



Supplement of

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

Christian Saravia et al.

Correspondence to: Christian Saravia (saravchr@b-tu.de)

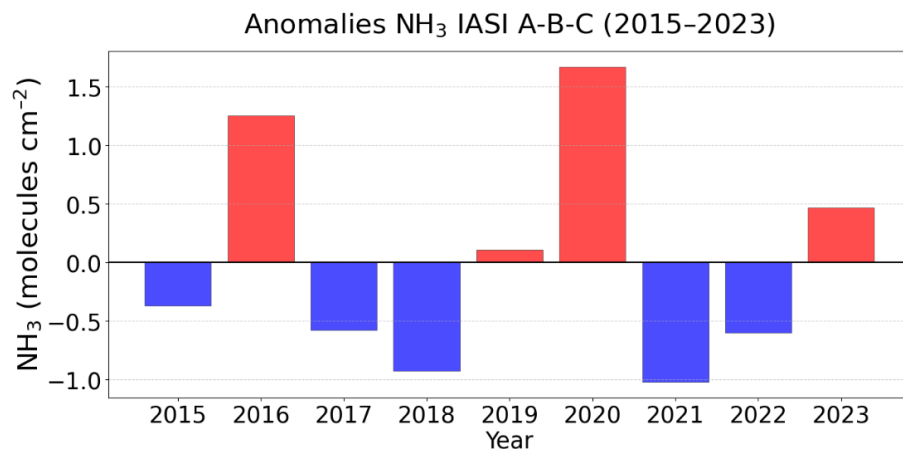
The copyright of individual parts of the supplement might differ from the article licence.

Table S1: Annual of NH₃ total column over Guatemala (2015–2023) from concatenated IASI A, B and C.

Year	Annual Mean	Min	Max	Std	Median
2015	4.64×10^{15}	3.52×10^{15}	9.24×10^{15}	1.58×10^{15}	4.19×10^{15}
2016	6.27×10^{15}	3.15×10^{15}	2.2×10^{16}	5.26×10^{15}	4.26×10^{15}
2017	4.43×10^{15}	3.55×10^{15}	6.78×10^{15}	9.62×10^{14}	4.28×10^{15}
2018	4.08×10^{15}	3.02×10^{15}	5.38×10^{15}	7.8×10^{14}	4.09×10^{15}
2019	5.12×10^{15}	3.22×10^{15}	1.08×10^{16}	2.56×10^{15}	4.11×10^{15}
2020	6.68×10^{15}	3.64×10^{15}	2.33×10^{16}	5.83×10^{15}	4.66×10^{15}
2021	3.99×10^{15}	2.90×10^{15}	5.07×10^{15}	5.72×10^{14}	3.95×10^{15}
2022	4.41×10^{15}	3.38×10^{15}	7.27×10^{15}	1.02×10^{15}	4.18×10^{15}
2023	5.48×10^{15}	3.29×10^{15}	1.13×10^{16}	2.80×10^{15}	4.33×10^{15}

5 Table S2: Monthly climatology of NH₃ total column over Guatemala (2015–2023) from concatenated IASI A, B and C.

Month	Monthly Mean	Min	Max	Std	Median
Jan	4.15×10^{15}	3.46×10^{15}	4.86×10^{15}	5.00×10^{14}	4.25×10^{15}
Feb	3.62×10^{15}	3.27×10^{15}	4.46×10^{15}	3.37×10^{14}	3.52×10^{15}
Mar	3.84×10^{15}	2.90×10^{15}	4.26×10^{15}	4.51×10^{14}	4.00×10^{15}
Apr	9.11×10^{15}	4.94×10^{15}	2.33×10^{16}	5.70×10^{15}	7.34×10^{15}
May	9.53×10^{15}	4.86×10^{15}	2.20×10^{16}	5.57×10^{15}	7.27×10^{15}
Jun	5.56×10^{15}	4.02×10^{15}	9.39×10^{15}	1.94×10^{15}	4.83×10^{15}
Jul	3.87×10^{15}	3.02×10^{15}	4.41×10^{15}	4.62×10^{14}	3.95×10^{15}
Aug	3.61×10^{15}	3.09×10^{15}	4.04×10^{15}	3.80×10^{14}	3.58×10^{15}
Sep	4.26×10^{15}	3.29×10^{15}	5.70×10^{15}	7.16×10^{14}	4.15×10^{15}
Oct	4.17×10^{15}	3.55×10^{15}	5.57×10^{15}	6.26×10^{14}	4.11×10^{15}
Nov	4.28×10^{15}	3.62×10^{15}	5.28×10^{15}	5.74×10^{14}	4.18×10^{15}
Dec	4.14×10^{15}	3.38×10^{15}	5.19×10^{15}	5.83×10^{14}	4.05×10^{15}



