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™ (NLDN) data to estimate the raw (i.e., unmixed and otherwise environmentally unmodified) vertical profile of lightning NOx (=NO + NO2) production. The latest LNOM estimates of mean lightning channel length, the lightning 10-m segment altitude distribution, and the vertical profile of lightning NOx production are obtained. The primary improvement to the LNOM is the inclusion of non-return stroke lightning NOx 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 NOx for an August 2006 run of CMAQ is discussed. An estimate of global annual lightning NOx production is also provided using the NASA satellite global lightning climatology.

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1. Introduction

The methodologies for estimating lightning NOx 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 NOx production per flash; see for example the summary table in Labrador et al. (2005), the review paper by Schumann and Huntrieser (2007), and the review table in Peterson and Beasley (2011). The variability in these estimates is linked to the differences in the measurements and estimation methods employed, and the natural variability of lightning. The NASA Marshall Space Flight Center introduced early versions of the Lightning Nitrogen Oxides Model (LNOM; Koshak et al., 2009, 2010) to combine routine observations of lightning in North Alabama thunderstorms with laboratory results provided by Wang et al. (1998); these laboratory results have been validated by Peterson et al. (2010).

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 NOx production profiles are then used to assess the impact of lightning NOx on an August 2006 run of the Community Multiscale Air Quality (CMAQ) modeling system. An estimate of global annual lightning NOx production is also provided using the NASA Optical Transient Detector (OTD) global lightning climatology.

2. The LNOM

2.1. Basic functionality

The LNOM 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 the LNOM analysis cylinder (height 0–20 km, and radius 20.31 km). This cylinder is the approximate volume equivalent of a 36 km x 36 km CMAQ grid cell; the cylinder dimensions can be adjusted as needed for other applications. The LNOM analyzes the VHF sources to estimate the total channel length of each flash. Both ground and cloud flashes are analyzed. 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 NOx production profile in the cylinder; see Fig. 1.

2.2. Parameterization of lightning NOx

To estimate the NOx produced by each 10 m segment of the channel, the LNOM interrogates the location of each segment. The segment’s location defines what NOx production mechanism(s) should likely be invoked. For example, consider a ground flash. Those segments in the main channel(s) to ground below the thundercloud negative charge region, or below the upper positive charge region of a positive polarity ground flash, are assumed to participate in return stroke NOx production. As such, the LNOM assumes that the NLDN peak lightning current \(I\) (in kiloamps) flows through the main channel(s) to ground. Those segments in any branches that might exist off the main channel(s) to ground likely carry smaller peak currents. However, a simplifying assumption of LNOM is to assume the same NLDN peak lightning current \(I\) flows through these branches too. This has the effect of possibly overestimating the contribution of NOx from return strokes. The laboratory results of Wang et al. (1998) are used to estimate the NO production by the return stroke channel segment. By combining Eqs. (6) and (9) in Wang et al. (1998), the NO production, \(Q\) (in \(\times 10^{21}\) NO molecules), from a 1 m element of the 10 m channel segment is estimated as:

\[
Q(I,h) = m[a + b|I| + cI^2] - B(p_o - p(h))
\]

Here, \(h\) is the geodetic altitude of the 1 m element, and \(p(h)\) is the variation of pressure with height appropriate for MM5 (Grell et al., 1994), the dynamical model used in conjunction with CMAQ. The variable \(m\) is the multiplicity (the number of strokes in a flash, and provided by the NLDN). The constant \(p_o\) is the surface pressure, and \((a, b, c, B)\) are positive empirical laboratory constants provided in Wang et al. (1998). The return stroke production from a 10 m segment is obtained by summing up the Q-contribution from each 1 m element, and the total return stroke production from the return stroke channel is obtained by summing up the Q-contribution from each 10 m segment. As expected, Eq. (1) shows that the NO production increases for a channel segment that has a larger peak current and a lower altitude. [Since the study by Wang et al. (1998) reported that 90–95% of the NOx produced from laboratory sparks was in the form of NO, the terminology “NO” and “NOx” is used interchangeably here.]

The actual computation of \(Q\) in the LNOM is more complicated than indicated in Eq. (1). In particular, the value of \(Q\) in Eq. (1) can go negative for high altitude low peak current segments (i.e., the last term in Eq. (1) proportional to \(B\) can exceed the sum of the first three terms). In addition, Eq. (9) in Wang et al. (1998) gives a positive value of \(Q\) at \(p = 0\) atm. To mitigate each of these problems, the LNOM employs 2 linear functions to model the depletion of \(Q\) with decreasing pressure. Since a subsequent stroke typically has a smaller peak current than in the preceding stroke, the LNOM assumes that the peak current of a subsequent stroke is half of the value of that found in the preceding stroke; this of course will not always be the case. The values of \(Q\) are converted to units of moles, and are added up for each 100 m layer in the analysis cylinder; this comprises
the lightning NOx production profile for the analysis cylinder in a given time period.

