NO_x Production by Lightning as Inferred Using NO_2 Slant Columns from GCAS during the GOES-R Validation Campaign

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Introduction

- Lightning produces NO because the extreme temperatures in lightning channels dissociate O_2 and N_2, which then combine to form NO, which quickly reacts with O_3 to form NO_2.
- On average, each lightning flash produces 100 to 400 moles of NO_x or 2 – 8 Tg N yr^{-1} [Schumann and Huntrieser, 2007] for a global flash rate of ~45 flashes s^{-1}. Much of the uncertainty stems from limited knowledge of NO_x production per flash (LNOx PE) or per unit flash length.
- Most LNO_x is injected into middle and upper troposphere where away from deep convection it is relatively long-lived and enhances the concentrations of upper tropospheric NO_y, OH, and O_3 and contributes to positive radiative forcing by O_3 and negative forcing by CH_4.
- In this study, we estimate LNO_x PE using columns of NO_2 retrieved by the Geo-CAPE Airborne Simulator on board the NASA ER-2 aircraft during the GOES-R Validation Campaign during Spring 2017 and flash rates from the Geostationary Lightning Mapper (GLM), the Earth Networks Total Lightning Network (ENTLN), and the NASA Marshall Fly's Eye GLM Simulator (FEGS)

GOES-R Validation Campaign

The GOES-R Validation Campaign was conducted during March – May 2017 using the NASA ER-2 (Fig. 1) aircraft based at Palmdale, CA and Warner-Robins, GA. Its primary purpose was validation of the Advanced Baseline Imager (ABI) and Geostationary Lightning Mapper (GLM) satellite instruments aboard GOES-R. The NASA Goddard Geo-CAPE Airborne Simulator (GCAS) UV/Vis spectrometer piggybacked on the aircraft mission to allow observations of NO_2 simultaneously with lightning detection by the NASA Marshall Fly's Eye GLM Simulator (FEGS).

Table 1. Daytime GOES-R Campaign Flights with GCAS Data and Cloud Physics Lidar (CPL) Cloud Heights

Date	Location	Start Time (UT)	End Time (UT)
4/20/17	Toronto LMA	2330	0015
4/22/17	N. Alabama LMA	2030	0030
5/8/17	NE Colorado LMA	2145	0100
5/12/17	LA/MS/Gulf of Mex	1415	2015
5/14/17	Atlantic Ocean off FL	1315	1715

Figure 1

GOES-16 GLM, ENTLN, and TEMPO

- Geostationary Lightning Mapper (GLM) aboard GOES-16, a geostationary satellite launched on 19 Nov 2016, maps the distribution of lightning flashes at ~10 km spatial resolution with mean detection efficiencies (DEs) exceeding 70%. DEs for this campaign were obtained via comparison with flashes from FEGS.
- The Earth Networks Total Lightning Network (ENTLN) detects low frequency sferics in the 1-12 MHz range. The CG and IC DEs were ~100% for CG flashes and ~79% for IC flashes.
- When launched into a geostationary orbit in 2022, TEMPO will scan North America from east to west hourly measuring changes in NO_2, O_3, and other pollutants
- In the future, we plan on taking advantage of the synergy between the two geostationary instruments by using TEMPO NO_2 with GLM flashes to obtain estimates of NO_x production per flash.
- A demonstration of this future synergy was possible through the GOES-R validation suborbital campaign.

Airborne Instruments

- FEGS (Fig. 2, *Quick et al., 2017)* is an airborne array of multi-spectral radiometers optimized to study the optical emission from lightning through the cloud top. It provides a one to-one comparison to GLM observations. FEGS uses a 5 x 5 array of radiometers sensing at 777 nm. Each radiometer is pointed in a different direction, such that flashes can be continuously sensed in a ~10 x 10 km field of view as the ER-2 aircraft passes over a storm.

- GCAS (Fig. 3, *Kowalewski and Janz,* 2014) contains two spectrometers that provide imaging capabilities from the UV to NIR. This spectral range is separated into UV/VIS (300-490 nm) and VIS/NIR (480 – 900 nm) channels. The UV/VIS channel is used primarily for atmospheric trace gas measurements. Column amounts of atmospheric pollutants (e.g., NO_2, O_3, HCHO, and aerosols are retrieved from the high resolution (0.6 nm) UV/Vis spectrometer spectra.

