows fluctuations with the highest median recorded in 2019 (524 m), in contrast to the lowest median observed in 2017 (415 m) which also demonstrated the minimum value (305 m) (Table S6). Although the annual medians varied moderately, the highest monthly BLH values The maximum vertical value was detected during 2020 (791 m) indicated a large intra annual variability during that yeardata range. At the monthly scale, April shows the highest BLH (median 671 m) and lowest during October (median 348 m). Furthermore, the distribution of monthly total precipitation indicates that the annual distribution of monthly totals presents tthe highest annual median values recorded in 2020 (68.99 mm) and 2022 (54.85 mm), while the lowest median is observed in 2019 (33.84 mm). which also shows the minimum value (7.5 mm). The maximum monthly precipitation values exceedsexceeded 130 mm (2017 and 2022). The monthly climatology presents peaks medians precipitation in the month of May onward, reaching median values in the month of June (96.47 mm), and September (94.75 mm) before declining during the dry season, whitle the minimum median occurring during the monthlowest ofin February (13 mm).~~

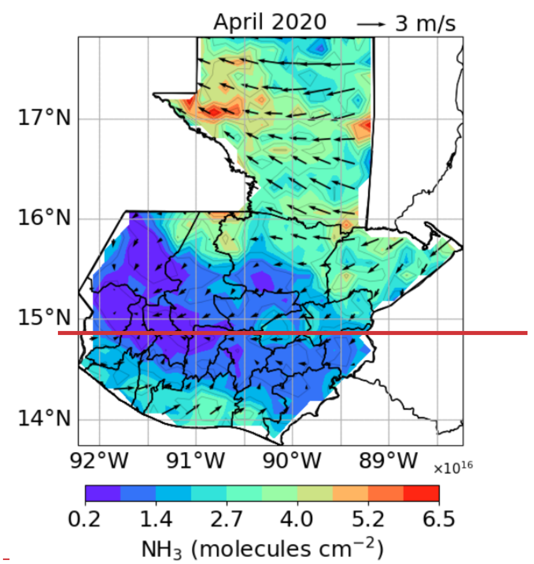
~~Fig. 7(b,e) presents the air temperature and relative humidity. The warmest median temperature during the year 2023 (22.8°C), whereas the maximum temperature was detected during 2020 (27.9°C). The coldest temperature was recorded during 2018 with 20.2°C. Additional, the warmest month is May (median 26.4°C) and the coldest is January (21.9°C). Relative humidity showed the highest median observed during 2016 (81%), while the lowest median year was 2019 (76%), the minimum year detected was 2020 with 63%, this also showed the largest vertical values. The years 2017 and 2022 exhibit the maximum values with 87%. The month medians indicate the lowest in April (mean 71%) and the highest in October (mean 84%).~~



~~**Figure 7: Boxplot distribution of meteorological variables over Guatemala (2015–2023) from ERA5 reanalysis, (a, c) show boundary layer height (m) (gray) and monthly total precipitation (mm) (turquoise), (b, d) relative humidity (RH %) (green) and temperature (°C) (yellow).**~~

~~3.5 Case Study of NH_3~~

~~NH_3 anomalies were observed in Guatemala in April 2020, marking the highest recorded monthly mean (Fig. S4). This peak is particularly remarkable as it occurred shortly after the implementation of COVID-19 lockdown measures (March 2020). The monthly mean spatial distribution of concatenated NH_3 in April 2020 (2.3×10^{16} molecules cm^{-2}), indicates distinct hotspots concentrated in the northern (Petén), north-central (Quiché) and southern (Escuintla) areas. The highest values were observed in the department of Petén, reaching up to (6.4×10^{16} molecules cm^{-2}) (Fig. 8). The corresponding environmental conditions, including wind vectors meter per second (m s^{-1}), with a strong easterly wind (~3 m s^{-1}) dominated the northern region, facilitating long-range transport of NH_3, while central Guatemala experienced moderate to stagnant wind conditions.~~