10 **Figure S1: Anomalies of NH₃ total column (× 10¹⁶ molecules cm⁻²) during the long-term mean, from concatenated IASI A, B and C over Guatemala (2015–2023).**

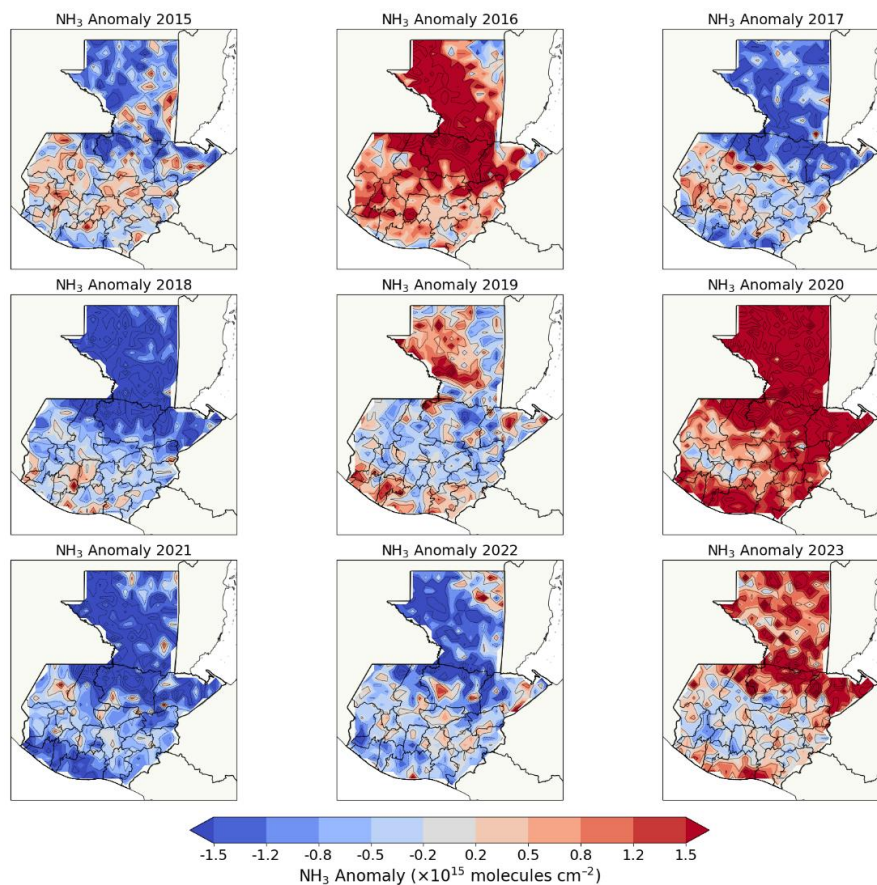


Figure S2: Annual area-wide of NH₃ anomalies of total column (× 10¹⁵ molecules cm⁻²) over Guatemala for the 2015–2023 period, from concatenated IASI A, B and C.

Table S3: Annual of NH₃ total column over Guatemala for the individual IASI sensor during the 2015–2023 period.

IASI A (2015–2020)					
Year	Annual Mean	Min	Max	Std	Median
2015	4.78×10^{15}	3.23×10^{15}	1.01×10^{16}	1.87×10^{15}	4.17×10^{15}
2016	6.31×10^{15}	3.43×10^{15}	2.32×10^{16}	5.62×10^{15}	4.17×10^{15}
2017	4.39×10^{15}	3.44×10^{15}	6.31×10^{15}	8.39×10^{14}	4.38×10^{15}
2018	4.01×10^{15}	3.07×10^{15}	5.35×10^{15}	7.21×10^{14}	3.84×10^{15}
2019	5.40×10^{15}	3.29×10^{15}	1.10×10^{16}	2.81×10^{15}	4.14×10^{15}
2020	6.82×10^{15}	3.67×10^{15}	2.18×10^{16}	5.30×10^{15}	5.08×10^{15}

IASI B (2015–2023)					
Year	Annual Mean	Min	Max	Std	Median
2015	4.50×10^{15}	3.24×10^{15}	8.37×10^{15}	1.34×10^{15}	4.06×10^{15}
2016	6.22×10^{15}	2.86×10^{15}	2.08×10^{16}	4.93×10^{15}	4.44×10^{15}
2017	4.47×10^{15}	3.27×10^{15}	7.25×10^{15}	1.11×10^{15}	4.18×10^{15}
2018	4.15×10^{15}	2.74×10^{15}	5.90×10^{15}	9.54×10^{14}	4.11×10^{15}
2019	4.83×10^{15}	3.04×10^{15}	1.05×10^{16}	2.46×10^{15}	4.92×10^{15}
2020	6.65×10^{15}	3.54×10^{15}	2.44×10^{16}	6.16×10^{15}	4.50×10^{15}
2021	4.19×10^{15}	2.95×10^{15}	5.04×10^{15}	6.02×10^{14}	4.25×10^{15}
2022	4.48×10^{15}	3.58×10^{15}	7.47×10^{15}	1.06×10^{15}	4.09×10^{15}
2023	5.64×10^{15}	3.20×10^{15}	1.13×10^{16}	2.83×10^{15}	4.72×10^{15}