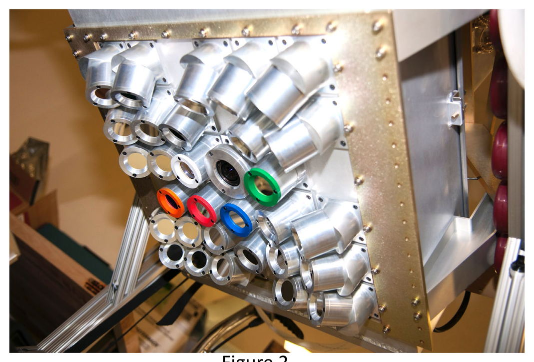


Figure 2

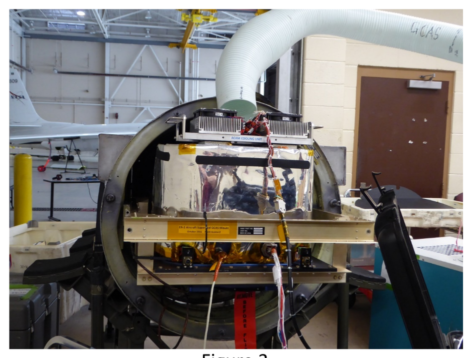
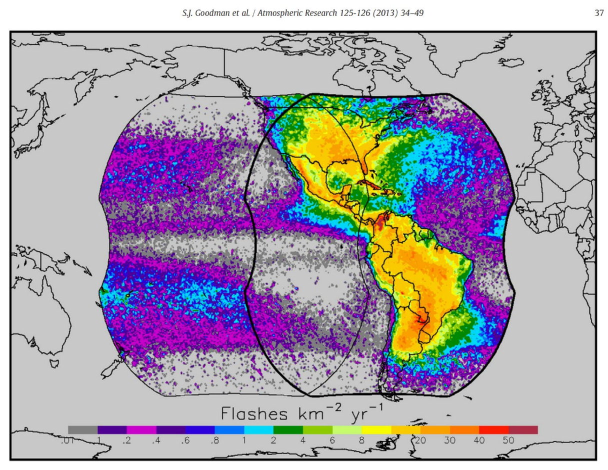
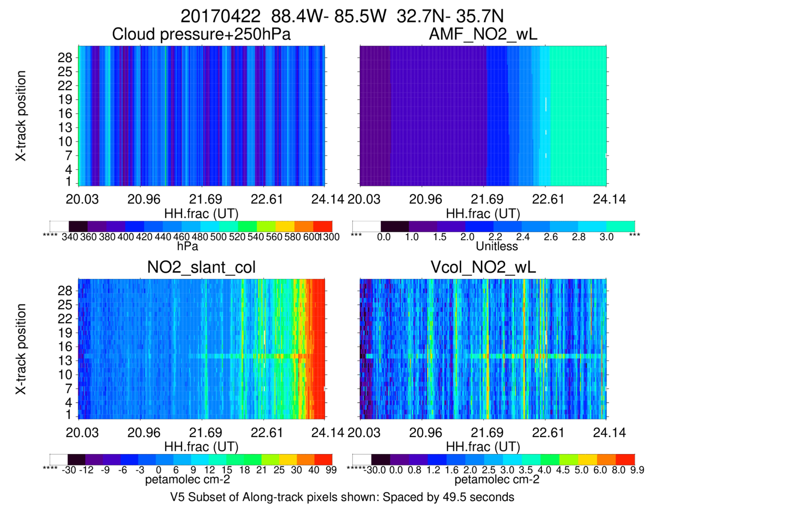


Figure 3



Combined FOV for GOES-17 and GOES-16 superimposed on climatological flash density from OTD-LIS (*Goodman et al*., 2013)



NO_2 vertical columns (lower right) are derived from slant columns (lower left) over pixels with CPL P < 300 hPa (upper left) using AMFs (upper right)

Algorithm

GCAS measures solar radiation backscattered from the surface and atmosphere (*Kowalewski and Janz*, 2014). NO_2 SCDs are derived by fitting a modeled spectrum to the observed spectrum using the QDOAS spectral fitting package.

GCAS is unable to obtain a solar reference spectra. Therefore, reference spectra required for trace gas retrievals are derived from nadir observations over a clean but cloudy region. The 2.5 minute period centered at 2213 UT May 8th was used during the GOES-R campaign.

SCDs are converted to tropospheric vertical column densities (VCDs) using air mass factors (AMFs) calculated with VLIDORT (*Lamsal et al*., 2017) and tropopause pressures from MERRA-2.