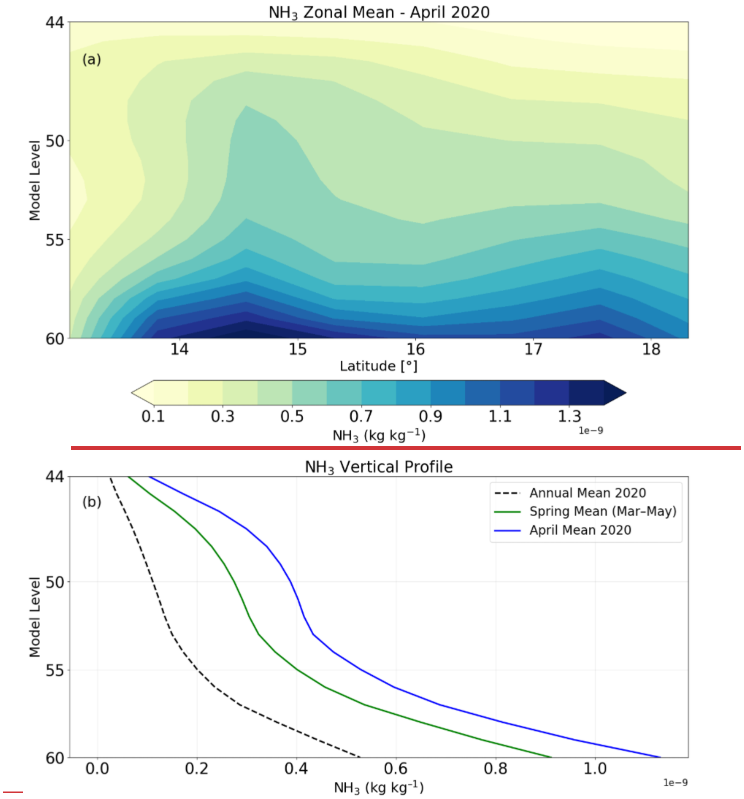


~~**Figure 8: Monthly mean area-wide of NH_3 total column ($\times 10^{16}$ molecules cm^{-2}) from the concatenated IASI A, B and C, and wind mean vectors from ERA5 over Guatemala (April 2020).**~~

~~Figure 9a shows the vertical and latitudinal distribution of atmospheric NH_3 over Guatemala using zonal means and area averaged vertical profiles in mass mixing ratios (kg kg^{-1}). The zonal mean cross-section of NH_3 throughout the atmosphere (vertical axis, model level 60 to 44) along the latitudes of Guatemala as a zonal mean during April 2020. It highlights a greater abundance of NH_3 in both the northern and southern areas. Furthermore, the NH_3 vary with both latitude and altitude, the~~

~~highest NH_3 are observed at lower model levels primarily confined near the surface (below approximately level 56). The highest NH_3 values are found between 14°N and 15°N latitude.~~

~~Fig. 9b further illustrates the area average vertical profiles of NH_3 for April (blue line), spring (March – May, green line) and the annual mean 2020 (black dashed line). The vertical profile of NH_3 shows the April 2020 mean (blue line) with ~1.0×10^{-9} kg kg^{-1}, the spring mean (March–May 2020, green line) of ~0.9×10^{-9} kg kg^{-1} and the annual mean for 2020 (black dashed line) with ~0.5×10^{-9} kg kg^{-1} respectively.~~

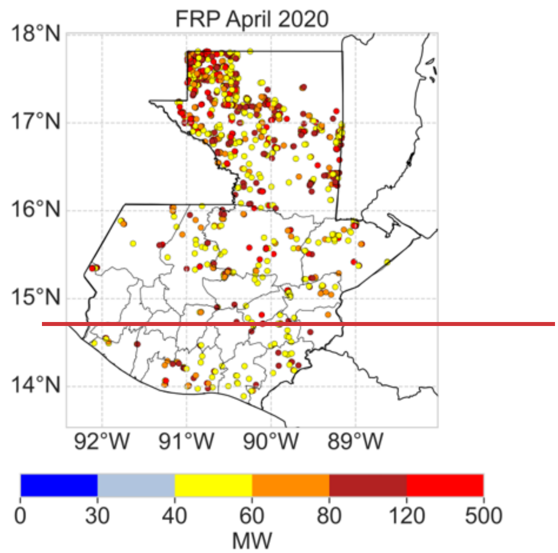


~~**Figure 9: (a) zonal mean of NH_3 mass mix ratio (kg kg^{-1}) across latitudinal bands (model level 60 to 44) for April 2020 and (b) vertical profile of NH_3 mass mix ratio (kg kg^{-1}) for April (blue line), spring (March – May, green line) and annual mean 2020 (black dashed line) over Guatemala from global reanalysis CAMS.**~~

~~3.6 Fire activity April 2020~~

~~Fire activity in spring 2020 showed an anomalous peak compared to the long-term pattern (Fig. 10, S5). As mentioned above, March to May indicate a general increase phase in fire activities in Guatemala. April 2020 recorded the highest monthly total number of detected fires across Guatemala throughout the entire study period (957). The spatial distribution of FRP distribution~~

~~illustrates widespread fire activity, affecting specifically in the northern Guatemalawestern (Petén) accounting for 674 detected fires (Table S7, Fig.S67), central-north (Quiché, Alta Verapaz, and Izabal), and southern areas (Escuintla, Santa Rosa, and Jutiapa). The corresponding burned areas patterns further confirm the extension of the fire's activityies during thise month, with the most extensive land burned occurred in the department of Petén.~~



~~**Figure 10: April 2020 shows the spatial distribution of area-wide of fires detected over the study period over Guatemala (2015–2023), using MODIS fire detection filtered by nominal confidence level ≥70% and FRP ≥40 MW.**~~

