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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 NO_x ($= NO + NO_2$) production. The latest LNOM estimates of mean lightning channel length, the lightning 10-m segment altitude distribution, and the vertical profile of lightning NO_x production are obtained. The primary improvement to the LNOM is the inclusion of non-return stroke lightning NO_x 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_x for an August 2006 run of CMAQ is discussed. An estimate of global annual lightning NO_x production is also provided using the NASA satellite global lightning climatology.

1. Introduction

The methodologies for estimating lightning NO_x 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_x 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 NO_x production profiles are then used to assess the impact of lightning NO_x on an August 2006 run of the Community Multiscale Air Quality (CMAQ) modeling system. An estimate of global annual lightning NO_x 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

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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 × 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 NO_x production profile in the cylinder; see Fig. 1.

2.2. Parameterization of lightning NO_x

To estimate the NO_x produced by each 10 m segment of the channel, the LNOM interrogates the location of each segment. The segment's location defines what NO_x 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 NO_x 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 NO_x 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:

$$Q(I,h) = m\left[a + b|I| + cI^2 - B(p_o - p(h))\right] . \qquad (1)$$

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 NO_x produced from laboratory sparks was in the form of NO, the terminology "NO" and "NO_x" 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

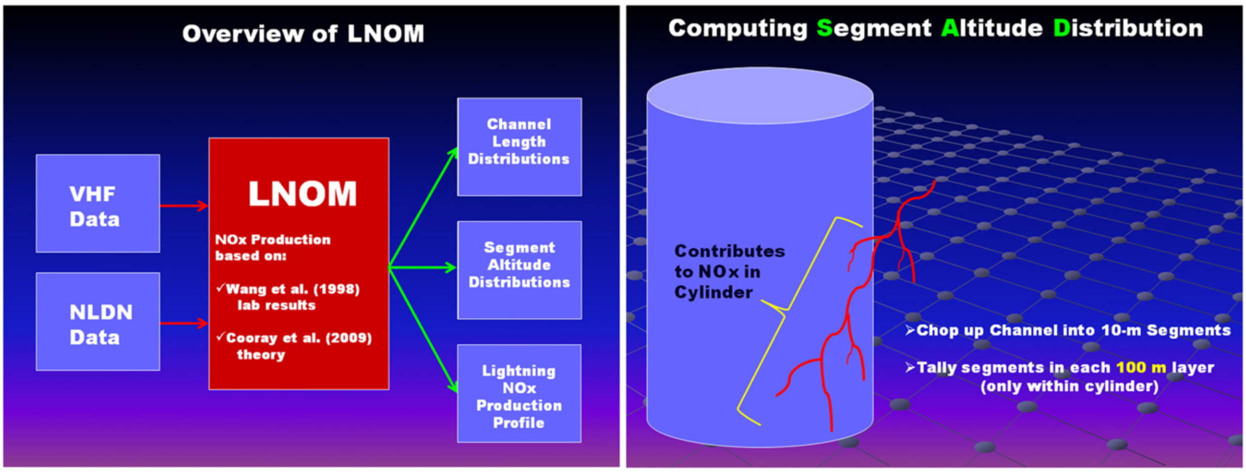

Fig. 1. Functionality of the LNOM showing (left) inputs & outputs, and (right) the analysis cylinder and details of channel segment altitude distribution computation.

the lightning NO_x 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 NO_x, but are often neglected by other investigators. For ground flashes, these additional NO_x 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 NO_x-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 NO_x 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 NO_x 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 NO_x 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 $A\sigma s$, where $\sigma = \eta i/v$, and s is the distance from the center of the 10 m segment to the termination point of the propagating channel. Here, η is the production efficiency (2×10^{20} NO_x 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 μ is the production efficiency of 2×10^{20} NO_x 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 $A\eta i\delta$, where $i = 100$ 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 NO_x 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 NO_x in cloud flashes relative to ground flashes.

