NO_2 and Lightning Observations during GOES-R Validation Flights: A Demonstration of Future TEMPO and GLM Synergy

Kenneth Pickering[1], Dale Allen[1], Lok Lamsal[2], Scott Janz[3], Matthew Kowalewski[2], Mason Quick[4], Richard Blakeslee[5], William Koshak[5]

[1]University of Maryland, [2] USRA/GESTAR, [3] NASA Goddard Space Flight Center, [4] University of Alabama Huntsville, [5] NASA Marshall Space Flight Center

Introduction

- Lightning produces NO because the extreme temperatures (>20000 K) in lightning channels dissociate molecular oxygen (O_2) and molecular nitrogen (N_2), which then combine to form NO, which quickly reacts with O_3 to form NO_2.
- Lightning is responsible for approximately 10-15% of NO_x emissions globally. This is roughly 2 – 8 Tg N yr-1 [Schumann and Huntrieser, 2007] or ~100 to 400 moles per flash. Much of the uncertainty (factor of four) stems from limited knowledge of NO_x production per flash or per unit flash length.
- Most of lightning-produced NO_x (LNO_x) is injected into middle and upper troposphere. Lifetime is longer relative to lower troposphere. NO_x in this region plays a key role in the chemistry of ozone, the importance of which as a greenhouse gas maximizes in the UT.
- We have previously used OMI NO_2 to obtain estimates of LNO_x production per flash over the Gulf of Mexico (*Pickering et al.*, 2016, *JGR*), in convective events during NASA's TC4 field program (*Bucsela et al.*, 2010, *JGR*), and over broad regions of the tropics *(Allen et al., 2018, in prep)* and midlatitudes *(Bucsela et al., 2018, in prep.)*.

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 NO2 simultaneously with lightning detection by the NASA Marshall Fly's Eye GLM Simulator (FEGS).

Table 1. Daytime GOES-R Campaign Flights with GCAS Data

Date	Location	Start Time (UT)	End Time (UT)
3/21/17	N. California	1940	2240
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

GOES-16 GLM and TEMPO

- The launch of the first Geostationary Operational Environmental Satellite R-series (GOES-R, now GOES-16) satellite occurred on November 19, 2016.
- GOES-16 carries the Geostationary Lightning Mapper (GLM), which continuously detects lightning flashes using the wavelength of 777 nm at ~10 km spatial resolution over the Americas and surrounding oceans with high efficiency.
- Geostationary measurements of NO_2, O_3, and aerosols are expected to be available over the Americas beginning with the launch of the TEMPO UV/Vis Spectrometer on a communications satellite, which will occur by 2021.
- We plan on taking advantage of the synergy between the two geostationary instruments by using NO_2 data from TEMPO along with flash data from GLM to Obtain more robust estimates of NO production per flash.
- A demonstration of this future synergy was possible through the GOES-R validation suborbital campaign.

Airborne Instruments

- FEGS (*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. 2, *Kowalewski and Janz,* 2014) contains two spectrometers that Provide hyperspectral imaging capabilities from the UV to NIR. This spectral range is separated into a UV/VIS channel (300 nm – 490 nm) for one spectrometer And a VIS/NIR channel (480 nm – 900 nm). the UV/VIS channel is used primarily For atmospheric trace gas measurements while the VIS/NIR channel provides spectral bands best suited to ocean color measurements. Column amounts of atmospheric pollutants (including NO_2, O_3, HCHO, and aerosols can be retrieved from the high resolution (0.6 nm) UV/Vis spectrometer spectra.