IASI C (2020–2023)					
Year	Annual Mean	Min	Max	Std	Median
2020	6.57×10^{15}	3.32×10^{15}	2.37×10^{16}	6.06×10^{15}	4.31×10^{15}
2021	3.79×10^{15}	2.84×10^{15}	5.09×10^{15}	6.36×10^{14}	3.56×10^{15}
2022	4.34×10^{15}	3.03×10^{15}	7.06×10^{15}	1.04×10^{15}	4.33×10^{15}
2023	5.31×10^{15}	3.29×10^{15}	1.13×10^{16}	2.78×10^{15}	3.93×10^{15}

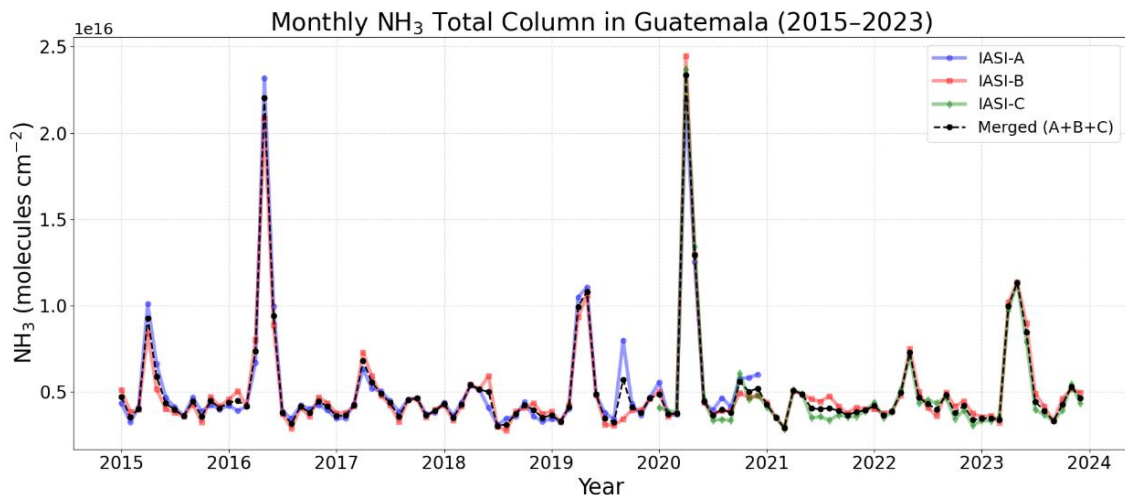


Figure S3: Monthly distribution of NH_3 total column ($\times 10^{16}$ molecules cm^{-2}) from IASI A (January 2015–December 2020), B (January 2015–December 2023) and C (January 2020–December 2023) over Guatemala (2015–2023).

25

Table S4: Summary statistics of detected fires over Guatemala from MODIS (MOD14/MYD14) filtered by a nominal confidence level $\geq 70\%$ and fire radiative power ≥ 40 MW. The annual mean column refers to the mean monthly fire counts per year, while minimum and maximum values correspond to the lowest and highest monthly fire counts observed within each year (2015–2023).

Year	Annual Mean	Min	Max	Std	Total Fire count	Median
2015	137	2	817	234.3	1646	35.5
2016	148	0	659	221.5	1779	50.5
2017	149	1	947	269.8	1783	28.5
2018	77	1	383	111.5	919	28
2019	133	1	741	219.4	1595	32
2020	129	0	957	272	1559	26
2021	75	0	400	115	902	30.5
2022	67	0	247	90	807	19
2023	119	2	564	170.6	1424	59

30

Table S5: Summary statistics of detected fires over Guatemala from MODIS (MOD14/MYD14) filtered by a nominal confidence level $\geq 70\%$ and fire radiative power ≥ 40 MW. The monthly mean column refers to the mean monthly fire counts per month, while minimum and maximum values correspond to the lowest and highest monthly fire counts observed within each month from 2015–2023.

Month	Monthly Mean	Min	Max	Std	Total Fire count	Median
Jan	78	50	114	22.8	700	76
Feb	105	63	144	25.2	946	108
Mar	211	110	305	76.9	1900	211
Apr	635	247	957	255.0	5715	659

May	261	147	509	116.1	2350	238
Jun	15	1	69	23.0	138	7
Jul	3	1	8	2.7	27	2
Aug	4	1	11	3.2	36	4
Sep	3	1	5	1.5	23	2
Oct	4	1	8	2.4	33	4
Nov	15	10	19	3.5	131	16
Dec	46	27	64	10.9	415	45

35

Table S6: Summary statistics of annual and climatology monthly distribution of meteorological variables over Guatemala (2015–2023), of boundary layer height (m), relative humidity (%), temperature (°C), and precipitation (mm) from monthly ERA5 reanalysis.