NO_x and NO_2 profiles needed to convert NO_2 VCDs to LNO_x VCDs are obtained from GEOS-5 GMI-Replay simulations performed with and without lightning NO_x.

GCAS data retrieved in form of 250 m x 250 m pixels (31 pixels cross track with averaging along track).

Uncertainty exists as to how far into the storm cloud GCAS is able to detect NO_2. We assume a depth of 250 hPa, which is the mean difference between the cloud pressure obtained by the CPL aboard the ER-2 during the May 12th flight, which occurred near the overpass time of OMI, and the OMI optical centroid pressure (OCP).

LNO_x Production per Flash = [$VCD_{NO2(median)}$ × Flash Area × rNO_x/NO_2] /[Avogadro's_number × Nflashes]

rNO_x/NO_2 = Flight-track averaged ratio of upper tropospheric LNO_x to LNO_2 from GEOS-5 on date & time of flight

Nflashes = Number of GLM or ENTLN flashes adjusted for 3 hour lifetime of NOx in near field of convection

Storm	Date	Time	Location	VCD	Flash area	rLNOx / LNO2	GLM (ENTLN) Flashes	GLM (ENTLN) DE	GLM (ENTLN) LNOx PE
Lake Erie	Apr 20	2312-2352	41-43.5 N 82-77 W	2.55	13710 (23634)	2.15	8627 (21028)	0.76 (0.84)	211 (163)
AL_NS cells	Apr 22	2025-2147	34-36N 88.5-86.5 W	2.27	11989 (16616)	3.60	15045 (21758)	0.78 (0.81)	151 (145)
AL_Ncell	Apr 22	2154-2316	34.5-35.5N 87.8-85.5 W	2.45	8698 (11656)	3.03	9798 (15199)	0.71 (0.81)	183 (155)
AL_Scell	Apr 22	2321-2435	33.8-34.6 N 88-86 W	2.53	6400 (8378)	2.14	8373 (11236)	0.68 (0.82)	125 (119)
CO_South	May 08	2146-2300	39.75-40.0 N 105-104.2 W	2.12	1136 (1348)	3.18	4162 (4355)	0.45 (0.84)	44 (51)
CO_North	May 08	2146-2345	40-41 N 105-104.2W	2.22	3698 (4485)	3.00	7913 (11428)	0.53 (0.85)	72 (63)
CO_East	May 08	2353-2459	40-51 N 104-102.9 W	2.25	5137 (7029)	1.94	10281 (16630)	0.54 (0.84)	53 (45)
MS_AL_Line	May 12	1410-1509	29.5-32.5N 92-87 W	2.43	11923 (21884)	3.28	10834 (18644)	0.64 (0.83)	192 (233)
Gulf Line	May 12	1520-1640	28-29.25 N 93-90.5 W	1.32	2404 (2791)	3.71	2985 (2416)	0.48 (0.85)	126 (184)
Coastal Line	May 12	1653-2013	29-31 N 91-87.5 W	1.94	27023 (35628)	3.79	28071 (34734)	0.65 (0.84)	297 (314)
Atl_Ecell	May 14	1240-1359	29-31 N 75.5-72 W	2.06	17156 (25757)	3.29	16296 (24467)	0.70 (0.84)	182 (203)
Atl_Wcell	May 14	1419-1710	29.1-30.1 N 75.5-73.5 W	1.77	7545 (9056)	3.40	9007 (8828)	0.64 (0.84)	240 (292)
									157 ± 76 (164 ± 87)

Thunderstorm Case Studies from the GOES-R Validation Campaign

NEXRAD Base Reflectivity and Flight Track | GCAS-derived VCD of NO2 | GLM Flashes | ENTLN flashes

April 22, 2017 Alabama Storm: As a cold front approached from the west the ER-2 overflew two supercells, initially NW and W of Huntsville, AL over the period 2030 to 2310 UT. The primary focus was on the northern storm between 2150 and 2310 (Figure 4). After the northern storm weakened, the focus shifted to the southern storm, now southeast of Huntsville. It was overflown from 2320 to 0030 UT (Figure 5).