Third, note that the LNOM lightning NO_x production profile, or vertical source profile (VSP; Koshak et al., 2010), is just the NO_x 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 NO_x 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 NO_x 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 NO_x producing mechanism, or that just assume fixed amounts of NO_x from a flash with no explicit model at all. Overall, we estimate that our lightning NO_x 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 NO_x statistics

The LNOM analysis of the five Augusts (2005–2009) has provided statistics of the amount of NO_x produced by ground

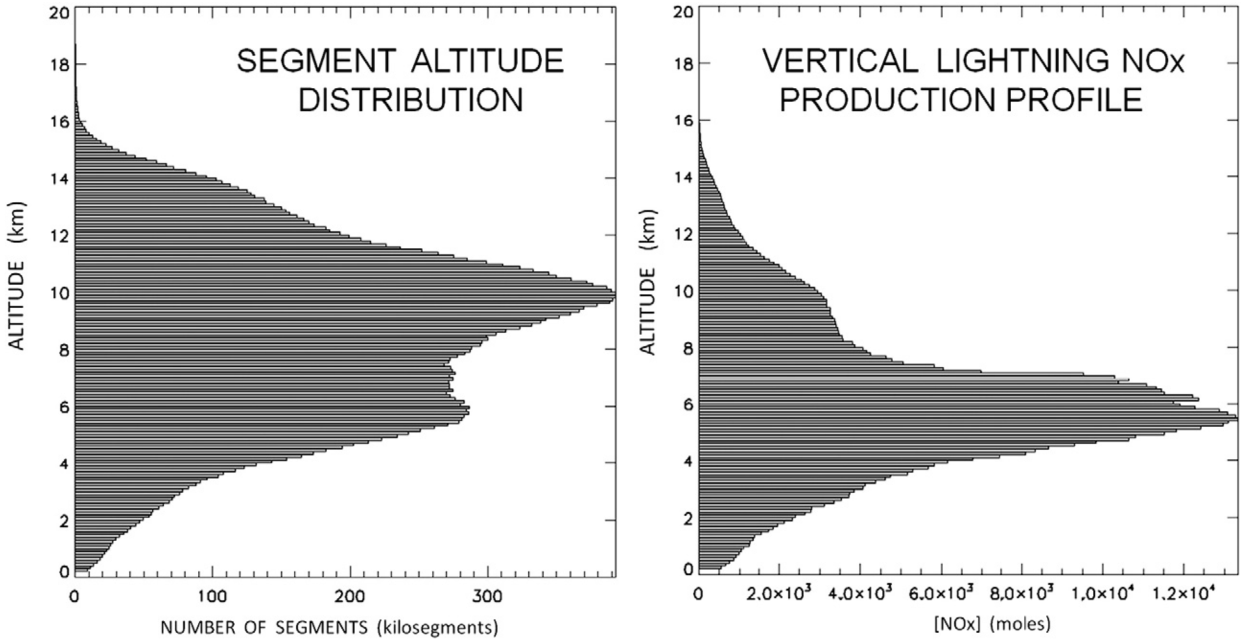

Fig. 2. Example of two LNOM output products for the August 2006 analysis period.

and cloud flashes, and by all flashes overall as shown in Table 1. To place our lightning NO_x 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 NO_x (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 observations (as in a field study) with theory and lab results in order to obtain optimal estimates of lightning NO_x production. 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 NO_x 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 associated 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 NO_x on CMAQ ozone predictions. Based on results by Cooper et al. (2007, 2009), lightning NO_x 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 NO_x 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 1
LNOM summary statistics [NO_x values are means in units of moles].

Period	# Ground flashes	# Cloud flashes	Total # of flashes	NO_x per ground flash	NO_x per cloud flash	NO_x 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
All 5 months	4832	27,873	32,705	484.15	34.78	101.17

Table 2
A comparison of lightning NO_x estimates on a per flash basis from several studies. [Adapted from Peterson and Beasley, 2011].