40

Boundary layer height (m)					
Year	Annual Mean	Min	Max	Std	Median
2015	478	327	669	108	474
2016	473	349	691	112	440
2017	454	305	684	115	415
2018	483	343	628	91	465
2019	525	325	709	119	524
2020	488	343	791	141	439
2021	482	391	665	93	446
2022	462	322	666	112	424
2023	508	339	749	133	462
Temperature (°C)					
Year	Annual Mean	Min	Max	Std	Median
2015	24.1	21.4	26.0	1.3	24.5
2016	24.1	21.5	27.0	1.7	24.6
2017	23.9	21.4	26.1	1.5	24.1
2018	23.8	20.2	26.1	1.5	24.4
2019	24.7	21.8	26.8	1.5	24.9
2020	24.5	21.5	27.9	1.7	24.8
2021	24.3	22.1	26.1	1.4	24.9
2022	24.0	21.7	26.4	1.4	24.2
2023	24.8	22.0	27.3	1.7	25.2
Relative Humidity (%)					
Year	Annual	Min	Max	Std	Median

Mean					
2015	80	73	86	4	80
2016	79	73	84	4	81
2017	79	69	87	6	79
2018	78	71	85	4	78
2019	77	69	85	5	76
2020	78	63	86	6	80
2021	78	71	82	4	79
2022	79	72	87	5	80
2023	76	66	85	6	77

Precipitation (mm)						
Year	Annual Total	Annual Mean	Min	Max	Std	Median
2015	1740	145	0.35	681	117	119
2016	1670	139	0.22	597	118	99
2017	1946	162	0.59	844	146	117
2018	1625	135	0.23	736	117	99
2019	1535	127	0.20	772	116	89
2020	2197	183	0.80	1283	166	164
2021	1654	137	0.42	860	112	113
2022	2078	173	1.06	862	141	142
2023	1681	140	0.10	913	124	109

Boundary layer height (m)					
Month	Monthly Mean	Min	Max	Std	Median
1	451	405	481	24	443
2	540	505	598	34	529
3	632	557	709	45	621
4	691	628	791	47	671
5	616	548	691	46	624
6	444	339	625	74	422
7	489	419	564	41	480
8	457	403	597	61	440
9	366	322	411	31	377
10	347	305	400	24	348
11	364	327	394	25	355
12	405	377	465	25	394

Temperature (°C)					
Month	Monthly	Min	Max	Std	Median

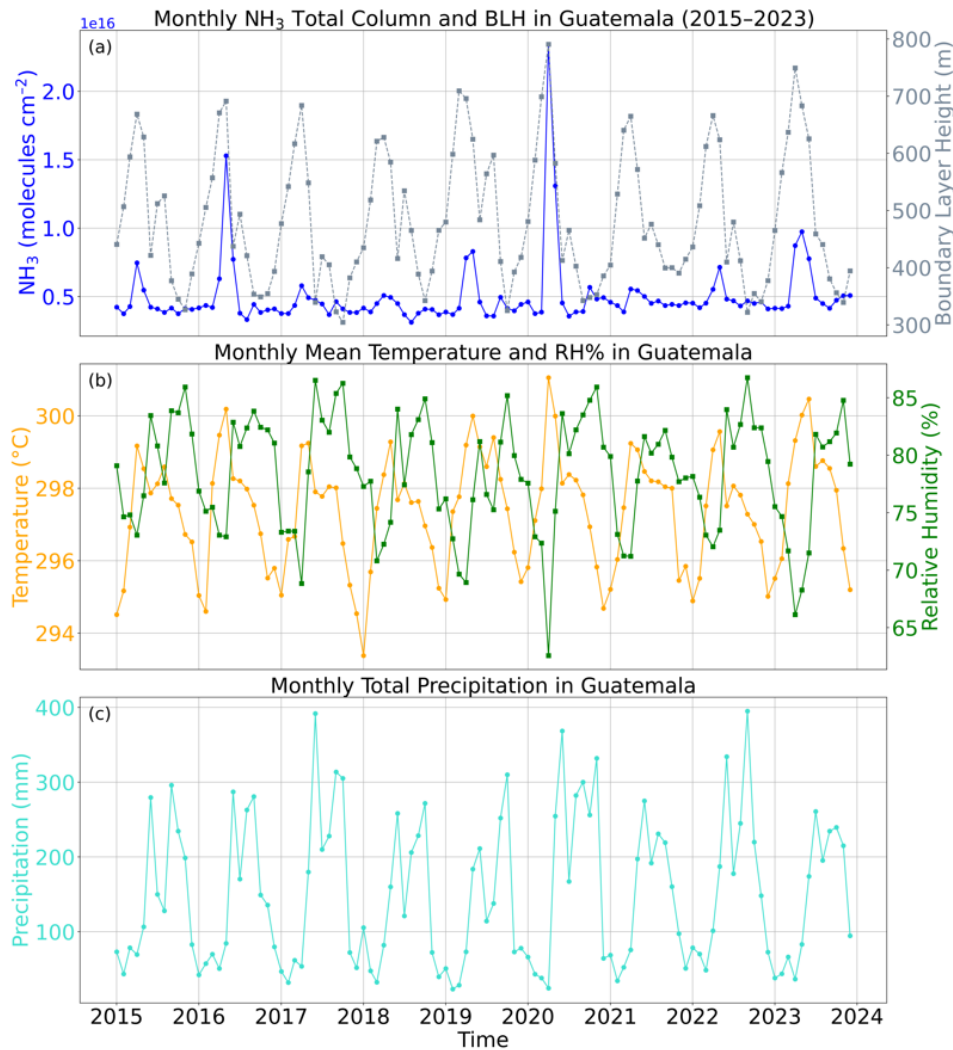
Mean					
1	21.8	20.2	22.7	0.6	21.9
2	22.9	21.5	24.2	0.8	22.9
3	24.4	23.5	25.0	0.5	24.4
4	26.2	25.2	27.9	0.7	26.0
5	26.4	25.4	27.0	0.5	26.4
6	25.2	24.4	27.3	0.9	25.0
7	25.1	24.6	25.5	0.2	25.1
8	25.1	24.5	26.3	0.5	25.0
9	24.7	24.1	25.4	0.4	24.7
10	24.1	23.3	24.9	0.5	23.9
11	22.9	22.2	23.6	0.5	23.1
12	22.2	21.4	23.4	0.6	22.1