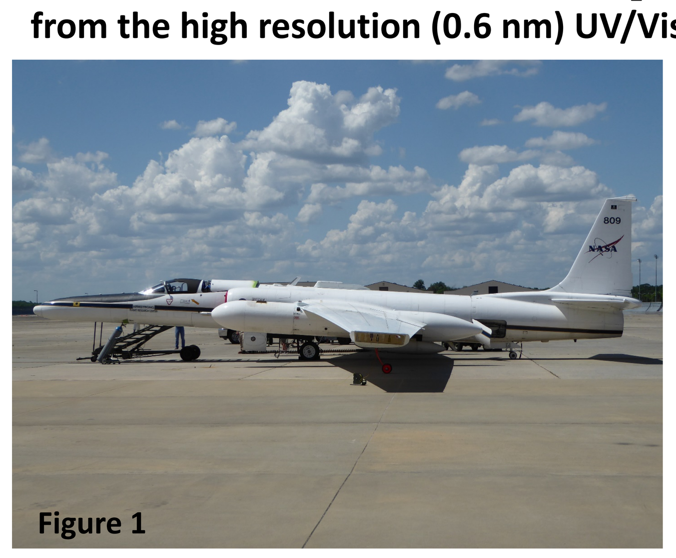


Figure 1

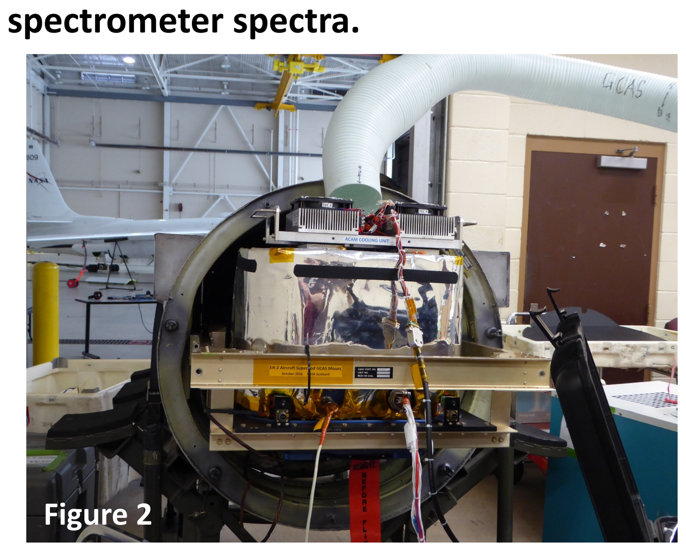


Figure 2

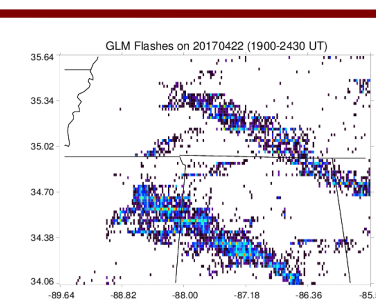
Algorithm

- To obtain NO2 slant column densities (SCDs) from GCAS-measured spectra, we use the Differential Optical Absorption Spectroscopy (DOAS) fitting method and QDOAS fitting algorithm.
- GCAS does not provide solar irradiance reference spectra; therefore, we use an average measured radiance spectrum for each row derived from ~140 consecutive radiance spectra measured over 2.5 minute intervals over a cloudy background location. This averaging approach improves the signal-to-noise ratio of the reference spectrum and minimizes errors in the retrievals.
- The spectral fitting is performed in the range of 425-460 nm and includes absorption by other trace gases and reference Ring spectrum, and uses a third order polynomial. The fitting procedure yields the differential (rather than absolute) NO_2 SCD, that is, with respect to the SCD at the reference location.
- Conversion of the differential SCDs to vertical column density (VCD) components above and below the tropopause is as described in *Lamsal et al.* (2017).
- Air mass factors (AMFs) necessary to convert SCD to VCD are computed using the VLIDORT code. AMFs are calculated using the Lambertian surface assumption with MODIS-derived bidirectional reflectance function (BRF) over the surface and 0.8 over the cloud. Cloud top and surface heights are derived from Cloud Physics Lidar (CPL) on board the ER-2 and the ETOPO Global Relief model, respectively.
- NO_2 and NO_x vertical profiles are taken from GMI-Replay simulations performed with and without lightning NOx.
- Thermal tropopause pressure required for separating stratospheric and tropospheric components is taken from the MERRA-2 reanalysis.