Recent upgrades to LNOM involve the addition of several important non-return stroke processes that produce NOx, but are often neglected by other investigators. For ground flashes, these additional NOx sources arise from the following discharge processes: hot core stepped leaders, stepped leader corona sheaths, hot core dart leaders, K-changes, continuing currents, and M-components. For cloud flashes, the NOx-sources are assumed to arise from the following discharge processes: hot core cloud flash leaders, cloud flash leader corona sheaths, and K-changes. [Earlier versions of LNOM used Eq. (1) to estimate NOx from cloud flashes where a value of I~4 kA (Uman, 1969) was assumed, but this was replaced by a production from cloud flash leaders, corona sheaths, and K-changes to improve accuracy.]

The NOx parameterization for all of these non-return stroke processes take on a few basic forms as described in Cooray et al. (2009) but have been generalized for implementation into LNOM (e.g., the 10 m channel segment from which NOx is computed is arbitrarily oriented with respect to the vertical atmospheric air density profile, so an integral over the segment is performed to account for these density variations and is called an attenuation factor, A, in units of meters). The parameterized forms for the hot core leaders (stepped, dart and cloud flash leaders) are all of the form A \delta, where \delta = \eta \delta/v, and s is the distance from the center of the 10 m segment to the termination point of the propagating channel. Here, \eta is the production efficiency (2 x 10^{20} NOx molecules per meter per coulomb), i is the leader current, and v the leader speed. The corona sheath production parameterization is of the form A \mu, where \mu is the production efficiency of 2 x 10^{10} NOx molecules per meter; the K-change and M-component production parameterizations also follow this same form but have an extra multiplicative factor related to the expected number of K-change events and M-components, respectively. Finally, the continuing current parameterization has the form \eta i \delta, where \delta = 100 A is the assumed continuing current magnitude, and \delta = 100 ms is the assumed continuing current duration.

2.3. Additional assumptions & interpretation of results

To better interpret our results, it is important to be aware of some additional underlying assumptions and, in some cases, necessary simplifications associated with LNOM analyses.

First, note that positive leaders do not produce enough VHF radiation to be well-mapped by networks such as the NALMA (Mazur et al., 1998; Shao et al., 1999; Mazur, 2002); this can lead to under-estimates in LNOM channel length computations.

Second, very little is known about how prevalent (if at all) or how energetic continuing currents might be within cloud flashes, so LNOM does not attempt to model this potentially important NOx source. By contrast, a fair amount is known about the frequency, current values, and durations of continuing currents within ground flashes. Since LNOM models continuing currents (and associated M-components) within ground flashes but not within cloud flashes, LNOM might be under-estimating NOx in cloud flashes relative to ground flashes.

Third, note that the LNOM lightning NOx production profile, or vertical source profile (VSP; Koshak et al., 2010), is just the NOx profile generated by lightning over time as if it had not been mixed or otherwise modified by the environment. In fact, the LNOM generates a NOx production profile on a per flash basis, and the sum of these individual profiles produces the VSP for a given period. Several mechanisms (e.g., chemical conversion, convective/advective transport, or removal such as wet scavenging) can modify the VSP. Modeling the effects of these mechanisms over a given period of time is the responsibility of the regional air quality model that ingests the VSP information, not the LNOM.

Fourth, though LNOM employs NLDN data to estimate return stroke currents, current values for other breakdown processes in a lightning discharge must be estimated based on literature values. Lightning current values provided in the older literature have been adjusted as discussed in Rakov and Uman (2003; pp. 126, 168, 331) and Cooray (2003; pp. 151–152). Based on these adjustments, LNOM assumes the following: 1.3 kA stepped leader currents, 1.7 kA dart leader currents, and 130 A cloud flash hot core leader currents.

Fifth, according to Cummins and Murphy (2009), NLDN-detected flashes with positive peak currents between 10–20 kA are in reality a mixture of ground and cloud flashes. Hence, flashes in the positive 10–20 kA range (which are relatively few) are deemed an “ambiguous” flash type by LNOM and are removed from further LNOM analyses. This has the benefit that VSPs for ground flashes are less likely contaminated by cloud flash results, and vice versa.