Relative Humidity (%)					
Month	Monthly Mean	Min	Max	Std	Median
1	77	73	80	2	77
2	75	73	78	2	75
3	72	70	75	2	72
4	70	63	73	3	71
5	75	68	79	3	75
6	82	71	87	4	83
7	80	77	83	2	81
8	81	75	83	2	82
9	83	81	87	2	84
10	83	80	86	2	84
11	82	78	86	3	82
12	79	75	82	2	79

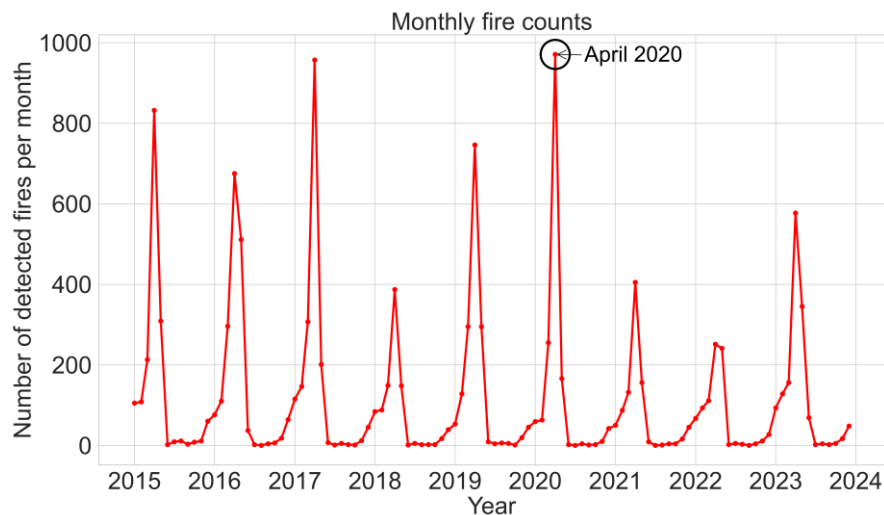
Precipitation (mm)					
Month	Monthly Mean	Min	Max	Std	Median
1	63	0.20	430	61	41
2	43	0.10	247	43	27
3	52	0.29	330	44	42
4	63	0.80	448	53	49
5	159	13	898	119	135
6	286	64	915	135	268
7	173	17	715	100	153
8	212	19	860	107	205

9	279	54	837	119	261
10	238	10	913	120	214
11	149	3	1283	138	114
12	68	0.23	410	60	48

50



55 **Figure S4: Monthly timeseries of NH₃ total column over Guatemala from concatenated IASI A/B/C, and meteorological variables from ERA5 reanalysis (2015–2023). (a) Boundary Layer Height (m) (gray) and NH₃ (blue), (b) Relative Humidity (%) (green), Temperature (°C) (yellow) and (c) Monthly Total Precipitation (mm) (turquoise).**



60 **Figure S5: Total number of detected fires by month from MODIS (MOD14/MYD14) filtered by a nominal confidence level $\geq 70\%$ and fire radiative power ≥ 40 MW over Guatemala (2015–2023), with April demonstrated the highest number of fires during the study period.**

Table S7: Detected fires count over Guatemala from MODIS (MOD14/MYD14) filtered by a nominal confidence level $\geq 70\%$ and fire radiative power ≥ 40 MW, during April 2020.

