

# The NASA Lightning Nitrogen Oxides Model (LNOM): Application to Air Quality Modeling

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**ABSTRACT:** Recent improvements to the NASA Marshall Space Flight Center Lightning Nitrogen Oxides Model (LNOM) and its application to the Community Multiscale Air Quality (CMAQ) modeling system are discussed. The LNOM analyzes Lightning Mapping Array (LMA) and National Lightning Detection Network<sup>TM</sup> (NLDN) data to estimate the raw (i.e., unmixed and otherwise environmentally unmodified) vertical profile of lightning NO<sub>x</sub> (= NO + NO<sub>2</sub>). The latest LNOM estimates of lightning channel length distributions, lightning 1-m segment altitude distributions, and the vertical profile of lightning NO<sub>x</sub> are presented. The primary improvement to the LNOM is the inclusion of non-return stroke lightning NO<sub>x</sub> production due to: (1) hot core stepped and dart leaders, (2) stepped leader corona sheath, K-changes, continuing currents, and M-components. The impact of including LNOM-estimates of lightning NO<sub>x</sub> for an August 2006 run of CMAQ is discussed.

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**ABSTRACT:** Recent improvements to the NASA Marshall Space Flight Center Lightning Nitrogen Oxides Model (LNOM) and its application to the Community Multiscale Air Quality (CMAQ) modeling system are discussed. The LNOM analyzes Lightning Mapping Array (LMA) and National Lightning Detection Network™ (NLDN) data to estimate the raw (i.e., unmixed and otherwise environmentally unmodified) vertical profile of lightning NO<sub>x</sub> (= NO + NO<sub>2</sub>). The latest LNOM estimates of lightning channel length distributions, lightning 10-m segment altitude distributions, and the vertical profile of lightning NO<sub>x</sub> are presented. The primary improvement to the LNOM is the inclusion of non-return stroke lightning NO<sub>x</sub> production due to: hot core stepped and dart leaders, stepped leader corona sheath, K-changes, continuing currents, and M-components. The impact of including LNOM-estimates of lightning NO<sub>x</sub> for an August 2006 run of CMAQ is discussed. Global estimates of lightning NO<sub>x</sub> are also provided using the NASA satellite global lightning climatology.

## 1. INTRODUCTION

The methodologies for estimating lightning NO<sub>x</sub> have involved theoretical and laboratory studies, studies that attempt to combine aircraft measurements with modeling results, and studies that are based on satellite observations. Unfortunately, there has been considerable variability in the estimates of lightning NO<sub>x</sub> production per flash; see for example the summary table in Labrador et al. (2004) and the review paper by Schumann and Huntrieser (2007). The variability in these estimates is linked to the differences in the measurements and estimation methods employed, and the natural variability of lightning. Recently, the NASA Marshall Space Flight Center introduced the Lightning Nitrogen Oxides Model (LNOM; Koshak et al., 2010) to combine routine and accurate measurements of lightning with Wang et al. (1998) lightning NO<sub>x</sub> laboratory results.

In the present study, we implement important upgrades to the LNOM, and apply it to analyze thunderstorms occurring over North Alabama for the following months: August 2005, August 2006, August 2007, August 2008, and August 2009. The LNOM-derived lightning NO<sub>x</sub> profiles are then used to assess the impact of lightning NO<sub>x</sub> on an August 2006 run of the Community Multiscale Air Quality (CMAQ) modeling system. Global estimates of lightning NO<sub>x</sub> production are also provided using the NASA Optical Transient Detector (OTD) and Lightning Imaging Sensor (LIS) global lightning climatology.

