J2A.8 GLM ESTIMATES OF LNOx OVER THE CONTINENTAL US: GROUND AND CLOUD FLASH DIFFERENCES

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1. INTRODUCTION

The studies in Koshak et al. (2014) and Koshak (2017) introduced ways of using space-based lightning imager flash optical energy data [such as obtained from the TRMM Lightning Imaging Sensor (TRMM/LIS), and the GOES-16 Geostationary Lightning Mapper (GLM)] to estimate lightning nitrogen oxides (LNOx) production. The flash optical energy data was used as a proxy to estimate total flash energy, and this total energy was multiplied by a thermochemical yield [Y_o ~ $9\text{x}10^{16}$ molecules/J; Borucki and Chameides (1984)] to obtain LNOx production in the flash. Flashes that were more optically energetic were assumed to have, on average, a larger total flash energy and therefore would produce more LNOx. GLM typically intercepts only a few hundred femto-joules (fJ) of optical energy due to a lightning flash, whereas the total flash energy is typically measured in giga-joules (GJ). Therefore, GLM only detects a very small fraction of the total flash energy. This fraction, or β-factor, has been chosen so that the mean LNOx per flash over a long (e.g. 1 yr) reference period is 250 moles (an often cited value in the literature; i.e. Huntrieser et al., 1998). This calibration technique represented the 1st step in attempting to estimated LNOx solely by TRMM/LIS or GLM, and has provided a reasonable way to trend relative changes in LNOx across different time-scales; i.e., it has shown interesting relative peaks of LNOx/flash in the winter months over the continental US (CONUS).

In this study, a new method is introduced and applied that employs not only flash optical energy, but also flash optical area, to better constrain GLM-derived LNOx estimates. The method uses a more quantitative approach for estimating total flash energy then the β-factor studies mentioned above. Overall, the new method (detailed in section 2) can be viewed as a 2nd step along the path to improving GLM-derived LNOx estimates. As such, and given the importance of LNOx in climate and air quality studies, it also represents an important advance in applying GOES-16 GLM observations to support ongoing National Climate Assessment (NCA) analyses (Koshak et al., 2015). The method is applied to millions of flashes observed by GLM over CONUS in June of 2020 (sections 3-5). National Lightning Detection Network™ (NLDN) data is used to discriminate ground and cloud flashes so that GLM-inferred LNOx production (section 5) from ground and cloud flashes can be compared. Conclusions are provided in section 6.

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2. VIRTUAL CAPACITOR METHOD (VCM)

2.1 Overview

The thunderstorm environment and lightning discharges are of course complicated, but one can start with an idealized dipole charge structure, with a main positive charge (P-region) at an altitude of about 10 km, and a main negative charge (N-region) at about 6.5 km. It is assumed that the P-region contains a charge $Q > 0$, and the N-region a charge $-Q$. Positive polarity ground flashes deposit a charge fQ to ground, where f is a fraction in the range 0-1. Similarly, negative ground flashes are assumed to deposit a charge $-fQ$ to ground, and a cloud flash is assumed to transfer a charge $-fQ$ from the N-region to the P-region. The value of f is difficult to pick since (in reality) it varies from flash to flash, but an optimal or typical value will ultimately be chosen as a simplifying assumption. Figure 1 summarizes the situation for a cloud flash [the situation for ground flashes would look similar, but of course the upper charge region would be either the P-region (for positive polarity ground flashes) or the N-region (for negative polarity ground flashes), and the lower charge region would represent the Earth surface and would therefore be below cloud base].

So in this highly simplified thundercloud model, one is only interested in the fact that a lightning discharge occurs between two altitude levels of equal and opposite charge, and that a vertical electric field E between the two charge altitudes drives the discharge current.