4 Discussion

4.1 Persistent agricultural sources of~~Dynamies of~~ NH_3 background~~over Guatemala~~

The variability of NH_3 total columns over Guatemala~~ is a~~ reflects~~sult of~~ the interaction between ~~frequently~~persistent~~persistent~~ agricultural sources, and episodic biomass burning~~, and meteorological modulation~~. Although annual median~~s~~ of NH_3 are relatively ~~stable~~ stable throughout the study period (3.95–4.66 × 10^{15} molecules cm^{-2}, Table S1), interannual differences were associated with~~variability~~ increases in ~~is driven primarily by changes in~~ maximum values and standard deviations in ~~high maximum values and the increase of variability over~~ some specific years (2016, 2019, 2020, and 2023) indicating that episodic events were superimposed on a relatively stable background. Across the study period (9 years) annual median of NH_3~~,~~ varied about 18% where the maximum values and standard deviations increased markedly during nine years with increased fire activity. This ~~indicating~~indicates that episodic ~~events were~~events primarily affected the magnitude and variability of NH_3 rather than its background ~~superimposed on relatively processes occur on top of a stable background~~values. These observations suggest thate persistent~~ce~~ agricultural activities likely maintain the regional NH_3 background, ~~of annual median values together with the recurring spatial hotspots identified in the predominantly agricultural areas suggests that NH_3 background is~~

~~maintained by continuous agricultural activities,~~ whereas biomass burning primarily contributes to short term enhancements specifically during the dry season. ~~This interpretation is further supported by the land cover analysis, which shows that cluster 1 with the highest NH_3 is associated mainly with cropland and rangeland areas, despite the presence of substantial tree cover. This stability suggests that background NH_3 values are largely controlled by persistent agricultural sources, consistent with previous studies showing that agricultural practices dominate global NH_3 emissions .~~

The spatial ~~distribution~~patterns further ~~support~~supports this interpretation.~~,ly~~ ~~i~~Increased NH_3 columns were~~are~~ consistently observed in the departments of Petén, Alta Verapaz, Quiche, Izabal and Escuintla during the study period ~~departments~~, ~~which are dominated by mixed agricultural landscapes (crops and rangeland). These hotspots persisted throughout the study period,~~ including years with relatively low annual ~~of~~ NH_3, suggesting the presence of continuous NH_3 sources rather than isolated episodic events. Land cover analysis indicates that cluster 1, which contains the highest NH_3 columns, is characterized by a greater proportion of cropland (16.7%) while tree cover remains extensive across all clusters. Although rangeland is also abundant, its relatively high proportion in ~~the low NH_3~~ cluster 3 (low NH_3-) suggests that rangeland alone cannot explain the observed NH_3 distribution.~~,~~ ~~I~~Instead, the larger cropland area in cluster 1 suggests a stronger contribution of agricultural activities to elevated NH_3 total column. The seasonal timing of these persistent hotspots is also consistent with agricultural practices in Guatemala, where land preparation, shifting cultivation, and biomass burning for crops are concentrated during the dry season (Liu et al., 2024b; Monzón-Alvarado et al., 2012; Ríos and Raga, 2018). These findings ~~-~~are consistent with previous studies showing that agricultural practices dominate global source of atmospheric NH_3 (McDuffie et al., 2020; Sutton et al., 2013), and with satellite observations from South Asia (Abeed et al., 2022), and Western Europe (Van Damme et al., 2018). Furthermore, cluster 1 ~~represents~~has the smallest spatial extent but ~~with~~ the highest NH_3 values, ~~indica~~demonstrating that ~~the~~ NH_3 is more strongly associated with localized agricultural land use than ~~with~~ the total area occupied. In ~~the~~ contrast, the central highlands exhibit ~~a~~ low NH_3 despite the presence of urban areas (Huehuetenango, Quiché, San Marcos, Sololá, Guatemala, Fig. 4), suggesting that urban emissions play a secondary role at the national scale. ~~Comparable patterns have been reported in other agricultural regions, including South Asia . Cluster analysis also supports the patterns by identifying the highest columns that are associated with intensive crop areas. Notable, the cluster 1 with the highest NH_3 represents the smallest spatial extent, indicating that the total column intensity rather than area coverage. In contrast, the central highlands exhibit lower NH_3 columns despite the presence of urban areas (Huehuetenango, Quiché, and San Marcos. Fig. 4) suggesting that urban areas could play a secondary role on the national scale.~~

While persistent agricultural activities appear to maintain the NH_3 background, the pronounced seasonal cycle demonstrates that additional processes regulate~~s~~ the short-term variability. Monthly ~~A pronounced seasonal cycle demonstrates the role of atmospheric conditions in modulating both the NH_3 and the removal process. The increase in~~ NH_3 levels reached their~~its~~ highest values during the months of March–April–May (MAM, mean 7.49×10^{15} molecules cm^{-2})~~,~~ which coincides with the regional fire season (mean total fire count 3321), and also increases the variability where events of high columns of NH_3

appeared. This seasonal increase ~~indicates~~points to ~~that~~ episodic biomass burning and meteorological conditions that modulate NH_3 above persistent agricultural background.~~Additionally, the positive moderate association between temperature (r=0.50, Fig. 11S5) suggests that higher temperatures enhance volatilization.~~