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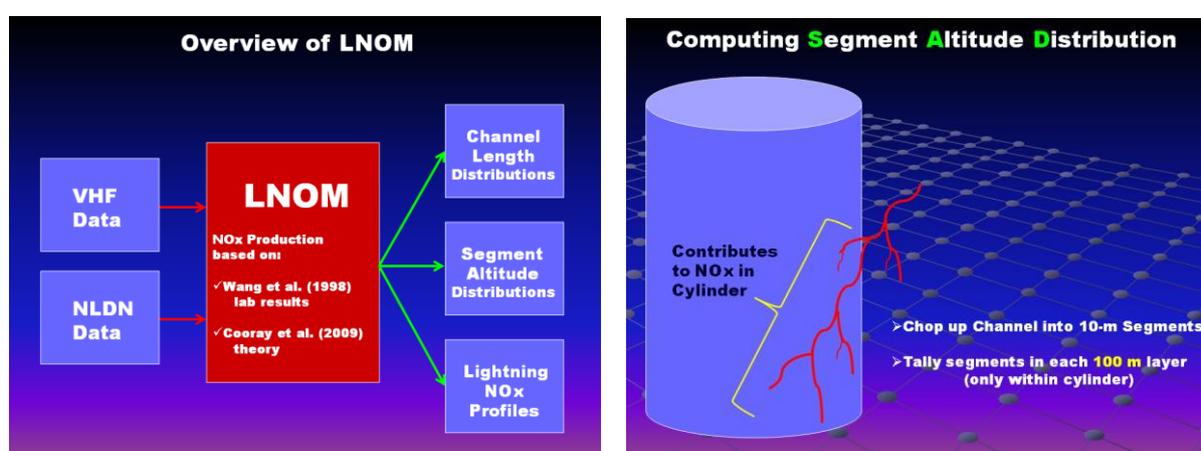
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## 2. THE LNUM

### 2.1 Basic Functionality

The LNUM ingests lightning VHF source location (and time-of-occurrence) data such as obtained from the North Alabama Lightning Mapping Array (NALMA). It also ingests location, time-of-occurrence, peak current, and stroke multiplicity data from the National Lightning Detection Network™ (NLDN). These data are used to determine the flash type (ground or cloud) of each flash occurring within an analysis cylinder (height 0-20km, and radius 20.31km). This cylinder is the approximate volume equivalent of a 36km x 36km CMAQ grid cell. The LNUM analyzes the VHF sources to estimate the total channel length of each flash. It also chops each portion of a flash contained in the analysis cylinder into 10-m segments to determine the Segment Altitude Distribution (SAD) within the cylinder. Finally, it computes the vertical lightning NO<sub>x</sub> profile in the cylinder; see Figure 1.



**Figure 1. Functionality of the LNUM showing (left) inputs & outputs, and (right) the analysis cylinder and details of channel segment altitude distribution computation.**

### 2.2 Recent Upgrades

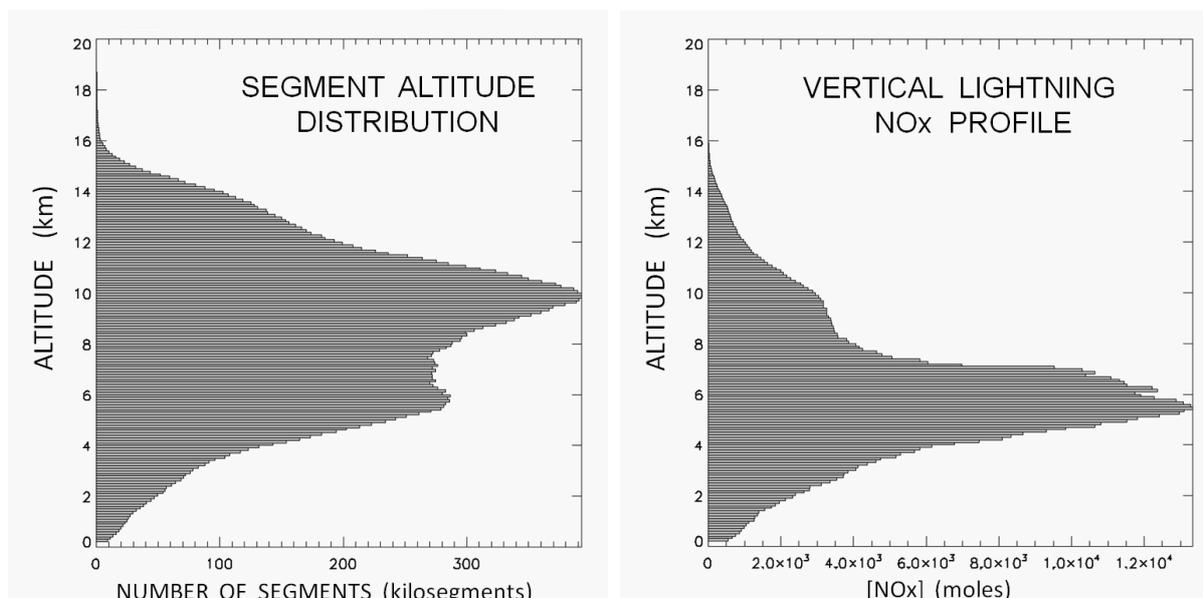
Upgrades to LNUM involve the addition of several important non-return stroke processes that produce NO<sub>x</sub> (see Cooray et al., 2009), but are often neglected by other investigators. Specifically, the LNUM upgrades include NO<sub>x</sub> contributions from: hot core stepped leader, hot core dart leaders, stepped leader corona sheath, K-changes, continuing currents, and M-components.