In fact, it is important to note that the entire thunderstorm (with all its complexity and possibly composed of multiple individual thundercloud cells) is "thrown out" and replaced with a virtual parallel plate capacitor, with circular charged capacitor plate area A separated by vertical distance d. This means that no attempt is made to model the thundercloud(s) with say the usual dipole or tripole charge distribution situated above a conducting plane, which would involve the use of image charges for solving an electrostatic boundary value problem. All of that modeling complexity is removed in favor of noting that any mostly vertical discharge can be simulated, or mimicked if you will, with a giant virtual capacitor. For example, one could envision the Gedanken ("thought") experiment of a huge laboratory capacitor with plate charge, plate area, and plate separation characteristics selected so as to create a huge laboratory spark that best or most closely represents the energetics of a particular natural lightning flash. This *Virtual Capacitor Method (VCM)* represents an alternative to the electrostatic boundary value problem, and the two approaches should not be conflated.

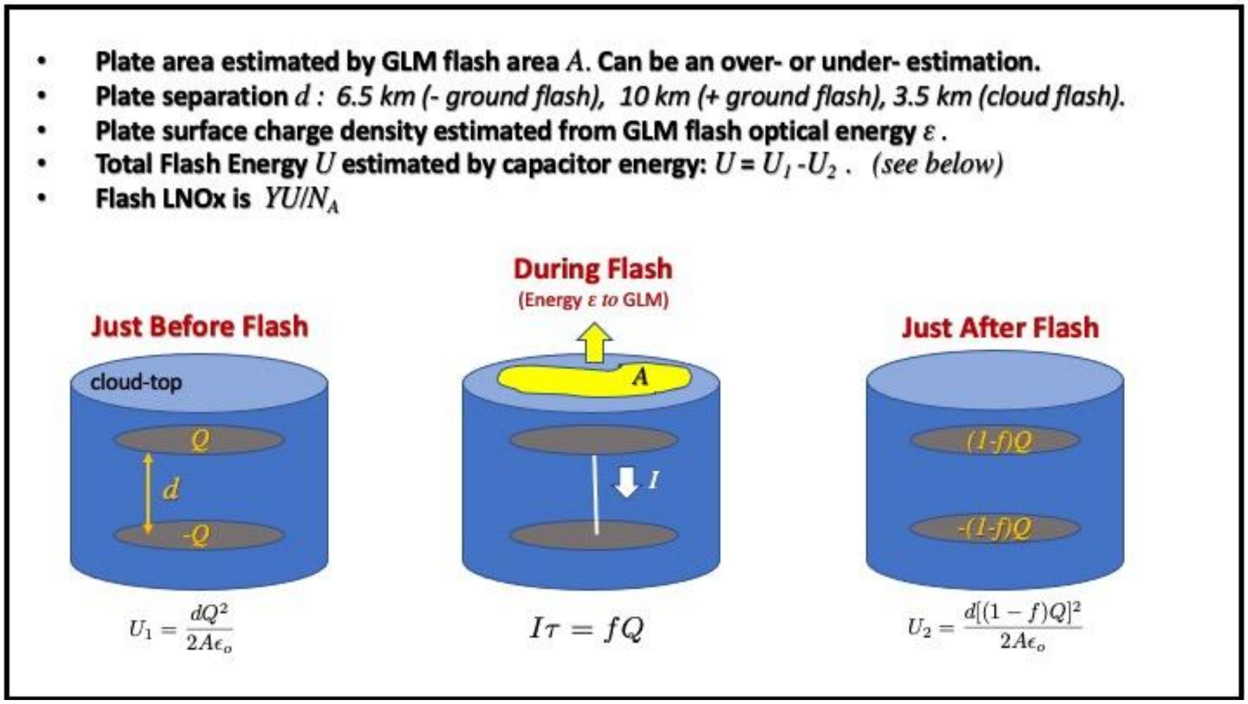

Figure 1. Illustration of the Virtual Capacitor Method for the case of a cloud flash. See main text for details.