~~The decline of NH_3 from June onwards defines a transition dominated by the atmospheric removal process where the monthly means NH_3 decreased by 42% between May and June (Table S2). This coincides with the rainy season (Fig. S4), when fire activity reduces, and wet deposition becomes more effective, as reported for Central America by~~ 4.2 ~~Fires, B~~Biomass burning, and ~~extreme events~~meteorological controls on seasonal and interannual NH_3 variability ~~over Guatemala~~

Although persistent agricultural activities likely maintain the background atmospheric ~~Fires represent an important driver of interannual variability in~~ NH_3 (Sect. 4.1), the seasonal and interannual variability is primarily explained by biomass burning~~over Guatemala.~~ ~~.~~ Monthly NH_3 exhibited a~~Years with enhanced fire occurrence, such as 2016, 2017, and 2019, coincide with elevated NH_3 columns. In contrast to the years with reduced fire counts 2018 and 2022 correspond to lower NH_3 levels. The~~ strong positive relationship ~~between~~ with ~~NH_3 and~~ fire activity (r=0.65, Fig. 8), with the highest values occurring during the fire season (MAM). During this period, mean NH_3 columns reached 7.49 × 10^{15} molecules cm^{-2}~~.~~, coinciding with a mean fire count of 3321. Following the onset of the wet ~~raining~~ season, fire activity declined by approximately 94% between May and June, accompanied by a 42% decrease in mean NH_3 (9.53 × 10^{15} molecules cm^{-2} to 5.56 × 10^{15} molecules cm^{-2}).~~,~~ This indicat~~ing~~es that biomass burning is the dominant driver of short-term NH_3 enhancements superimposed on the persistent agricultural background.

~~supports the role of biomass burning as a major episodic source.~~ The spatial distribution of fires further supports~~reinforces~~ this interpretation~~link~~, with recurrent fire hotspots in northern Guatemala (Petén) and the southern coast (Escuintla). Petén shows the strongest area of fire activity, including the officially designated protected areas that correspond to the large Maya Biosphere reserve (CONAP, 2016). The observed pattern of fire activity is predominantly anthropogenic. Previous studies indicate that most fires globally are human induced (FAO, 2007), and in Central America lighting occurrence is minimal during the dry season (November–April) (Kucieńska et al., 2010) when fire activity is highest. The coincidence between fire occurrence hotspot, cropland regions, and elevated NH_3 suggests that agricultural burning and land preparation practices substantially contribute to the seasonal increase~~d~~ of NH_3.

~~Interannual variability in fire activity is modulated by m~~Meteorological conditions further modulate the magnitude of biomass burning on atmospheric NH_3. Periods with increased fires activity were~~are generally~~ associated with ~~the increase~~higher ~~of~~ temperature (r=0.42) and ~~atmospheric conditions such as~~ BLH (r=0.76), indicating that warmer conditions promote both fire occurrence and vertical distribution of NH_3. Although the relationship with monthly precipitation was weak (r=–0.07), the seasonal transition to the rainy period coincided with a substantial reduction in both fire activity and atmospheric NH_3~~–~~, consistent with enhanced wet removal during the we season. Years characterized by ~~For example,~~ extreme temperature conditions (2016, 2020, 2023) from Table S6, were consistent reported by~~with~~ INSIVUMEH (2023)~~ ground observations~~. These years~~,~~ occurred during~~linked it with the~~ the episode of El Niño Southern Oscillation (ENSO), which modulates temperature and precipitation conditions in the region of Central America (Anderson et al., 2023). Similar patterns were reported for Amazonia, where NH_3 emission from biomass burning exhibit strong spatial and temporal variability, with interannual peaks linked to severe droughts and late fire-season activity, highlighting the influence of ENSO events (Anderson et al., 2023; Whitburn et al., 2016).~~,~~ Similarly,~~and~~ in Southeast Asia, particularly Indonesia, ~~largely~~ widespread human-induced fires for land clearing burned extensive tropical forest and peatlands (Chang et al., 2021; Whitburn et al., 2016).

~~The neutral ENSO during April 2020 event provides a clear example of extreme conditions of~~ ~~NH_3~~~~, fires and meteorological conditions. That period coincides with the highest fire activity during the study period (957) (Fig. S~~~~5~~~~6), coinciding with the maximum~~ ~~NH_3~~ ~~column (2.33 × 10~~~~^{16}~~ ~~molecules cm~~~~$^{-2}$~~~~), indicating strong biomass burnings (Fig. S~~~~6~~~~7). Although 2020 recorded the highest annual median precipitation (69 mm) (Table S6), April 2020 was characterized with one of lowest monthly precipitations (9 mm) (Fig. S4), consistent with short dry conditions within the year. Elevated temperatures (27.9° C.) likely enhanced volatilization from the fire and agricultural sources, while relatively dry atmospheric conditions reduced the process of removal. Boundary layer height (791 m) also contributed to the observed values, with enhanced vertical mixing increasing the~~ ~~NH_3~~ ~~in the vertical column, the confinement to the lower troposphere was visible predominantly where the agricultural areas source was detected (Fig. 9). Despite the COVID-19 restriction,~~ ~~NH_3~~ ~~reached the highest value during this period. Similar increases in atmospheric~~ ~~NH_3~~ ~~during lockdown conditions have been reported in previous studies, attributed to the persistence of agricultural burnings (Evangeliou et al., 2025; Lovarelli et al., 2021; Viatte et al., 2021; Xu et al., 2022)~~