### 2.3 Examples of LNUM Output

Examples of the LNUM output for the August 2006 analysis period in Northern Alabama are provided in Figure 2. The LNUM also provides the component NO<sub>x</sub> profiles due to each separate production mechanism (i.e., return strokes, hot core stepped leaders, hot core dart leaders, stepped leader corona sheaths, K-changes, continuing currents, and M-components). The sum of these components gives the final result shown in the right-side plot of Figure 2. The average channel length of a flash (across all five Augusts) ranged from 38.9 km to 69.6 km.

## 3. LIGHTNING NO<sub>x</sub> STATISTICS

The LNUM analysis of the five Augusts (2005-2009) has provided statistics of the amount of NO<sub>x</sub> produced by ground and cloud flashes, and by all flashes overall as shown in Table 1.

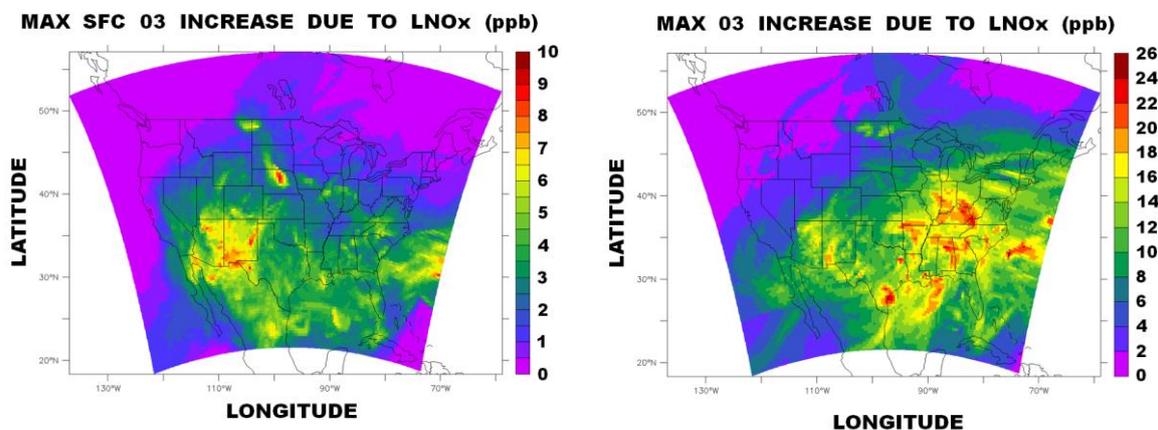


**Figure 2.** Example of two L NOM output products for the August 2006 analysis period.

<b>Table 1. L NOM summary statistics [NO<sub>x</sub> is in moles; NO<sub>x</sub> values are flash-count-weighted means].</b>						
Period	# Ground Flashes	# Cloud Flashes	Total # of Flashes	NO <sub>x</sub> per Ground Flash	NO <sub>x</sub> per Cloud Flash	NO <sub>x</sub> per Flash
August 2005	1023	5306	6329	403.26	26.34	87.27
August 2006	1067	6986	8053	601.41	34.03	109.21
August 2007	1058	5766	6824	450.17	37.22	101.24
August 2008	1237	7563	8800	380.70	33.52	82.32
August 2009	447	2252	2699	756.08	54.97	171.09
Totals/Means	4832	27,873	32,705	<b>484.15</b>	<b>34.78</b>	101.17

#### 4. IMPACT ON AUGUST 2006 CMAQ RUN

We summed the August 2005-2009 lightning NO<sub>x</sub> profiles and divided by the number of flashes (to obtain per flash NO<sub>x</sub> profiles). The August 2006 NLDN data was then used to find the number of ground flashes in each



**Figure 3.** Impact of lightning NO<sub>x</sub> on ozone (left) at surface, and (right) at all levels.

CMAQ grid cell; climatological Z-ratio data was used to estimate the associated number of cloud flashes. The ground and cloud flash counts were then multiplied by the respective per ground and per cloud flash lightning NO<sub>x</sub> profiles to estimate the lightning NO<sub>x</sub> profile within each CMAQ grid cell. The August 2006 CMAQ run was then completed. Figure 3 shows the impact of LNO<sub>x</sub>-derived lightning NO<sub>x</sub> on CMAQ ozone predictions.