2.2 Estimating the Area of N- and P- Regions

As shown in Figure 1, the charged capacitor plates, representing the charged N- and P- regions, are shown in brown. The areas of these charge regions, modeled by the capacitor plate areas, are estimated using the GLM flash area, which can be either an over-estimate (cloud lights up beyond the physical extent of the charged regions) or an under-estimate (cloud is so optically thick that it significantly depletes the cloud-top illumination area). The thunderstorm charge region area, the capacitor plate area, and the GLM flash area are all denoted by the variable A, but it should be understood that they are all technically distinct/different; again the GLM flash area is used to estimate the other two.

2.3 Total Electrostatic Energy of the Flash

The electrostatic energy of a parallel plate capacitor is $Q^2/(2C)$, where $C = \epsilon_o A/d$, and ϵ_o is the permittivity of free space. Figure 1 shows this thunderstorm energy, U_1, just before the flash, as well as just after the flash, U_2. Hence, the thunderstorm goes from a higher energy state to a lower energy state, having dissipated flash energy $U = U_1 - U_2$. Note that during the flash, one can think of an average flash current I that transfers a total charge fQ from the P-region to the N-region during flash time τ.

2.4 LNOx Produced by the Flash

The LNOx is estimated by multiplying the total flash energy U by the thermochemical yield Y, and dividing by Avogadro's Number N_A to convert into moles.

According to Chameides et al. (1977), the yield associated with a cylindrical lightning channel segment of length L and radius r is proportional to the segment volume $\pi r^2 L$ times the air density. Since the scale-height of the atmosphere is approximately 8.5 km, the air density decreases appreciably with altitude. This implies that a channel segment at higher altitude would result in fewer air molecules being raised to the freeze-out temperature (T ~ 2300 K) and hence less NOx production. Integrating the air density profile in a standard atmosphere (scale height 8.5 km) across distance d of the channel (i.e., the capacitor plate separation) gives the following relative weights for the thermochemical yield of the 3 different discharges employed in the VCM: 0.692 (+ ground flashes), 0.535 (- ground flashes), and 0.157 (cloud flashes). Hence, the yield is $Y = wY_o$ where w is the weight for the particular discharge, and Y_o is the base value given above from Borucki and Chameides (1984).

2.5 Relation Between Current and Optical Energy

In reality, the current I depicted in Figure 1 is composed of one or more transient surges of current that varies appreciably both in space and in time, and is responsible for the optical emission that illuminates cloud-top. The GLM optical group data product is typically associated with an individual stroke or current surge, and occupies one GLM frame time of 2 ms, by definition. Therefore, one can consider such a current surge and the associated optical group that GLM would register due to that surge.

A hot plasma column model, assumed to be in Local Thermodynamic Equilibrium (LTE), and that includes both thermal blackbody and line emissions, is provided in Li and Zhang (2000). In effect, their result provides a detailed physical model for the optical emission from a current channel segment, but without any intervening cloud scattering medium (i.e., they applied their model to describe laboratory arc welding). One can integrate their model expression over 4π steradians, over the GLM bandpass, and over one GLM frame time for an optical group, and then multiply by a coefficient η_j to account for cloud-multiple scattering attenuation and the finite solid angle of the optical group at cloud-top as viewed by GLM. When this is done, a linear relationship is obtained relating the j^{th} current segment I_j to the associated j^{th} group optical energy ε_j detected by GLM to give

$$\varepsilon_j = K_j I_j \;, \tag{1}$$

where the kernel K_j depends on a host of physical variables (i.e., GLM center wavelength and GLM frame duration, the coefficient η_j , the driving electric field strength E, and several channel segment characteristics: radius, length, temperature, absorption coefficient, and thermal coefficient). Following da Silva et al. (2019), the hot plasma current is assumed to be ohmic so that

$$E = I_j \rho_j \;, \tag{2}$$

where ρ_j is the channel resistance per unit channel length. In addition, the field E driving the current is related to the capacitor plate charge density σ in the familiar way

$$\sigma = \epsilon_o E \;\; . \tag{3}$$

Solving (2) for I_j , eliminating E with (3), substituting the result for I_j into (1), and summing over the $j = 1, \ldots , n$ groups in the flash gives a relationship between the flash energy and thundercloud (i.e. capacitor plate) charge density

$$\varepsilon = \; [(1/\epsilon_o)\Sigma_j \, K_j / \rho_j \,]\, \sigma \;\; . \tag{4}$$