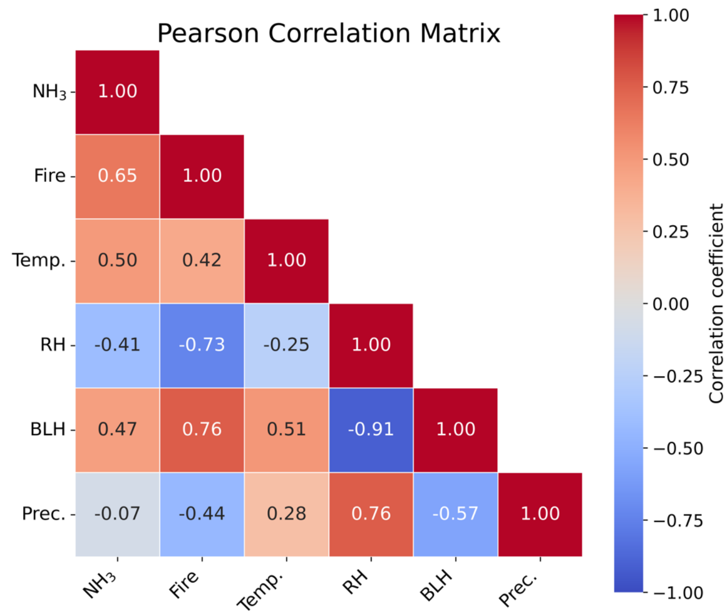


Figure 8: Pearson correlation matrix of NH_3 and meteorological variables over Guatemala (2015–2023): Fire, temperature (Temp,°C), relative humidity (RH, %), boundary layer height (BLH, m), and monthly total precipitation (Prec, mm).

4.3 April 2020 extreme episode associated with biomass burning and meteorological conditions on NH_3

The mechanisms discussed ~~previously~~above converged during April 2020, producing the most intense atmospheric NH_3 episode observed during the study period. This event ~~presents~~provides an illustrative example of how a combination of persistent agricultural activity, biomass burning, and favorable meteorological conditions~~combine to~~ can produce extreme NH_3 ~~.~~levels. This~~e~~ month recorded the highest NH_3 total column observed during the study period (2.3×10^{16} molecules cm^{-2}, Fig. 9), despite occurr~~ed~~ing shortly after the implementation of COVID-19 lockdown measures in March 2020. Similar increases in atmospheric NH_3 during lockdown conditions have been reported in previous studies, which attributed this trend to the persistence of agricultural activities and biomass burning (Evangeliou et al., 2025; Lovarelli et al., 2021; Viatte et al., 2021; Xu et al., 2022). The spatial distribution indicates distinct NH_3 hotspots concentrated in the northern (Petén), north-central (Quiché) and southern (Escuintla), with the highest values ~~were~~ observed in the department of Petén, reaching up to (6.4×10^{16} molecules cm^{-2}). Wind vectors were characterized by strong easterly winds (~3 meter per second, m s^{-1})~~,~~ that dominated the northern region, potentially facilitating the transport of NH_3, while central areas of Guatemala experienced moderate to stagnant wind conditions.

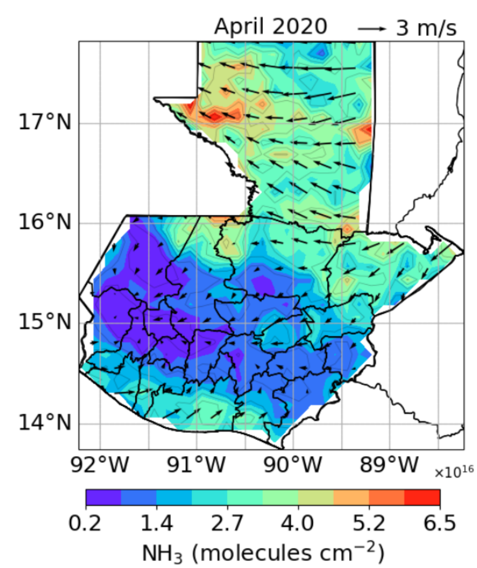


Figure 9: Monthly mean area-wide of NH_3 total column ($\times 10^{16}$ molecules cm^{-2}) from the concatenated IASI A, B and C, and wind mean vectors from ERA5 over Guatemala (April 2020).