## 5. GLOBAL LIGHTNING NO<sub>x</sub>

Using the statistics in Table 1, an estimate of global lightning NO<sub>x</sub> can be obtained. Christian et al. (2003) gives a global annual total of about  $N = 1,387,584,000$  flashes. Mackerras et al. (1998) estimates a global ground flash fraction range of between 0.154-0.215, which has a midpoint  $m = 0.1845$ . Using the weighted means from Table 1 give a total annual lightning NO<sub>x</sub> of:  $mN(484.15) + (1-m)N(34.78) = 1.633E11$  moles = 2.287 Tg(N).

## 6. CONCLUSIONS

It is feasible to combine LMA/NLDN data, laboratory measurements, and theory to make estimates of lightning NO<sub>x</sub> that are useful in air quality and global climate studies. The fixed 250 or 500 moles/flash values customarily assumed in the literature, with production by ground and cloud flashes set equal, is not optimal given the results in Table 1. The impact of lightning on air quality is significant (Figure 3). Finally, our 2.287 Tg(N) estimate of global annual lightning NO<sub>x</sub> is regarded as a lower bound since most lightning occurs in the tropics where the tropopause is higher, leading to longer channel lengths and hence more lightning NO<sub>x</sub> production.

## ACKNOWLEDGMENTS

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## 1. INTRODUCTION

There has been considerable variability in the estimates of lightning NO<sub>x</sub> production per flash; see for example the summary table in Labrador et al. (2005), the review paper by Schumann and Huntrieser (2007), and the studies by DeCaria et al. (2000, 2005), Beirle et al. (2004, 2010), Langford et al. (2004), Rahman et al. (2007), Huntrieser et al. (2008), Jourdain et al. (2010), Ott et al. (2010), and Peterson and Beasley (2011). The variability in these estimates is linked to the differences in the estimation methods employed, and the natural variability of lightning.