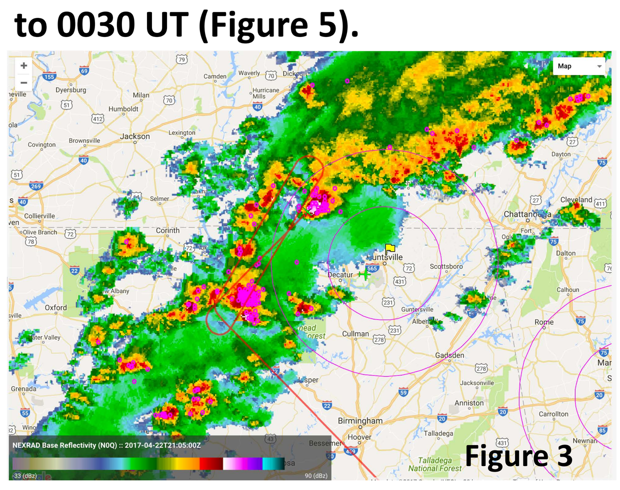
Thunderstorm Case Studies from the GOES-R Validation Campaign

April 22, 2017 Alabama Storms

As a cold front approached from the west the ER-2 overflew two supercells, initially NW and W of Huntsville, AL (Figure 3) 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, and was overflown from 2320 to 0030 UT (Figure 5).



GLM observed 8786 flashes over area traversed by two cells. Using mean VLNOx= 7.5 x 10^{15} molec cm^{-2} yields 150 – 300 moles LNOx per flash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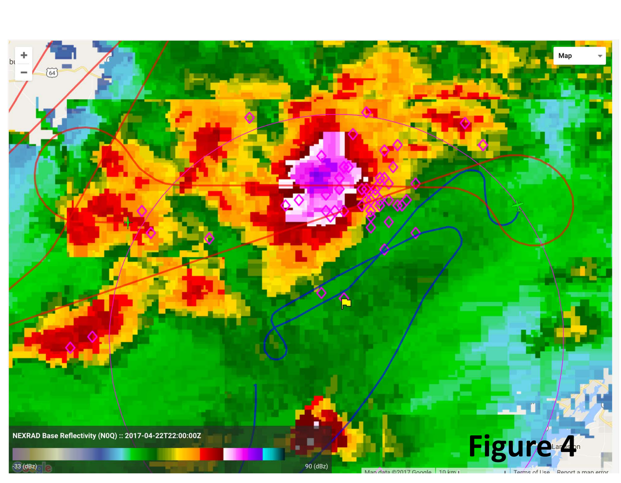
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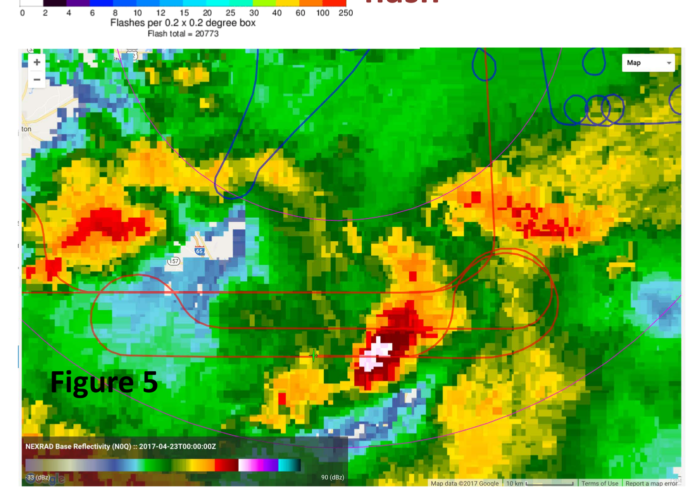
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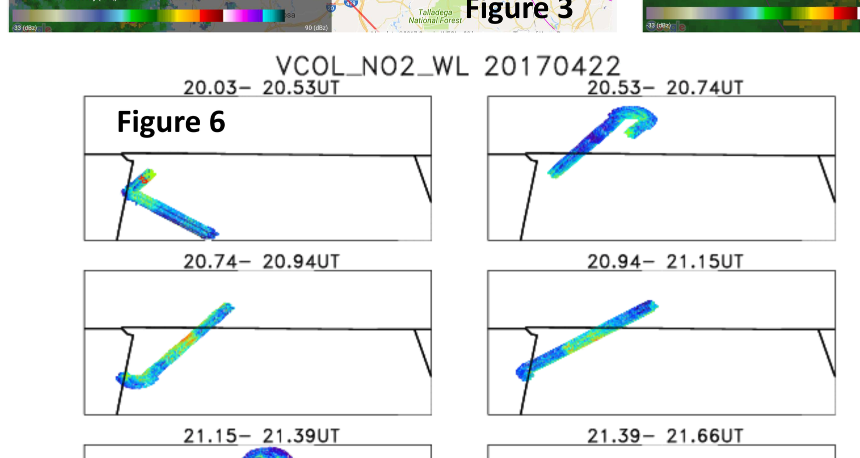