65

Department	Fire Count
Petén	674
Izabal	52
Alta Verapaz	48
Quiché	36
Escuintla	31
Zacapa	22
Jalapa	19
Huehuetenango	16
Jutiapa	15
Santa Rosa	10
El Progreso	6
Baja Verapaz	4
San Marcos	4
Retalhuleu	4
Chimaltenango	3
Quetzaltenango	3
Chiquimula	2
Sacatepéquez	2

Guatemala	1
Suchitepéquez	1

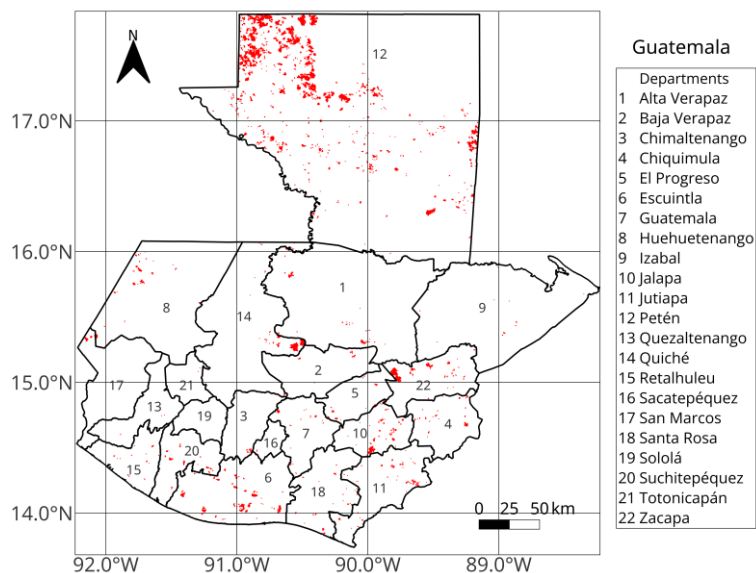


Figure S6: The Burned areas (red) during the month of April 2020 from MODIS (MCD64A1) Aqua and Terra over Guatemala.

70

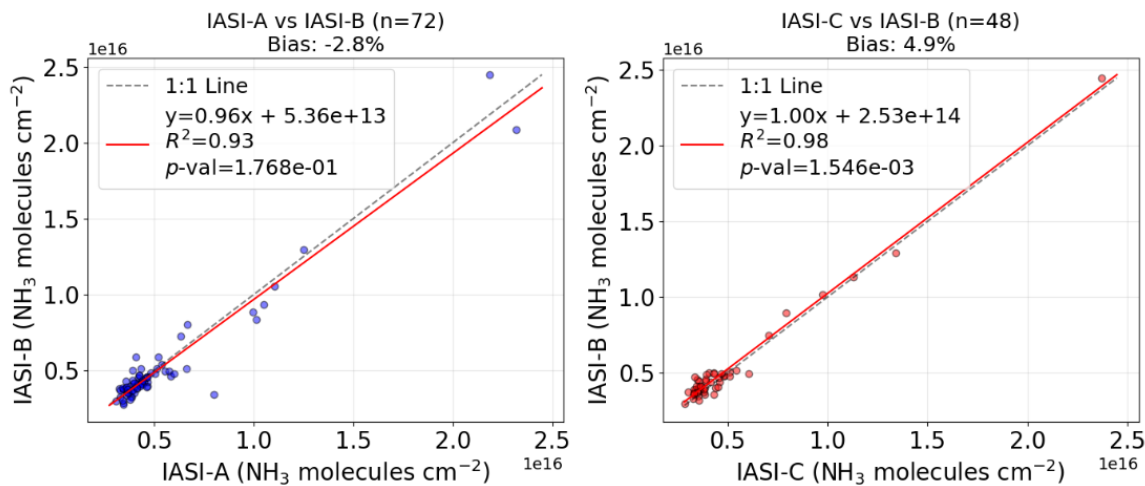
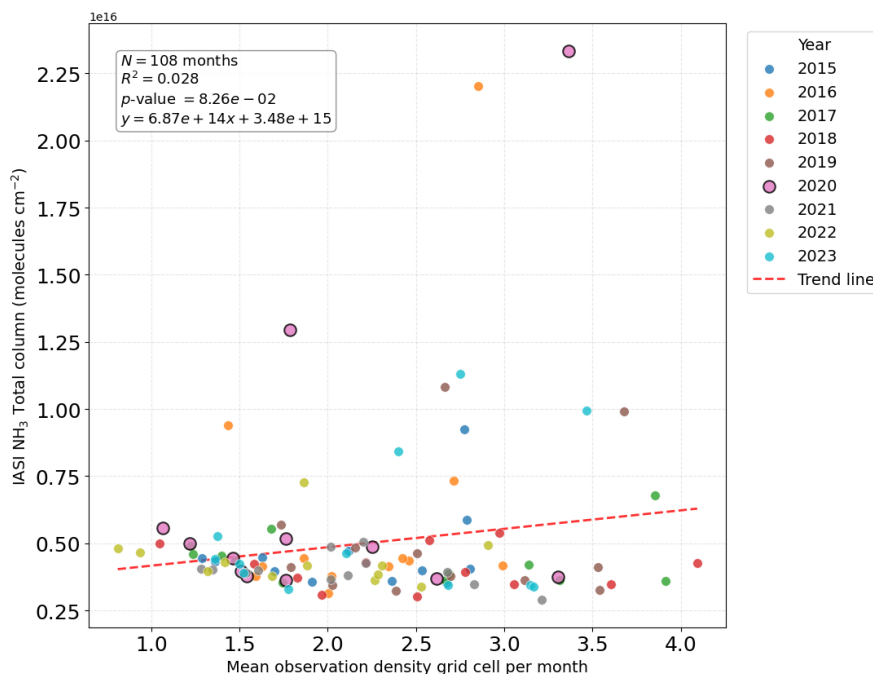