The NASA Marshall Space Flight Center introduced the Lightning Nitrogen Oxides Model (LNOM; Koshak et al., 2009, 2010) to combine routine, state-of-the-art measurements of lightning with laboratory empirical results of lightning NO<sub>x</sub> production derived from Wang et al. (1998). The LNOM has recently been updated to include several non-return stroke lightning NO<sub>x</sub> production mechanisms described in Cooray et al. (2009): hot core stepped and dart leaders, stepped leader corona sheath, K-changes, continuing currents, and M-components. The impact of including LNOM-estimates of lightning NO<sub>x</sub> for an August 2006 run of CMAQ is discussed. The input data into the LNOM includes VHF lightning source data [such as from the North Alabama Lightning Mapping Array (NALMA)], and ground flash location, peak current, and stroke multiplicity data from the National Lightning Detection Network (NLDN). Figure 1 summarizes LNOM data processing.

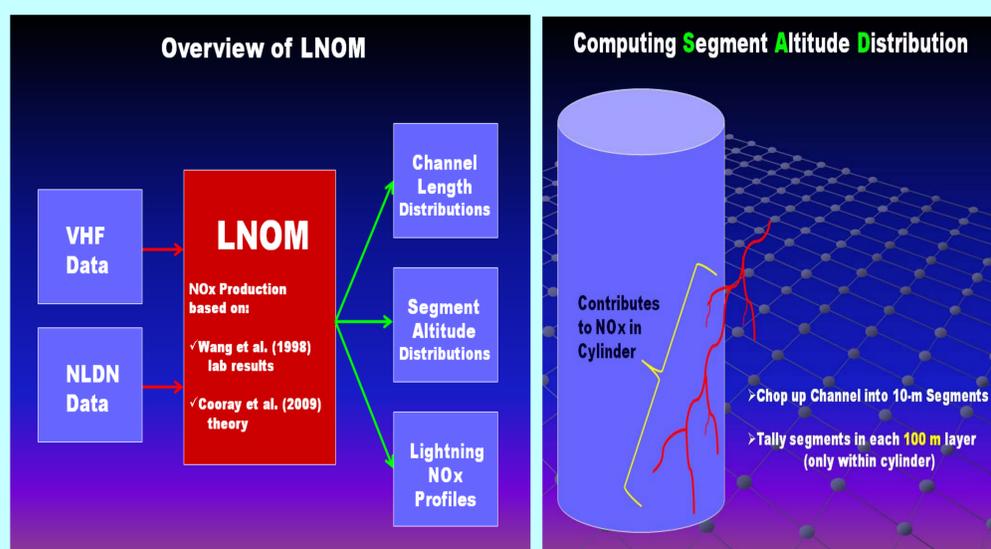


Figure 1. Functionality of the LNOM showing inputs, outputs, and details on channel segment altitude distribution computation.

## 2. EXAMPLES OF LNOM OUTPUT FOR AUGUST 2006

Figure 2 below provides examples of the LNOM output. LNOM output was also obtained for Aug 2005, Aug 2007, Aug 2008, and August 2009.

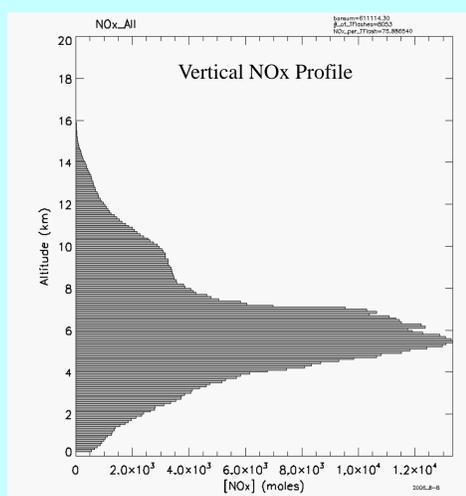
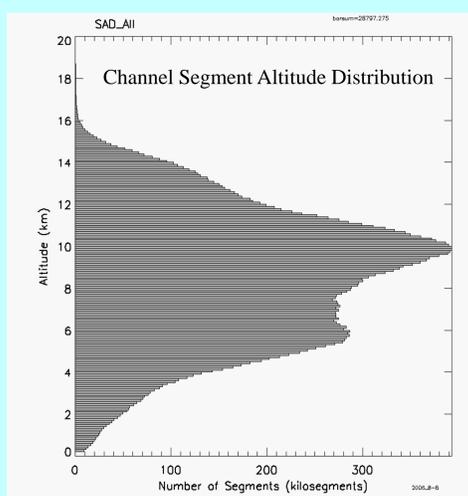
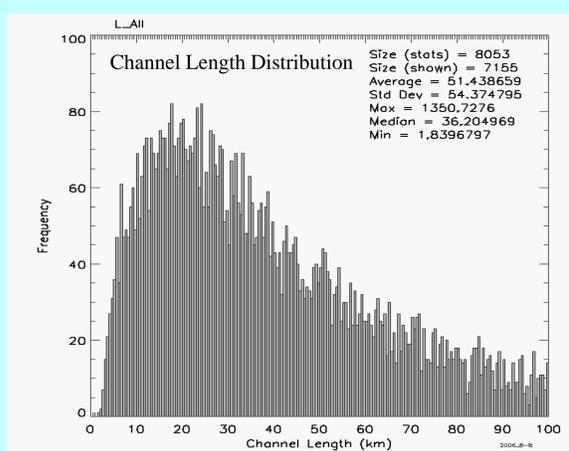