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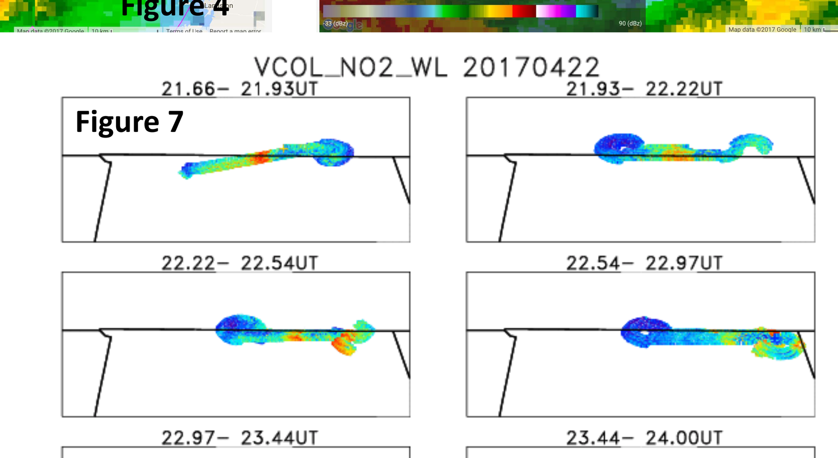

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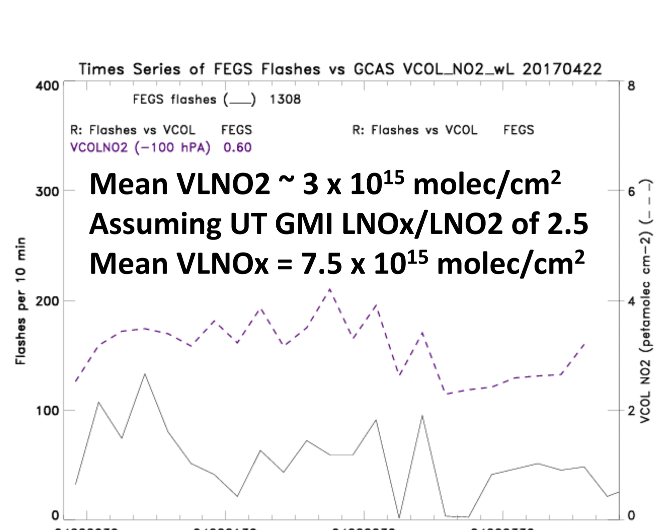
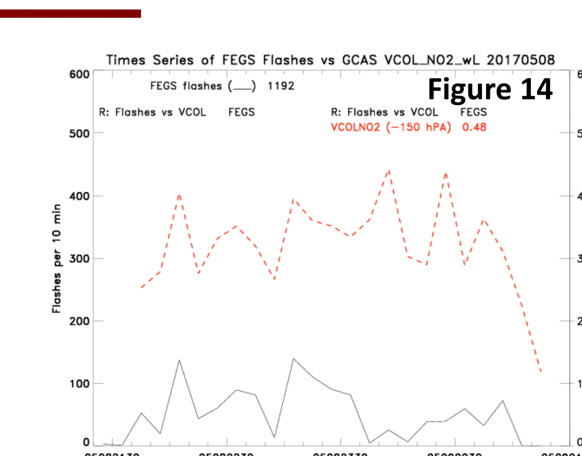


Figure 8

- GCAS data are retrieved in the form of 250 m x 250 m pixels (21 pixels cross track with averaging along track).
- Uncertainty exists concerning how far into the storm cloud GCAS was able to detect NO_2. We tested several pressure offsets (100, 150, 200, 250, 300, 400 hPa) below the CPL cloud top, and the results for the offset producing the largest correlation with FEGS flashes is displayed in Figures 6-8 and 12-14.
- April 22: Maximum NO_2 columns observed over northern storm 2140 – 2232 UT. FEGS flashes peak during this period, but flash rates were larger earlier.
- May 8: Maximum NO_2 column observed over northern storm early (2140-2210 UT) and again later (2255-2320 UT). Even larger maxima were found in the eastern storm (2340-0040 UT). However, FEGS flash rates peaked in the northern storm.
- Vertical NO_2 columns -- moderately correlated with FEGS flashes in both flights.