This result says that if the thundercloud charge regions (i.e., the N- and P- region) charge density σ is high, the electric field E will be large and will drive a strong current implying a very bright (optically energetic) channel emission that results in a strong cloud-top flash optical energy ε observed by GLM, everything else being equal. Since the expression in square brackets in (4) is complicated and varies from flash-to-flash, and there are no direct measurements of its value, one can average both sides of (4) over many flashes, and solve for the term in square brackets to get a typical value. When this is done, (4) becomes

$$\sigma = \; (\varepsilon / \varepsilon_{ave})\, \sigma_o \;, \tag{5}$$

where ε_{ave} is the average flash optical energy across a sufficiently long analysis period, and σ_o is 1 C/km^2, a reasonable magnitude for the charge density of the N- or P- regions in a thundercloud (Marshall and Stolzenburg, 1998).

2.6 Summary

Using the VCM, the production P of LNOx (in moles) given GLM flash optical energy ε and GLM flash area A can be summarized as follows:

$$\begin{aligned} P &= \; [wY_o / N_A] \; U \\ U &= \; [d\,(2\text{-}f\,)\, f / (2A\,\epsilon_o)] \; Q^2 \\ Q &= \; \sigma A \; = \; (\varepsilon / \varepsilon_{ave})\, \sigma_o A \,. \end{aligned} \tag{6}$$

The fraction f of the total charge Q deposited by the flash is difficult to pick, and there are perhaps many opinions on what value to use. Clearly, it varies from flash-to-flash. It is a measure of how well or efficiently the flash can tap the thundercloud charge. From a Bayesian standpoint, one might begin with a prior unbiased (i.e., middle-of-the-road) estimate of $f = 0.5$. But in this initial study, the often cited value of P = 250 moles per flash is used to constrain the value of f. When this is done, a value of $f = 0.1807$ results in a mean value of P = 250 moles/flash from the VCM (see VCM results given later for additional details).

3. APPLICATION OF THE VCM

In this study, the VCM is applied to analyze flashes that occurred over CONUS for the entire month of June 2020. Figure 2 shows the analysis region, and as an example, GLM flash locations for one of the days in the month (5 June 2020) are provided.

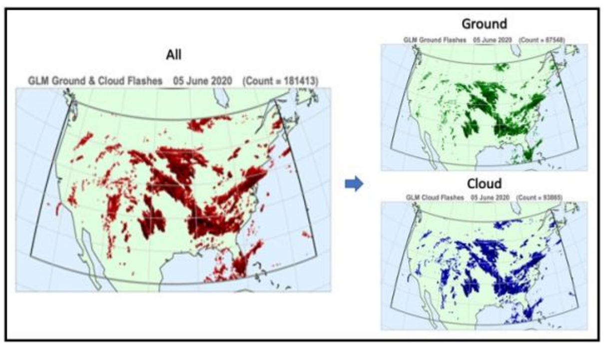

Figure 2. Example of flash-typing the GLM flashes.

NLDN data were used to determine flash-type (i.e., ground or cloud flash). If at least one NLDN ground flash was both within 50 km and within 1 sec of a GLM flash, the GLM flash was assumed to be a ground flash. If no NLDN ground flash could be found that was both within 200 km and within 1 sec of the GLM flash, the GLM flash was assumed to be a cloud flash. Additionally, if no NLDN ground flashes were within 2 sec (no matter how spatially close to the GLM flash) the GLM flash was assumed to be a cloud flash. If none of these conditions were met, the GLM flash was regarded to have an uncertain flash-type and was removed from the analysis. For June 2020, a total of 4,369,525 GLM flashes were successfully flash-typed (2,076,981 as ground flashes, and 2,292,544 as cloud flashes). Figure 2 shows an example of how the GLM flashes on June 5 were separated into ground and cloud flashes.