In summary, relatively minimal simplifying assumptions are made within LNOM. The LNOM reasonably preserves the essential channel geometry, channel length, and channel altitude characteristics afforded by the NALMA data, thereby accounting for channel tortuosity and channel branching. LNOM also accounts for NOx production from several different discharge processes within the lightning channel that are often neglected. Hence, we believe that LNOM provides a substantial improvement over those methodologies that unrealistically assume vertical or horizontal “stick” channel models with a single NOx producing mechanism, or that just assume fixed amounts of NOx from a flash with no explicit model at all. Overall, we estimate that our lightning NOx production profiles are accurate to within about 10%, assuming the production mechanisms are correct.

2.4. Examples of LNOM Output

Examples of the LNOM output for the August 2006 analysis period in Northern Alabama are provided in Fig. 2. The LNOM also provides the component VSP 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 Fig. 2. The average channel length of a flash (across all five Augusts) ranged from 38.9 km to 69.6 km.

3. Lightning NOx statistics

The LNOM analysis of the five Augusts (2005–2009) has provided statistics of the amount of NOx produced by ground
and cloud flashes, and by all flashes overall as shown in Table 1.
To place our lightning NOx results into context relative to the
results from other investigators, we provide a summary in
Table 2 that was adapted from Peterson and Beasley (2011).
To avoid any confusion, we do not use the word “Theoretical”
to describe the methodology employed by LNOM [as was done in
Peterson and Beasley (2011)]. This is because LNOM
analyzes each flash using NALMA/NLDN measurements.
Though LNOM employs laboratory and theoretical results
found in Wang et al. (1998) and Cooray et al. (2009), as well
as additional theoretical assumptions for estimating NOx
(see Sections 2.2 and 2.3), it should be emphasized that
LNOM results are fundamentally based on flash-specific
lightning observations. LNOM combines flash-specific ob-
servations (as in a field study) with theory and lab results in
order to obtain optimal estimates of lightning NOx produc-
tion. Therefore, it is no surprise that our values are
comparable to those found by some of the other investigators
in Table 2.

4. Impact on August 2006 CMAQ run

We summed the August 2005–2009 VSPs and divided by
the number of flashes (to obtain per flash NOx production
profiles). The August 2006 NLDN data was then used to find
the number of ground flashes in each CMAQ grid cell: climatological Z-ratio data was used to estimate the associ-
ated number of cloud flashes. The ground and cloud flash
counts were then multiplied by the respective per ground and
per cloud flash VSPs to estimate the VSP within each CMAQ
grid cell. The August 2006 CMAQ run was then completed.

Fig. 3 shows the impact of LNOM-derived lightning NOx on
CMAQ ozone predictions. Based on results by Cooper et al.
(2007, 2009), lightning NOx was responsible for a maximum of
25–30 ppb of tropospheric ozone in August 2006 in parts of the
southeastern United States; this value compares well with
the ~24 ppb max increase given in the top plot of Fig. 3 (note
that contributions from stratospheric intrusions are not
included). We find that the impact to the boundary layer
(BL, lower plots in Fig. 3) is comparable to previous studies;
e.g., Kaynak et al. (2008) estimated a 2 ppb impact on BL ozone
concentration from lightning NOx emissions, and Allen et al.
(2012) suggested that lightning-NO adds 1.5–4.5 ppbv to 8-h
maximum BL ozone. Exceptions are the larger values shown in
the lower left plot of Fig. 3 over the southwest and a few other
localized regions.

The maximum and average increases in each vertical layer
across the entire horizontal CMAQ domain are provided in

<table>
<thead>
<tr>
<th>Period</th>
<th># Ground flashes</th>
<th># Cloud flashes</th>
<th>Total # of flashes</th>
<th>NOx per ground flash</th>
<th>NOx per cloud flash</th>
<th>NOx per flash</th>
</tr>
</thead>
<tbody>
<tr>
<td>August 2005</td>
<td>1023</td>
<td>5306</td>
<td>6329</td>
<td>403.26</td>
<td>26.34</td>
<td>87.27</td>
</tr>
<tr>
<td>August 2006</td>
<td>1067</td>
<td>6986</td>
<td>8053</td>
<td>601.41</td>
<td>34.03</td>
<td>109.21</td>
</tr>
<tr>
<td>August 2007</td>
<td>1058</td>
<td>5766</td>
<td>6824</td>
<td>450.17</td>
<td>37.22</td>
<td>101.24</td>
</tr>
<tr>
<td>August 2008</td>
<td>1237</td>
<td>7563</td>
<td>8800</td>
<td>380.70</td>
<td>33.52</td>
<td>82.32</td>
</tr>
<tr>
<td>August 2009</td>
<td>447</td>
<td>2252</td>
<td>2699</td>
<td>756.08</td>
<td>54.97</td>
<td>171.09</td>
</tr>
<tr>
<td>All 5 months</td>
<td>4832</td>
<td>27,873</td>
<td>32,705</td>
<td>484.15</td>
<td>34.78</td>
<td>101.17</td>
</tr>
</tbody>
</table>
Cloud flashes; e.g., cloud flashes might have lightning NOx production from continuing currents. Finally, other sources of upper tropospheric NOx, such as free-tropospheric emissions from aircraft are not included.