May 8, 2017 Colorado Storms

Upslope flow behind a cold front draped across northern Colorado aided in initiating strong convection in a very unstable air mass. Two supercell storms were observed by the ER-2, one initially over Greely, CO and one over Denver (Figure 9). The first lightning flash occurred at 2148 UT as the ER-2 approached the storms. A roughly north/south pattern (Figure 10) was flown over the two compact high flash rate supercells until the southern storm dissipated (~2300 UT) at which time the focus shifted to only the northern storm (2302-2345 UT). A storm farther to the east was then targeted (0010-0100 UT) (Figure 11).



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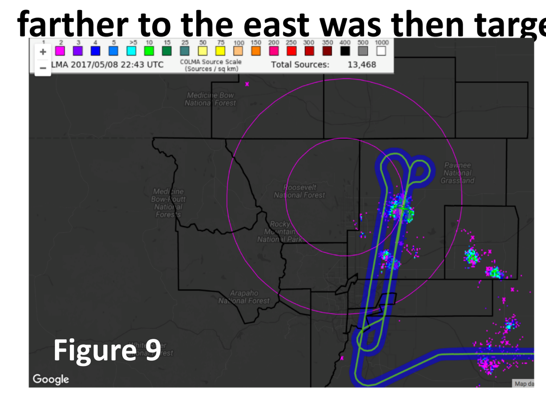
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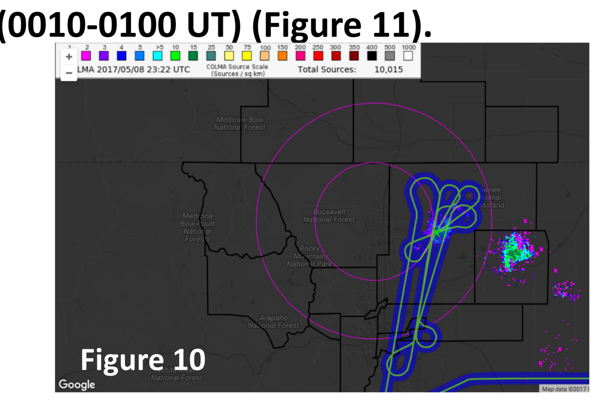
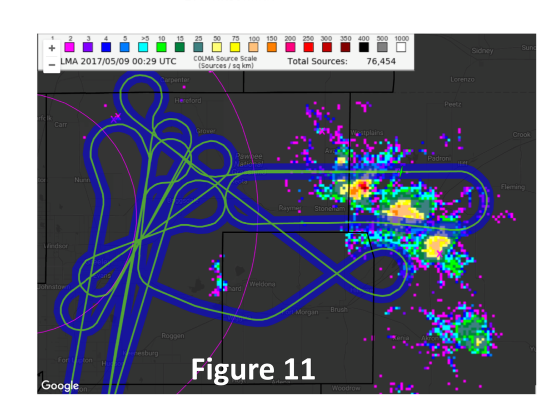