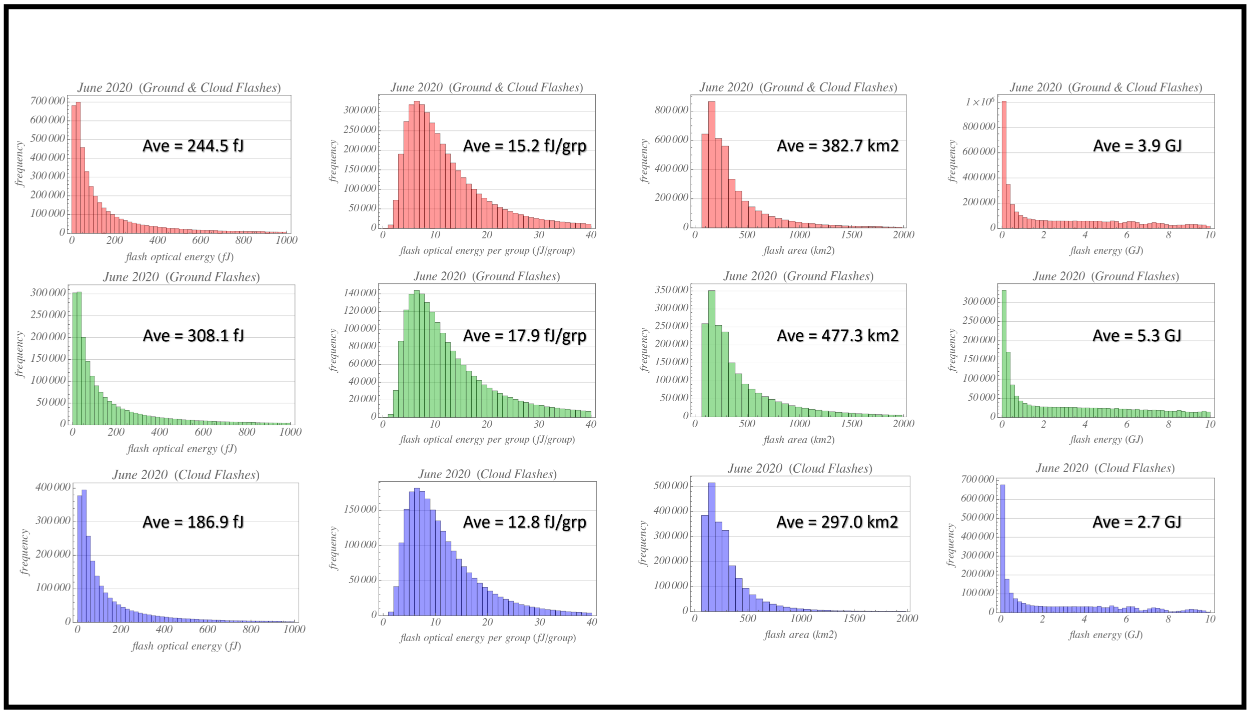

Figure 3. Frequency distributions of GLM observations are in first three columns: (col. 1) flash optical energy, (col. 2) optical energy per group, (col. 3) flash area. The associated VCM total electrostatic flash energy estimates are provided in fourth column. Top row is for all flashes, middle row for ground flashes, and bottom row for cloud flashes.