The vertical distribution of atmospheric NH_3 further supports the interpretation that the April 2020 event was dominated by near surface NH_3 ~~with~~ as evidenced by the averaged vertical profiles of the ~~in~~ mass mixing ratios (kg kg^{-1}). The zonal cross-section of NH_3 shows the highest ~~NH_3~~ values below approximately model level 56, ~~found~~located between 14°N and 15°N latitude (Fig. 10a).~~,~~ This indicat~~ing~~es that the enhanced columns originated primarily within the lower troposphere rather than from long~~-~~-range transport. This vertical confinement is consistent with the values register from agricultural activities and biomass burning ~~that~~which remained concentrated near the surface during the event. Furthermore, the area average vertical profiles in Figure 10b~~, further illustrates the area average vertical profiles further~~ demonstrate the exceptional character of the April 2020 episode. Mean NH_3 mixing ratios (~1.0 × 10^{-9} kg kg^{-1}) exceeded both the spring average~~mean~~ (~0.9 × 10^{-9} kg kg^{-1}) and the annual 2020 mean (~0.5 × 10^{-9} kg kg^{-1}), indicating that the event represented a substantial enhancement beyond~~above~~ normal seasonal conditions rather than typical dry season variability.

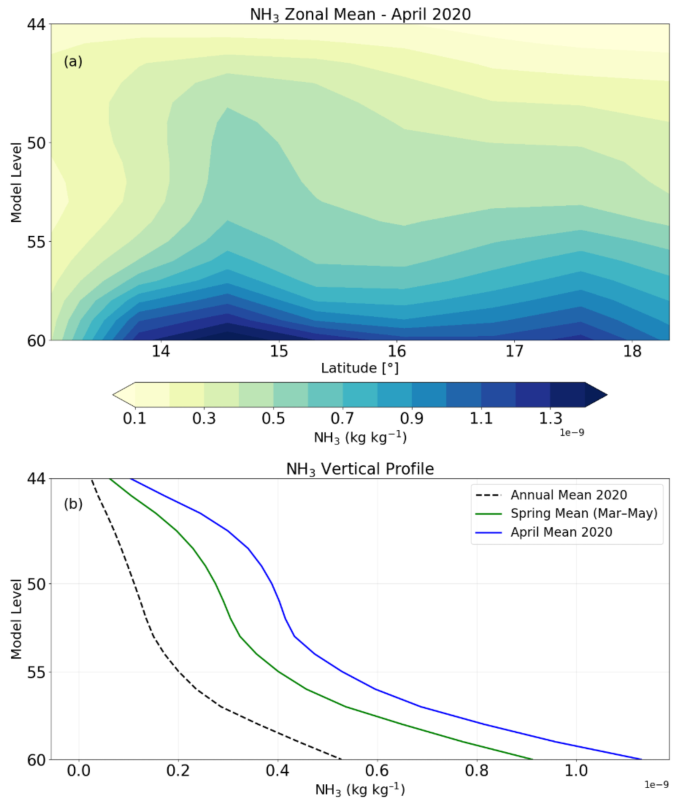


Figure 10: (a) zonal mean of NH_3 mass mix ratio (kg kg^{-1}) across latitudinal bands (model level 60 to 44) for April 2020 and (b) vertical profile of NH_3 mass mix ratio (kg kg^{-1}) for April (blue line), spring (March – May, green line) and annual mean 2020 (black dashed line) over Guatemala from global reanalysis CAMS.

The concurrent fire activity strongly supports biomass burning as the principal driver of this exceptional event. April 2020 recorded the highest monthly number of detected fires across Guatemala throughout the entire study period (957 fires;~~,~~ Fig.

11, S5). Most detections occurred in ~~the~~ northern Guatemala (Petén) accounting for 674 active fires (Table S7, Fig.S6), ~~together~~alongside ~~with~~ widespread burning across the north-central (Quiché, Alta Verapaz, and Izabal), and southern areas (Escuintla, Santa Rosa, and Jutiapa). The spatial correspondence between fire hotspots, burned areas, and NH_3 maxima provides additional evidence that biomass burning substantially amplified atmospheric NH_3 during this month.

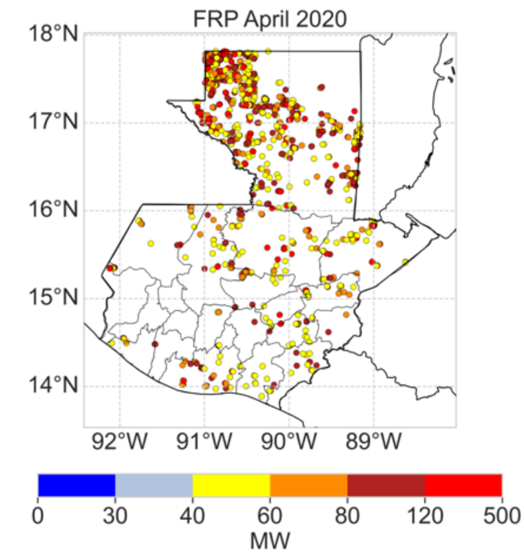


Figure 11: April 2020 shows the spatial distribution of area-wide of fires detected over the study period over Guatemala (2015–2023), using MODIS fire detection filtered by nominal confidence level ≥70% and FRP ≥40 MW.