Figure S7: Cross comparison of monthly mean of NH_3 total column ($\times 10^{16}$ molecules cm^{-2}) from IASI A, B and C over Guatemala (2015–2023). Left (blue), correlation IASI-A vs. IASI-B with 72 months overlapping. Right (red), correlation IASI-C vs. IASI-B with 48 months overlapping.

75



80 **Figure S8: Correlation analysis of the concatenated monthly NH_3 total column and observation per grid cell month⁻¹ over Guatemala (2015–2023), each point represents the monthly average with a specific colour by year. The weak correlation ($R^2=0.028$ and $p<0.001$) suggest the annual variability of NH_3 that is large independent of sample frequency. The 2020 (black edge circle) demonstrate highest column (April, top-right) despite the moderate observation sample density.**

Section S1.

Aggregation and uncertainty estimation

The standard error (SE) was calculated as:

$$SE = \frac{\sigma}{\sqrt{N}}$$

85

where σ is the standard deviation and N is the number of valid observations (pixels). The relative uncertainty (RU) was computed as:

90

$$RU(\%) = \frac{SE}{\mu} \times 100$$

where μ represents the mean NH_3 total column.

Table S9: Annual summary of statistics of the of the concatenated NH₃ total column density, and IASI metrics over Guatemala (2015–2023). The table include annual mean (molecules cm⁻²), standard error of the mean (SEM) (molecules cm⁻²), relative uncertainty (%), total pixel counts, and mean monthly observations per 0.25 grid cell.

Year	Annual Mean (molec cm ⁻²)	Standard Error (molec cm ⁻²)	Relative Uncertainty (%)	Total Pixel (annual sum)	Obs. Grid Cell per Month
2015	4.64×10^{15}	4.58×10^{14}	9.85	15696	2.16
2016	6.27×10^{15}	1.52×10^{15}	24.26	15931	2.19
2017	4.43×10^{15}	2.78×10^{14}	6.27	17142	2.36
2018	4.08×10^{15}	2.25×10^{14}	5.52	18286	2.52
2019	5.12×10^{15}	7.38×10^{14}	14.43	19255	2.65
2020	6.68×10^{15}	1.68×10^{15}	25.19	14305	1.97
2021	3.99×10^{15}	1.65×10^{14}	4.14	15162	2.09
2022	4.41×10^{15}	2.94×10^{14}	6.68	13432	1.85
2023	5.48×10^{15}	8.09×10^{14}	14.76	16485	2.27

Table S10: Annual and monthly climatology summary of statistics of the observation density grid cell month⁻¹ and pixel per month over Guatemala (2015–2023).

Observation density grid cell per month year

Year	Annual Mean	Standard deviation	Min	Median	Max
2015	2.16	0.57	1.29	2.24	2.81
2016	2.19	0.52	1.44	2.18	2.99
2017	2.36	1.02	1.22	2.21	3.91
2018	2.52	0.86	1.04	2.54	4.09
2019	2.65	0.68	1.74	2.59	3.68
2020	1.97	0.76	1.07	1.76	3.37
2021	2.09	0.60	1.28	2.07	3.21
2022	1.85	0.64	0.81	1.87	2.91
2023	2.27	0.77	1.36	2.25	3.47