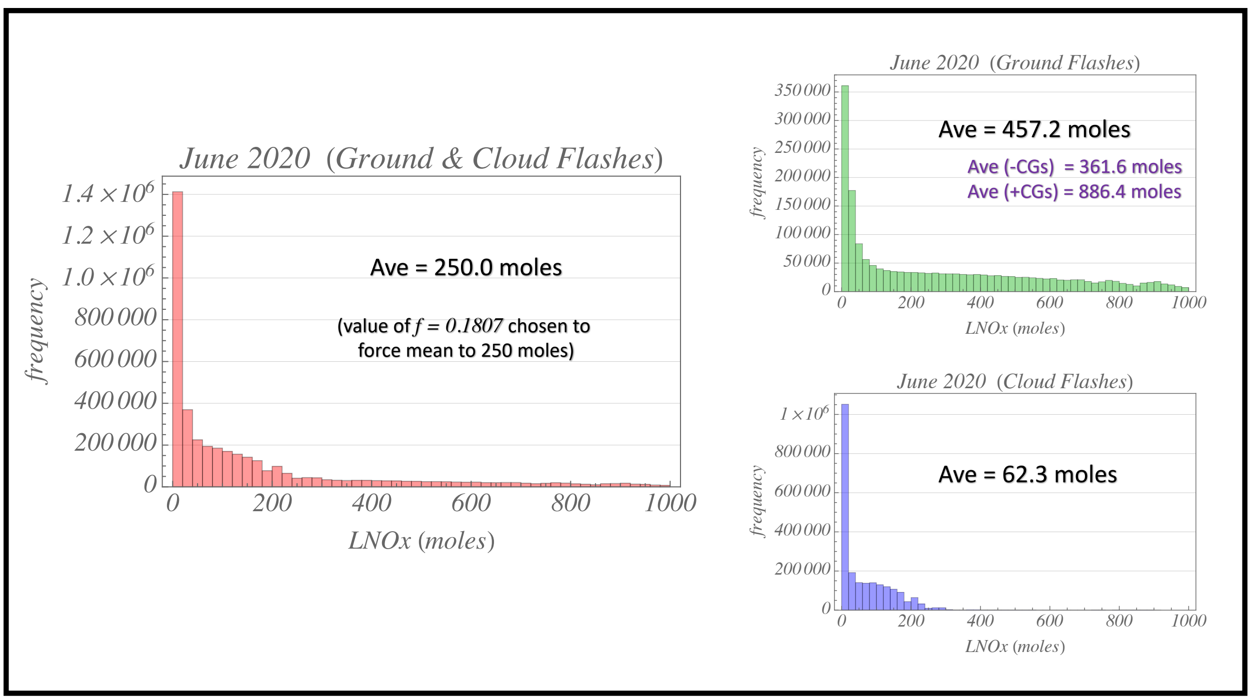

Figure 4. VCM LNOx results. Because the GLM observations show larger optical energies & areas for the ground flashes, the associated LNOx values from the VCM are significantly larger for ground flashes compared to cloud flashes. If all the weights to the thermochemical yields are set equal to unity, the gap between ground and cloud flash LNOx tightens (see section 5 of main text for details).

4. GLM DATA & VCM-DERIVED ENERGY

Figure 3 provides the frequency distributions of the GLM observations (first 3 columns) and the associated VCM-derived total electrostatic flash energy results (fourth column), for all flashes (top row), ground flashes (middle row), and cloud flashes (bottom row). The GLM observations clearly indicate that the flash optical energy is larger on average for ground flashes (308.1 fJ) than for cloud flashes (186.9 fJ). This pattern holds for the group energies as well. The GLM flash areas are also larger on average for ground flashes (477.3 km^2) than for cloud flashes (297.0 km^2). These facts lead to about a factor of 2 larger average flash energy for ground flashes (5.3 GJ) compared to cloud flashes (2.7 GJ).

5. LNOx RESULTS

The larger GLM flash optical energies and areas that lead to larger VCM-derived total electrostatic flash energy for ground flashes, coupled with the higher thermochemical yields for ground flashes (section 2.4) result in substantially larger LNOx values for ground flashes (457.2 moles) compared to cloud flashes (62.3 moles), as shown in Figure 4. The ratio is 457.2/62.3 = 7.34. A second run of the VCM was done with the thermochemical yield weights, w, all set to 0.5. This gave average ground and cloud flash LNOx results of 393.4 moles and 198.2 moles, respectively, or a ratio of 1.98. Therefore, it is worth noting the substantial effects of air density fall-off with altitude, in comparison to flash energy itself, when examining LNOx production.