4.4~~3~~ Robustness and ~~I~~implications of the concatenated satellite observation of ~~and consistency of dataset~~ NH_3

The ~~dataset~~ concatenated dataset ~~sensor~~ integrated ~~mplemented~~ a total of 228 months of observation data ~~over~~ across the 108 months of the study period, providing stable ~~observations~~ timeseries for analyzing NH_3 variability over Guatemala. A~~The~~ comparison during the overlapping period shows a strong correlation between sensors, with R^2 above 0.9 and regression slopes close to 1 (Fig. S7~~9~~). This indicates that the inter~~-~~sensor differences are relatively small compared to the observed variability over time. Furthermore, ~~T~~the biases represent only a small fraction of the mean NH_3 column, supporting the use of a concatenated dataset for long~~-~~term analysis. This consistency is further supported by the monthly L3 total column f~~o~~rom individual IASI sensors (Fig. S3 and Table S3), ~~this~~ align~~s~~ing with previous ~~studies~~ time~~-~~series studies for the three sensors and demonstrating robustness ~~the consistency~~ over 10 different remote regions (Clarisse et al., 2023, Van Damme et al., 2014).

The observation sampling density ~~stays~~ remains relatively stable over time, ranging from~~between~~ 1.85–2.65 obs. grid cell month^{-1} with mean annual pixel counts ~~mean (~~ between 978~~–~~ and 1492~~)~~ (Table S10). The year 2020, which exhibits the highest

NH_3 is associated with ~~the~~ a lower observation density (1.97 obs. grid cell month^{-1}), indicating that the observed maximum is not driven by ~~added more~~increased sampling effort. This is further supported by the absence of a significant relationship between sampling frequency ~~of the sampling~~ and NH_3 levels (R^2=0.028, Fig. S8), confirming that the observed variability is not an ~~object~~ artefact of ~~the~~ sampling bias. Moreover, the standard errors (Table S9) remain small relative to the magnitude of interannual variability.~~,~~ ~~that~~ This indicates that the observed differences between years exceed the measurement uncertainty and robustness of the NH_3 column patterns. On a~~The~~ seasonal scale, ~~presents~~ a clear pattern emerges:~~,~~ ~~the maximum~~peak columns coincide with ~~the period~~ months of high sampling density (MAM), while ~~the~~ lower columns during the rainy season occur under a ~~reduced observation density with~~ 17% ~~of~~ reduction in ~~oberservation~~observation density, likely due to increased cloud cover. The lower sampling density detected is located over high altitude regions such as Sierra de las Minas (Fig. S9~~10~~), ~~that~~which is associated with persistent cloud forests (Chaluleu, 2020; Holder, 2003, 2006).

Although topography varies considerably~~e~~ across Guatemala (Fig. 1), the major NH_3 hotspots are more closely associated with agricultural land use than with elevation gradients. The observed spatial distribution of NH_3 does not simply follow ~~the~~ elevation patterns. Elevated NH_3 columns are observed over low- and mid~~-dle~~ elevation ~~of~~ agricultural areas (Petén, Alta Verapaz, Quiché, Izabal and Escuintla).~~,~~ In contrast, ~~where~~ some low--elevation areas exhibit~~s~~ relatively low NH_3, despite having~~exhibiting~~ some of the highest satellite observation densities~~y~~ (Fig. S9). This pattern is consistent w~~h~~ith the limited extent of agricultural activities in th~~at~~ese specific low-yielding zones, ~~high elevation~~ rather than indicating~~on~~ an elevation-related retrieval artifact. These observations indicate that the spatial variability of NH_3 primarily reflects differences~~t~~ in total column sources rather than terrain-induced ~~that induces~~ biases.

Finally, the use of the L3 dataset, based on averaging L2 retrievals, ensures that the observations retain~~keeps~~ the original retrieval signal. Guatemala's tropical location also~~further~~ provides ~~a~~ favorable thermal contrast conditions for infrared NH_3 retrievals, supporting robust~~the~~ NH_3 ~~measurements~~ detection despite a relatively moderate background total column.

5 Conclusion

This study provides the first long-term ~~integrated~~ spatiotemporal assessment of the concatenated IASI A/B/C ~~of the~~ atmospheric NH_3 total column dataset, utilizing both ~~with~~ day and night overpasses~~ing~~ over Guatemala from ~~(~~2015~~–~~ to 2023~~)~~. ~~Using multi-satellite observations c~~By c~~C~~ombin~~ed~~ing these measurements with MODIS fire detections ~~MODISactivity~~, land cover maps, and ERA5 meteorological reanalysis data~~,~~. ~~T~~the analysis~~results~~ revealed ~~distinct~~ a ~~pronounced~~consistent seasonal cycle and marked interannual variability~~patterns~~.~~,~~ The~~with~~ highest NH_3 levels occurr~~ing~~ed during the dry season (March–May), followed by ~~and~~ a rapid decline associated with the onset of the rainy season. While ~~the a~~a~~A~~nnual median of the NH_3 column remained stable (ranging from 3.95~~–~~ to 4.66 × 10^{15} molecules cm^{-2}), ~~whileereas~~ episodic enhancement~~s~~ events, particularly in 2016, 2020 and 2023, produced substantially higher maximum values.~~driven by a stable agricultural baseline, onto which the episodic biomass burning events are superimposed during the dry season.~~

The combined analysis ~~indicate~~indicates that NH_3 variability results from the interaction between persistent agricultural sources and episodic biomass burning under favorable meteorological conditions. Agricultural land use, particularly cropland, appears to maintain a relatively stable ~~background of~~ NH_3~~,~~ background, whereas biomass burning during the dry season produces pronounced short-term enhancements. These peaks are further influenced by elevated temperatures and changes in boundary layer height, which favor the volatilization and vertical mixing of NH_3. The sharp reduction in ~~Spatiotemporal highest~~ NH_3 following the onset of the rainy season highlights the importance of wet deposition ~~removal~~ in clearing~~removing~~ the atmospheric NH_3 over ~~the~~ tropical ~~regions~~environments.