5. Global lightning NOx

Using the statistics in Table 1, a preliminary estimate of global lightning NOx can be obtained. Based on Optical Transient Detector (OTD) observations, 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 and 0.215, which has a midpoint of m = 0.1845. Using the weighted means from the last row of Table 1 gives a total annual lightning NOx of:

\[ mN(484.15) + (1-m)N(34.78) = 1.633 \times 10^{11} \text{ mol} = 2.287 \text{ Tg(N).} \]

6. Conclusions

It is feasible to combine LMA/NLDN data, laboratory measurements, and theory to make estimates of lightning NOx, that are useful in air quality and global climate studies. The 250 or 500 mol/flash values customarily assumed in the literature, with production by ground and cloud flashes set equal, are not optimal for air quality studies given the values in Table 1. The impact of lightning on air quality is significant (Zhou et al., 2005) and the results in Fig. 3 reaffirm this conclusion. In addition, note that our 2.287 Tg(N) estimate of global annual lightning NOx is within range, but on the low end, of the best estimate value of 5 ± 3 Tg(N) given in the review paper by Schumann and Huntrieser (2007). Our estimate is also within the range of the 1.4 and 3.5 Tg(N) estimates recently obtained by Huntrieser et al. (2011) for storms studied in the African Monsoon Multidisciplinary Analysis (AMMA) campaign. Considering the different techniques used for arriving at these estimates, the reasonable correspondence in estimated values is encouraging. Because we have analyzed storms where the tropopause height is low relative to its height in the tropics (where a large fraction of the total global lightning occurs), we speculate that the relatively lower tropopause could lead to shorter channel lengths and hence less lightning NOx production per flash, on average, assuming all else equal. But, increased vertical cloud extent is only one driving factor behind increased channel length. Horizontal channel propagation is also a fundamental consideration, and is highly complicated since it involves not only the charging characteristics of a thundercloud but also of nearby thunderclouds, and the overarching meteorological regimes that may or may not bring individual thunderclouds into close proximity. Moreover, Huntrieser et al. (2008, 2009, 2011) suggest that since tropical thunderstorms have less vertical shear of the horizontal wind, they would produce smaller lightning channel lengths than thunderstorms at higher latitudes. With all these competing factors (and other factors not emphasized here), it is presently difficult to assess why one global lightning NOx estimate is higher or lower than another.

Finally, it should be emphasized that although the LNOM employs some lightning NOx parameterizations developed in Cooray et al. (2009), there are still differences between the LNOM and Cooray lightning NOx estimates. Most notable, LNOM obtains more lightning NOx for ground flashes than for cloud
flashes. Overall, the most important differences between LNOM and Cooray et al. (2009) modeling methods are: (1) LNOM uses more recent values in the literature for the ground flash stepped and dart leader currents which are both substantially larger than the values employed by Cooray, (2) LNOM employs the return stroke NO<sub>x</sub> production parameterization given by Wang et al. (1998), not the one used by Cooray, (3) For the Cooray parameterizations that the LNOM does employ, the LNOM generalizes them to account for actual (LMA-derived) channel geometry/lengths, channel segment orientation and channel segment altitude (i.e., air density). That is, the Cooray et al. (2009) paper considers unrealistic straight line vertical or horizontal channel segments (no branching or tortuosity), (4) LNOM employs actual NLDN-derived peak currents, not the fixed current estimates of Cooray, and (5) when parameterizing continuing current, the LNOM accounts for polarity whereas Cooray does not (i.e., about 10% of ground flashes are positive polarity and about 75% of these

![All Levels: Max Increase in O3 due to LNOx (ppb)](image1)

**Fig. 3.** Impact of lightning NO<sub>x</sub> (LNO<sub>x</sub>) on ozone concentrations. Top figure provides the maximum increase in ozone found when considering all levels, and the bottom two figures provide additional details for the boundary layer (BL).

![BL: Max Increase in O3 due to LNOx (ppb)](image2)

![BL: Average Increase in O3 due to LNOx (ppb)](image3)

![Fig. 3.](image4)

![Fig. 4.](image5)

![Fig. 4.](image6)
have continuing currents, as oppose to only 30% for negative polarity ground flashes).

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References