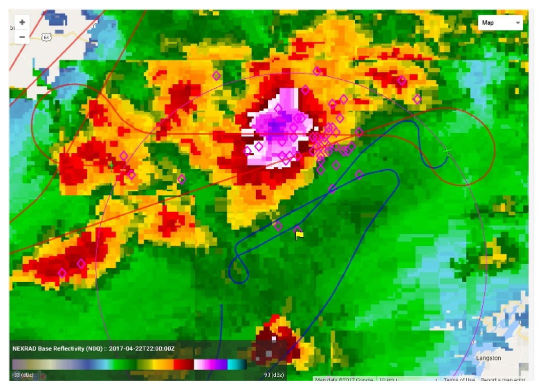
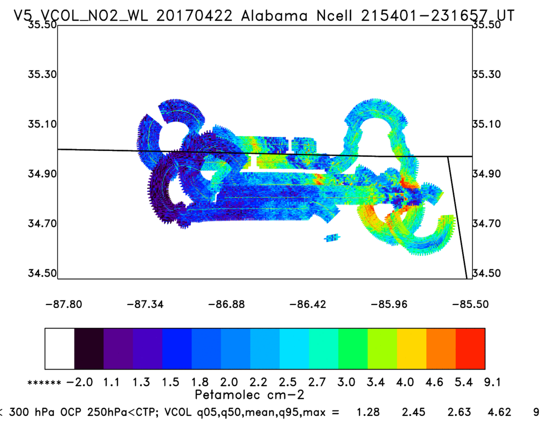
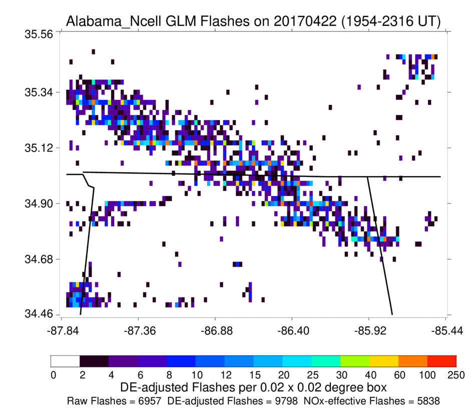
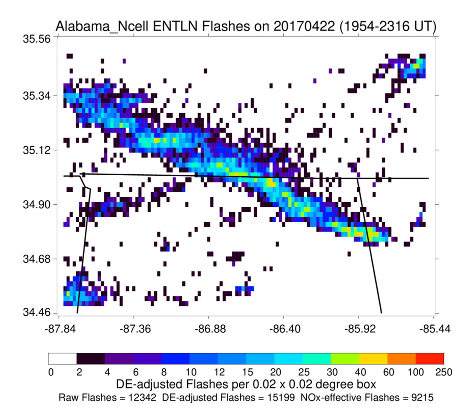


Figure 4







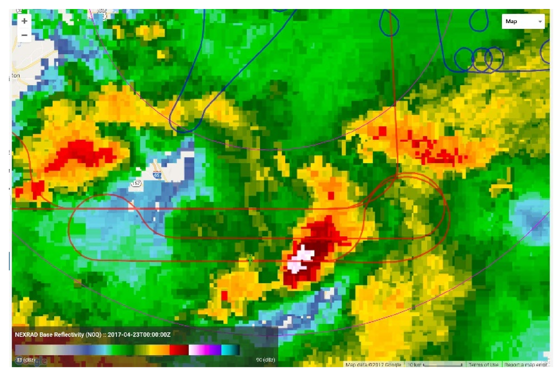
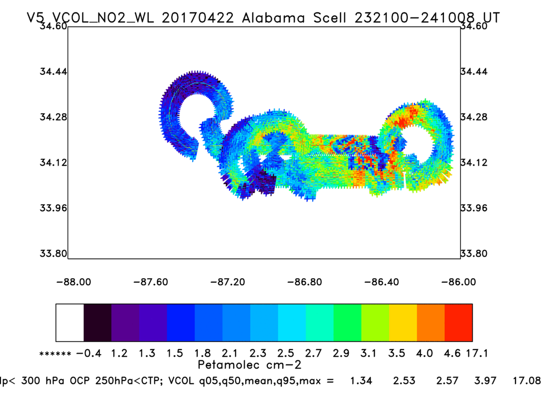
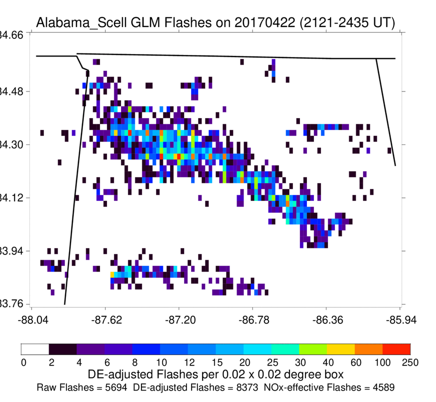
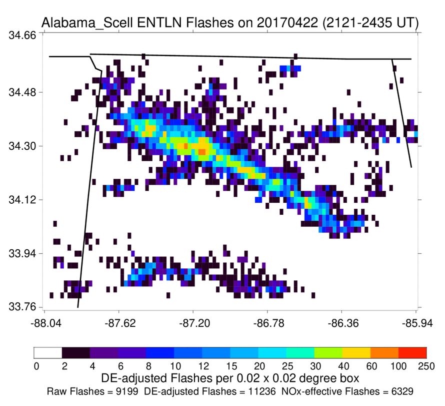