These findings are consistent with previous satellite studies reporting strong seasonal cycles of the NH_3 driven by agricultural activity and biomass burning in Europe, South Asia, and other t~~T~~ropical regions. However, this study extends ~~that~~this understanding to Central America, where long-~~-~~term satellite assessments of atmospheric NH_3 have hitherto been largely unavailable. The integration of multiple IASI sensors demonstrates that long-~~-~~term, concatenated satellite observations provide a robust~~elevant~~ characterization of NH_3 variability in data-sparse~~ over the~~ tropical regions.~~total columns are detected and restricted to the north (Petén and Quiché) and southern (Escuintla). These hotspots coincide with areas of intensive cropland and rangeland practices. The disproportionate small but high intensity agricultural cluster, suggest that localized land use practice is the primary control on Guatemala atmospheric nitrogen budget. Conversely, the secondary role of urban emission is evident in lower NH3 in the central high middle lands despite the high population densities. Seasonally, a peak in NH3 occurs during MAM months, strongly correlated with fire activity and elevated temperatures. The decline of NH3 (42%) in June demonstrates a transition from the rainy season. April 2020 exemplified the linking between fire activity and NH3, when nearly 1,500 km2 burned areas were affected (Fig. S~~6~~~~7).~~

The study nevertheless has also some~~several~~ limitations.~~,~~ First, satellite retrievals remain affected by cloud cover and surface conditions, particularly in humid tropical and mountainous regions, which can reduce observation density and introduce seasonal biases. In addition, satellite-derived NH_3 columns ~~derived~~ represent atmospheric abundance rather than direct emission~~s~~ fluxes, limiting direct source quantification. Although the integration of multiple datasets provides valuable qualitative insights~~ interpretability~~, further studies combining ground-based observations with~~and~~ chemical transport modeling are required~~would~~ to improve source attribution and process understanding.

Finally, this~~e~~ ~~robustness of this~~ study demonstrates~~d~~ that long-~~-~~term satellite observations can successfully distinguish between persistent NH_3 background levels and episodic biomass burning enhancements in tropical environments. These results improve our understanding of how agricultural activity, fire dynamics~~activity~~ and meteorological variability interact to regulate atmospheric NH_3, with important implications for secondary inorganic aerosols formation, nitrogen deposition, and regional atmospheric composition. Consequently, t~~T~~hese findings provide a solid foundation for future studies integrating satellite observations, atmospheric chemistry models, and machine learning approaches to better quantify NH_3 sources and their implications for~~on the~~ air quality, ecosystems~~soil~~ and climate. ~~by stable observation density and correlation between sampling frequency and NH_3. The favorable thermal contrast is tropics that allow IASI to detect signals even at moderate background values. These findings provide a baseline for future air quality policies and nitrogen deposition studies, also to understand the role of NH_3 as a precursor to particulate matter in Central America, highlighting the importance of integrating satellite observation with ground-based monitoring and evaluation to better constrain the impact of land management and the atmosphere.~~

Data availability

Monthly atmospheric ammonia column products from the Infrared Atmospheric Sounding Interferometer (IASI A/B/C), versioned Level-3 data cover global grids, AERIS-IASI portal: https://iasi.aeris-data.fr/nh3/. Monthly meteorology variables are provided by the ERA5 reanalysis dataset (https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels-monthly-means?tab=download). Active fire detections MODIS-Aqua/Terra from the NASA-Earth Observing System's Fire Information for Resource Management System (FIRMS) database (https://firms.modaps.eosdis.nasa.gov/). Burned area monthly L3 global 500m grid V061 (https://www.earthdata.nasa.gov/data/catalog/lpcloud-mcd64a1-061). Atmospheric Composition Global Reanalysis 4 (EAC4), produced by the Copernicus Atmosphere Monitoring Service (CAMS) (https://ads.atmosphere.copernicus.eu/datasets/cams-global-reanalysis-eac4?tab=overview).

Author contributions

Conceptualization, C.S. and K.T.; methodology, C.S. and K.T.; formal analysis, C.S.; investigation, C.S. and P.S.; resources, C.S. and P.S.; data curation, C.S.; writing (original draft preparation), C.S.; writing (review and editing), C.S., P.S., and K.T.; visualization, C.S.; supervision, K.T.

Competing interest

The authors declare that they have no conflict of interest.

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