6. CONCLUSIONS

The complicated nature of a lightning discharge and the thunderstorm electrical environment make it difficult to remotely infer flash energy (and hence LNOx). However, this study has introduced a Virtual Capacitor Method (VCM) for making reasonable estimates of LNOx from GLM observations (i.e., flash optical energy, and flash area).

A large charge density on the N- and P- regions of a thundercloud produces a strong vertical electric field that drives a strong lightning discharge current, and hence produces a strong optical emission which illuminates cloud-top and can be detected by GLM. Therefore, GLM flash optical energy is related to thundercloud charge density [equations (4) & (5)].

Multiplying the inferred charge density by the GLM flash area (a proxy for the area of the N- and P- regions; i.e., the capacitor plate areas) gives the net charge on each plate.

Nominal altitudes of the N- and P- regions are assumed so that the capacitor plate separation can be computed.

Hence, with the capacitor plate charge, plate area, and plate separation, the flash energy can be found [see Figure 1], as well as the sought after LNOx production (i.e., by multiplying the flash energy by the thermochemical yield); see the summary equations in (6).

The VCM was applied to analyze millions of GLM flashes over CONUS, and the flashes were segregated into ground and cloud flashes using NLDN data. LNOx results were provided (section 5), and reveal that ground flashes produce substantially more LNOx than cloud flashes, even if the relative effects of air density on thermochemical yield are ignored.

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7. REFERENCES

- Borucki, W. J., and W. L. Chameides, 1984: Lightning: estimates of the rates of energy dissipation and nitrogen fixation, *Rev. Geophys. Space Phys*., 22, 363–372.
- Chameides, W. L., D. H. Stedman, R. R. Dickerson, D. W. Rusch, and R. J. Cicerone, 1977: NOx production in lightning, *J. Atmos. Sci.*, 34, 143-149.
- da Silva, C. L., R. G. Sonnenfeld, H. E. Edens, P. R. Krehbiel, M. G. Quick, and W. J. Koshak, 2019: The plasma nature of lightning channels and the resulting nonlinear resistance, *J. Geophys. Res. - Atmos*., 124, 9442-9463. https://doi.org/10.1029/2019JD030693.
- Huntrieser, H., H. Schlager, C. Feigl, and H. Holler, 1998: Transport and production of NOx in electrified thunderstorms: Survey of previous studies and new observations at midlatitudes, *J. Geophys. Res.* , 103 , 28,247–28,264.
- Koshak, W. J., 2017: Lightning NOx estimates from space-based lightning imagers, *16th Annual Community Modeling and Analysis System (CMAS) Conference*, Chapel Hill, NC, October 23-25.
- Koshak, W. J., K. L. Cummins, D. E. Buechler, B. Vant-Hull, R. J. Blakeslee, E. R. Williams, H. S. Peterson, 2015: Variability of CONUS Lightning in 2003-12 and Associated Impacts, *J. Appl. Meteorol. Climatology*, 54, No. 1, 15-41.
- Koshak, W. J., B. Vant-Hull, E. W. McCaul, and H. S. Peterson, 2014: Variation of a lightning NOx indicator for national climate assessment, *XV International Conference on Atmospheric Electricity*, Norman, Oklahoma, June 15-20.
- Li, P. J. and Y. M. Zhang, 2000: Analysis of an arc light mechanism and its application in sensing of the GTAW process, *Welding Journal*, 79, 252 – 260.
- Marshall, T. C. and M. Stolzenburg, 1998: Estimates of cloud charge densities in thunderstorms, *J. Geophys. Res.*, 103, No. D16, 19769-19775.