Figure 5

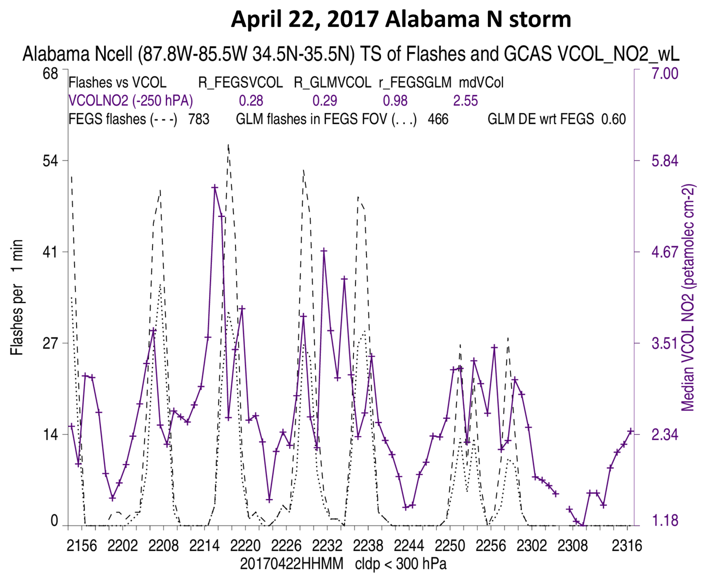




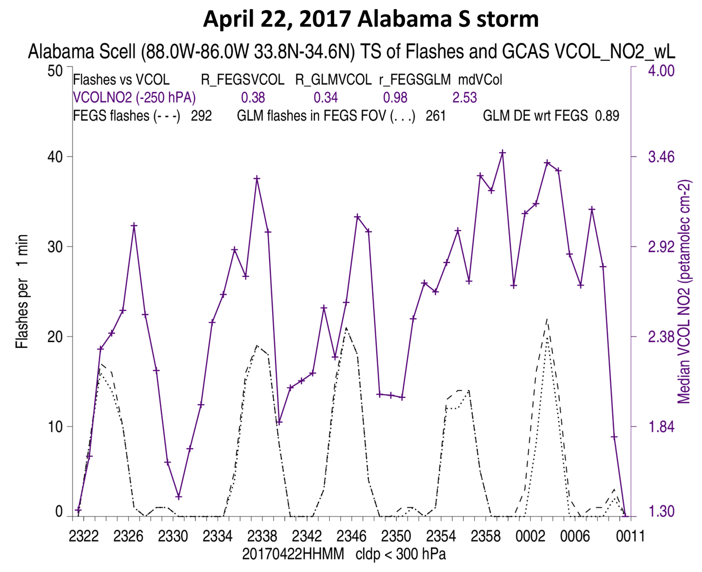


NO_2 VCD, GLM, and FEGS flashes as a f(t)

