Production efficiency of lightning NO\textsubscript{x} at northern mid-latitudes

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ABSTRACT
Lightning is the major source of NO\textsubscript{x} (NO + NO\textsubscript{2}) in the mid to upper troposphere. We estimate the production efficiency (PE) of lightning NO\textsubscript{x} (LNO\textsubscript{x}) in mole/flash from Ozone Monitoring Instrument (OMI) and World Wide Lightning Location Network (WWLLN) data in three northern mid-latitude regions during June-July-August 2007 – 2011. This study includes the largest number of convergent events to date to estimate the LNO\textsubscript{x} PE using both satellite NO\textsubscript{x} data and ground-based lightning measurements. We infer an average of 321 ± 180 moles LNO\textsubscript{x} per lightning flash and find evidence of a dependence of PE on the lightning flash rate, consistent with some previous ground and aircraft-based studies.

INTRODUCTION
Oxides of nitrogen are critical trace gases in the troposphere and are precursors for nitrate aerosol and ozone, an important greenhouse gas. Quantitative estimates of the global contribution of lightning depend critically on the assumed PE. Previous theoretical, laboratory, aircraft, modeling and satellite studies give values that vary by more than an order of magnitude. In their review study, Schumann and Huntrieser [2007] suggest an average value of 250 moles LNO\textsubscript{x} – N\textsubscript{NO} per lightning flash. This is more than three times the value based on 302 moles LNO\textsubscript{x} – N\textsubscript{NO} generated by lightning in the same box. This is illustrated in Figure 4.

WORLD WIDE LIGHTNING LOCATION NETWORK
The WWLLN is an array of very low frequency (VLF) sensors that detect silences from lightning (e.g., Virts et al., 2013). The data are calibrated against optical transient detector (OTD) and lightning imaging sensor (LIS) climatologies (Cecil et al., 2014), and binned on a 1° x 1° grid. For this study, flash detections were counted 1 hour before the OMI overpass to ensure only freshly produced LNO\textsubscript{x} was measured and to minimize effects of advection loss.

GLOBAL MODELING INITIATIVE (GMI)
NASA’s GMI model [Duncan et al., 2007; Ziemke et al., 2006; Strahan et al., 2013] is a chemical transport model used here for LNO\textsubscript{x} and LNO\textsubscript{x} profiles, computed as differences of model runs with and without a lightning source. Profile shapes are used for scaling NO\textsubscript{x} observed above the clouds to obtain total LNO\textsubscript{x} columns. We use year-specific monthly mean GMI output based on recent emissions inventories.

Figure 1: Sensor locations color-coded by deployment year and estimated detection efficiencies for two years.

Figure 2: GMI profile examples.

GLOBAL MODELING INITIATIVE (GMI)
The OMI NO\textsubscript{x} data are the NASA Standard Product version 3.0 (Krotkov et al., 2017), specifically total slant column densities (SCD\textsubscript{OMI}), stratospheric air mass factors (AMF\textsubscript{OMI}) and stratospheric vertical column densities (VCD\textsubscript{OMI}) that were smoothed zonally to minimize aliasing of small local tropospheric enhancements into the stratosphere. We also compute AMF\textsubscript{BG}*, which is the ratio of the modeled tropospheric NO\textsubscript{x} SCD to the modeled total LNO\textsubscript{x} + VCD. The retrieved LNO\textsubscript{x} + VCD is

Figure 3: Mean data for JJA 2007 – 2011 averaged temporally over the 1° longitude x 1° latitude flashing boxes. (a) LNO\textsubscript{x} + VCD from OMI measurements, (b) OMI NO\textsubscript{x} background, (c) LNO\textsubscript{x} = LNO\textsubscript{x} – BG, (d) mean daily WWLLN flash counts in flashing boxes. The red lines outline the three continental regions examined in this study. Continental-scale correlations of LNO\textsubscript{x} with lightning are evident by inspection (e.g., E. USA and E. Asia), but less clear on smaller scales.

For all flashing boxes over the three geographic regions and 460 days, we computed the correlation coefficients, r, for LNO\textsubscript{x} with 1-hour flash counts at different times and locations. Correlations are small but provide strong evidence the LNO\textsubscript{x} observed in a given box is fresh LNO\textsubscript{x} generated by lightning in the same box. This is illustrated in Figure 4.

Figure 4: Blue boxes show Pearson’s r between flashes in a given box and LNO\textsubscript{x} in surrounding boxes. Those in (a) and (c) are correlations between flashes and LNO\textsubscript{x} from the previous and following days, respectively, and (b) are same-day correlations.

REGRESSION ANALYSIS
Data in all flashing boxes were binned by 1-hour flash rates in 500 flash/hour bins and compared with the corresponding binned LNO\textsubscript{x}. We have fitted two 2-parameter functions to the data: a straight line (blue) and a power function (red dash) as shown below. Comparison of the chi-squared for the two fits indicates the linear fit is in better agreement with the data.

Figure 5: Regression of OMI LNO\textsubscript{x} against binned WWLLN flash counts. (a) linear-axis scaling and (b) log-log scaling. Orange and green lines have arbitrary vertical placement, but their respective slopes indicate a linear and a non-existent relationship between LNO\textsubscript{x} and flashes. AVERAGE PE
Dividing total moles LNO\textsubscript{x} by total flashes in all flashing boxes yields an overall average PE independent of flash rate. Considering the major systematic uncertainties in this study, we obtain a value of 321 ± 180 mole/flash.

For a global flash rate of 46* [Cecil et al., 2014], this corresponds to 6 x 3.6 Tg N/yr, which is within the range of the 5 x 3 Tg N/yr from the review study of Schumann and Huntrieser [2007].

ACKNOWLEDGMENTS
This work is funded under a NASA Atmosphere Venture project titled by Nickolya Krotkov. Megan Davies performed the PE lightning simulations.