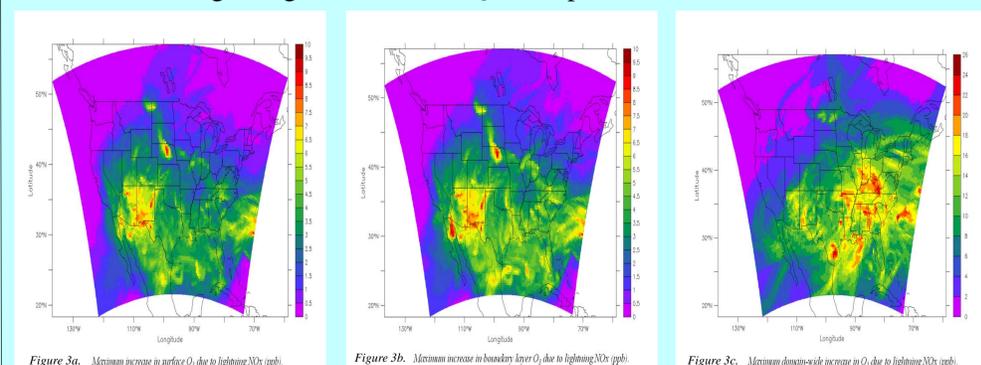
Figure 2. LNOM output: (top) channel length distribution, (lower left) channel segment altitude distribution, and (lower right) vertical NO<sub>x</sub> profile.

## 3. LIGHTNING NO<sub>x</sub> & CHANNEL LENGTH STATISTICS

Period	# Ground Flashes	# Cloud Flashes	Total # of Flashes	NO <sub>x</sub> per Ground Flash	NO <sub>x</sub> per Cloud Flash	NO <sub>x</sub> per Flash
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Total Flashes & Weighted Mean NO <sub>x</sub>	4832	27,873	32,705	484.15	34.78	101.17

## 4. APPLICATION TO CMAQ

We summed the Aug 2005-2009 lightning NO<sub>x</sub> profiles and divided by the number of flashes (to obtain per flash NO<sub>x</sub> profiles; we also obtained the separate per ground flash and per cloud flash lightning NO<sub>x</sub> profiles). The August 2006 NLDN data was then used to find the # ground flashes in each Community Multiscale Air Quality (CMAQ) grid cell; climatological Z-ratio data was used to estimate the associated # of cloud flashes. The flash counts were then multiplied by the per flash lightning NO<sub>x</sub> profiles to estimate the lightning NO<sub>x</sub> profile input into each CMAQ grid cell. The Aug 2006 CMAQ run was then completed. Figure 3 shows the impact of LNOM-derived lightning NO<sub>x</sub> on CMAQ ozone predictions.



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