April 22, 2017 Alabama N storm



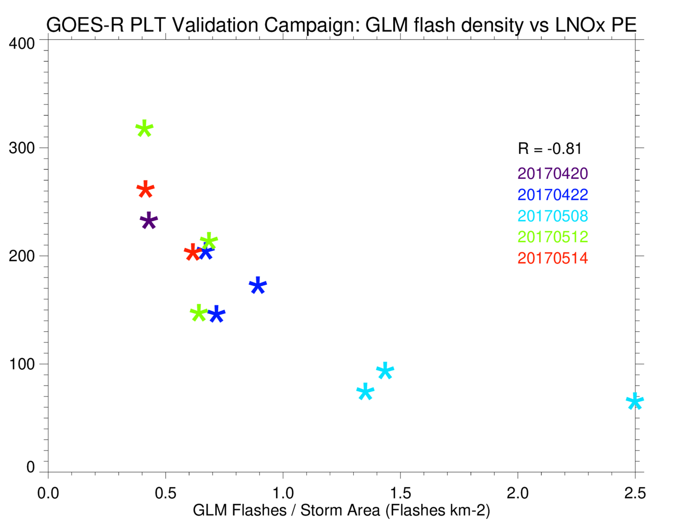
April 22, 2017 Alabama S storm

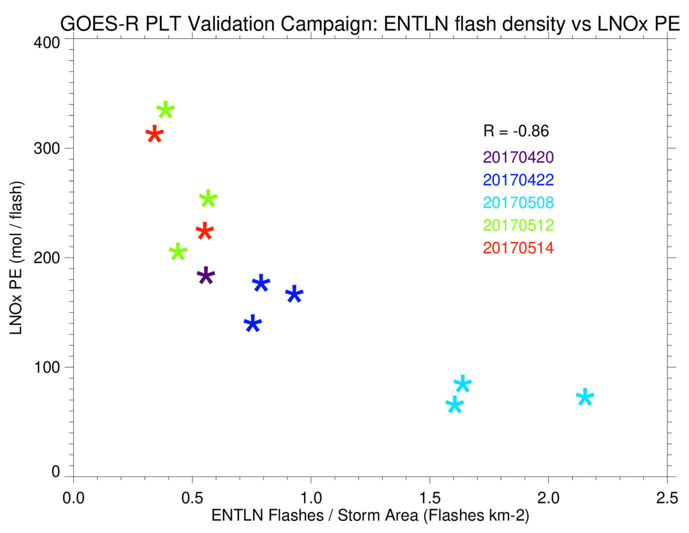


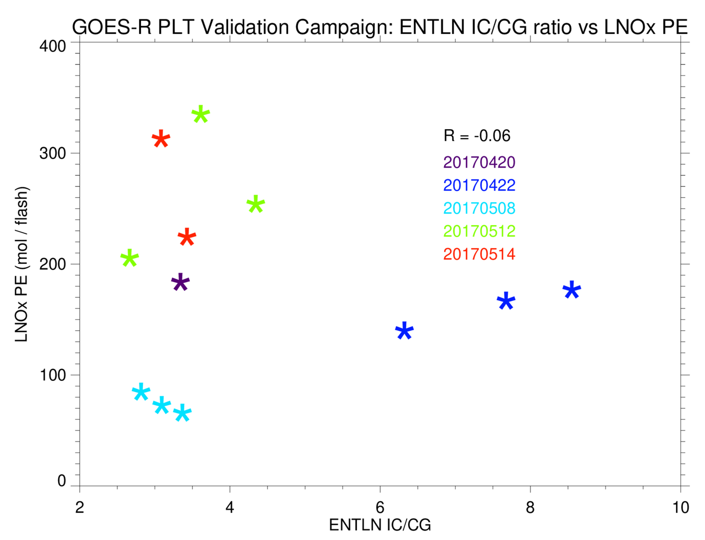
Uncertainties

- Are GCAS NO_2 columns in swaths along the flight tracks representative of the storm?
- How representative of background conditions is the GCAS reference column?
- Are modeled NO_x/NO_2 ratios representative of ratios observed in an actual convective system given uncertainties in UT NO_y chemistry (e.g., *Silvern et al.*, 2018) and the model simulation?
- ENTLN assumes a CG DE of 100% and IC DE of 79%. GLM DE is determined with respect to FEGS data. How accurate are GLM and ENTLN flash counts and what percentage of the flashes contribute to the observed columns?
- These calculations assume a NO_x lifetime of ~3 hrs in near-field of convection (Nault et al., 2016).

LNO_x PE is inversely correlated with flash density but uncorrelated with IC/CG ratio. If an IC flash made much less NO_x than a CG flash, would expect a negative correlation.







Conclusions

- GCAS NO_2 columns were analyzed in relation to observed lightning during 12 storms overflown by the ER-2 aircraft on 5 flight days during the GOES-R Validation Campaign
- LNO_x PE was found to be ~160 ± 80 mol per flash approximately the same as the 180 ± 100 mol/flash found by Bucsela et al. (2019) for mid-latitude lightning through analysis of OMI NO_2 data.
- LNOx PE is similar using GLM and ENTLN, as a greater number of ENTLN flashes is accompanied by larger storm area
- LNO_x PE is negatively correlated with flash density (R=-0.81) consistent with belief that storms with high flash densities have smaller individual flash channel lengths and produce less NO_x per flash. However, it is uncorrelated with the IC/CG ratio.

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