Pixel per month per year

Year	Annual Mean	Standard deviation	Min	Median	Max
2015	1177	401	575	1137	1679
2016	1222	375	785	1155	1797
2017	1316	663	574	1205	2332
2018	1391	571	485	1421	2464
2019	1492	479	755	1423	2223
2020	1145	488	573	991	2037
2021	1140	389	598	1112	1868
2022	978	428	300	1036	1741

2023	1249	521	669	1297	2097
Observation density grid cell climatology monthly					
Month	Monthly Mean	Min	Max	Std	Median
1	2.63	2.11	3.91	0.61	2.30
2	2.82	2.26	3.54	0.41	2.68
3	3.13	2.28	4.0	0.52	3.16
4	3.10	2.20	3.85	0.52	2.97
5	2.33	1.67	2.85	0.48	2.57
6	1.48	0.93	2.40	0.48	1.35
7	1.71	1.36	2.50	0.35	1.60
8	1.78	1.28	2.38	0.41	1.74
9	1.50	0.81	1.82	0.31	1.53
10	1.64	1.06	2.02	0.33	1.68
11	2.02	1.27	2.78	0.58	1.88
12	2.55	1.76	3.60	0.50	2.52
Pixel climatology monthly					
Month	Monthly Mean	Min	Max	Std	Median
1	1596	1282	2368	372	1396
2	1707	1370	2142	250	1622
3	1899	1381	2477	319	1914
4	1878	1332	2332	319	1798
5	1410	1015	1726	293	1559
6	899	567	1453	294	822
7	1038	823	1517	216	973
8	1082	776	1443	253	1056
9	910	490	1104	190	931
10	996	645	1223	203	1020
11	1225	737	1682	352	1139
12	1547	1068	2181	308	1529

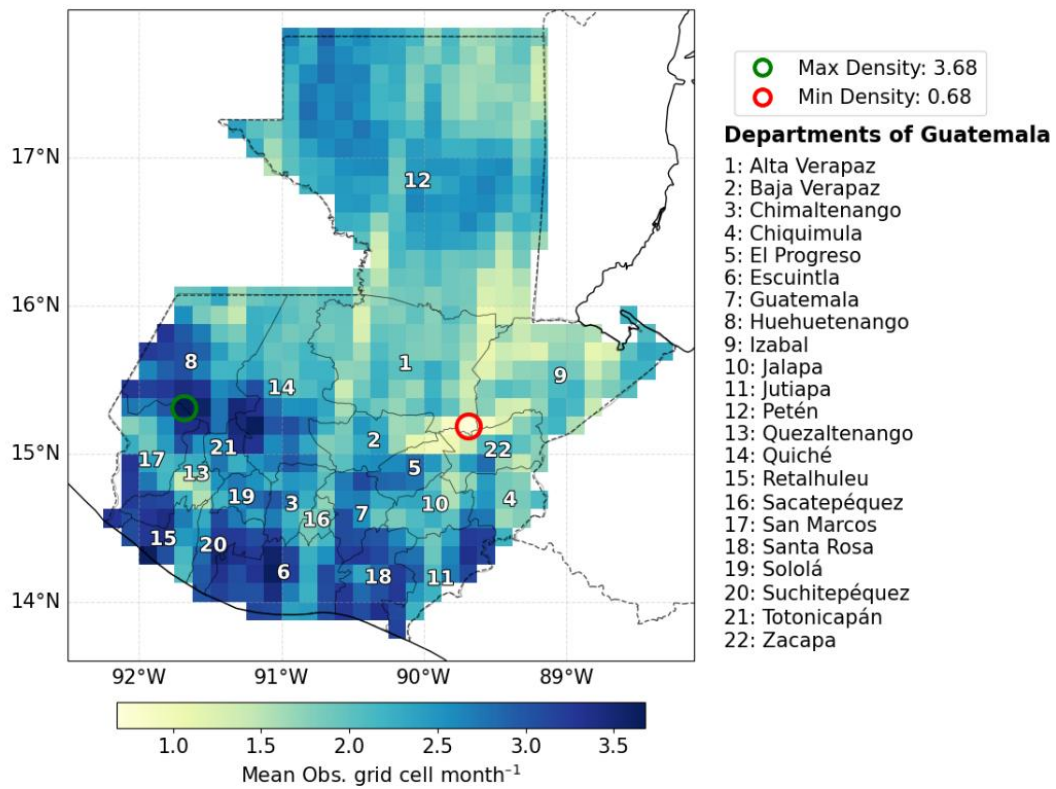


Figure S9: Spatial area-wide of means of observation grid cell month⁻¹ over Guatemala (2015–2023), representing the highest and lowest distribution detection, green circle showing the highest with the green circle showing the highest density obs. located in Huehuetenango department (15.35°N, 91.73°W, elevation ~1900 m), and with the red circle showing the lowest density obs. located in Sierra de las Minas, Alta Verapaz department (15.19°N, 89.69°W, elevation ~1600 m).