Figure 10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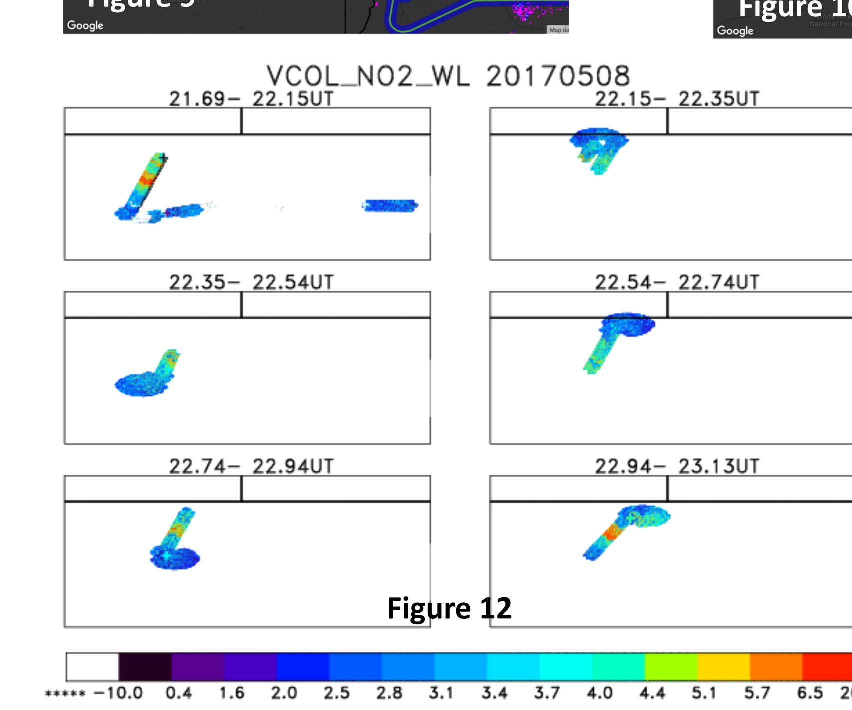

Figure 12

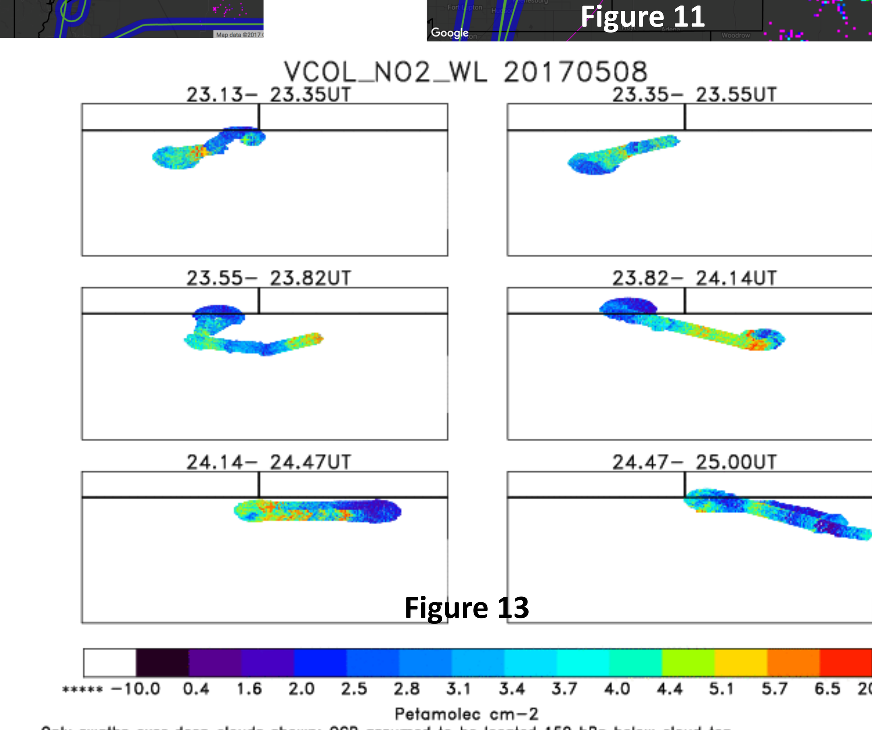

Figure 13

Summary

GCAS NO_2 columns were observed over six storms overflown by the ER-2 aircraft during the GOES-R Validation Campaign.
GCAS NO_2 columns were moderately correlated with FEGS flashes observed simultaneously.
A rough estimate of mean NOx production per flash in the April 22 Alabama storm was 150 - 300 moles per flash.

Next Steps

LNO_x should be better correlated with an accumulation of flashes over a period prior to and during the aircraft overpass.
GLM data will be used to estimate the numbers of contributing flashes.

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