First author	Year	Methodology	Molecules/flash	Moles/flash
Levine	1981	Laboratory	5.00E + 24	8.30
Kumar	1995	Field study	5.00E + 24	8.30
Dawson	1980	Theoretical	8.00E + 24	13.28
Beirle	2010	Satellite	1.00E + 25	16.61
Tuck	1976	Theoretical	1.10E + 25	18.27
Hill	1980	Theoretical	1.20E + 25	19.93
Koshak	2010	LNOM data analyses	1.41E + 25	23.40
Cooray	2009	Theoretical	2.00E + 25	33.21
Lawrence	1995	Review	2.30E + 25	38.19
Nesbitt	2000	Field study	2.67E + 25	44.25
Huntrieser	2002	Field study	2.70E + 25	44.84
Wang	1998	Laboratory	3.10E + 25	51.48
Peyrous	1982	Laboratory	3.20E + 25	53.14
Ridley	2004	Field study	3.20E + 25	53.14
Beirle	2006	Satellite	5.40E + 25	89.67
Koshak	*(This study)*	*LNOM data analyses*	*6.09E + 25*	*101.17*
Sisterson	1990	Theoretical	8.20E + 25	136.17
Noxon	1976	Field study	1.00E + 26	166.06
Chameides	1977	Theoretical	1.00E + 26	166.06
Kowalczyk	1982	Theoretical	1.00E + 26	166.06
Bucsela	2010	Satellite	1.05E + 26	174.36
Schumann	2007	Review	1.50E + 26	249.09
Huntrieser	2011	Field study	1.51E + 26	250.00
DeCaria	2000	Theoretical	1.56E + 26	258.39
Fehr	2004	Field study	2.10E + 26	348.72
Rahman	2007	Field study	2.40E + 26	398.54
Chameides	1979	Theoretical	2.50E + 26	415.14
DeCaria	2005	Theoretical	2.77E + 26	460.00
Martini	2011	Theoretical	2.89E + 26	480.00
Ott	2010	Theoretical	3.01E + 26	500.00
Jourdain	2010	Theoretical	3.13E + 26	520.00
Drapcho	1983	Field study	4.00E + 26	664.23
Franzblau	1989	Field study	3.00E + 27	4981.73

Fig. 4. For context, Cooper et al. (2006) showed that lightning and pollutants combine to cause ozone enhancements in the upper troposphere for the eastern U.S. in summer 2004 [11–13 ppbv of the 16 ppbv ozone enhancement above eastern North America was due to in-situ ozone production from lightning NO_x with the remainder due to transport of ozone from the surface or in-situ ozone production from other sources of NO_x]. Moreover, Allen et al. (2010) showed that the contribution of lightning NO to monthly average summertime 300 hPa ozone varies from 15–24 ppbv. In addition, Allen et al. (2012) showed that lightning NO adds up to 20 ppbv to upper tropospheric model ozone. The upper troposphere ozone values shown in Fig. 4 are comparable or lower than these typical values. Our values are also lower than ozonesonde observations (Wang et al., in press; Newchurch et al., 2003), but this is expected since our simulations only address one source of uncertainty, namely lightning NO_x. In addition, there are other considerations. First, our default lateral boundary conditions calculated from climatology do not account for long-range ozone transport. Second, lightning may occur in the upwind region outside the NLDN coverage area and generate lightning NO_x mainly in the upper troposphere; this lightning NO_x may enhance the local ozone concentration or may transport downwind into the model domain. Third, due to lack of observations, we cannot fully parameterize lightning NO_x production within cloud flashes; e.g., cloud flashes might have lightning NO_x production from continuing currents. Finally, other sources of upper tropospheric NO_x, such as free-tropospheric emissions from aircraft are not included.

5. Global lightning NO_x

Using the statistics in Table 1, a preliminary estimate of global lightning NO_x 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 NO_x of: $mN(484.15) + (1 - m)N(34.78) = 1.633 \times 10^{11}$ mol = 2.287 Tg(N).

6. Conclusions

It is feasible to combine LMA/NLDN data, laboratory measurements, and theory to make estimates of lightning NO_x 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 NO_x 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 NO_x 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 NO_x estimate is higher or lower than another.

Finally, it should be emphasized that although the LNOM employs some lightning NO_x parameterizations developed in Cooray et al. (2009), there are still differences between the LNOM and Cooray lightning NO_x estimates. Most notable, LNOM obtains more lightning NO_x for ground flashes than for cloud

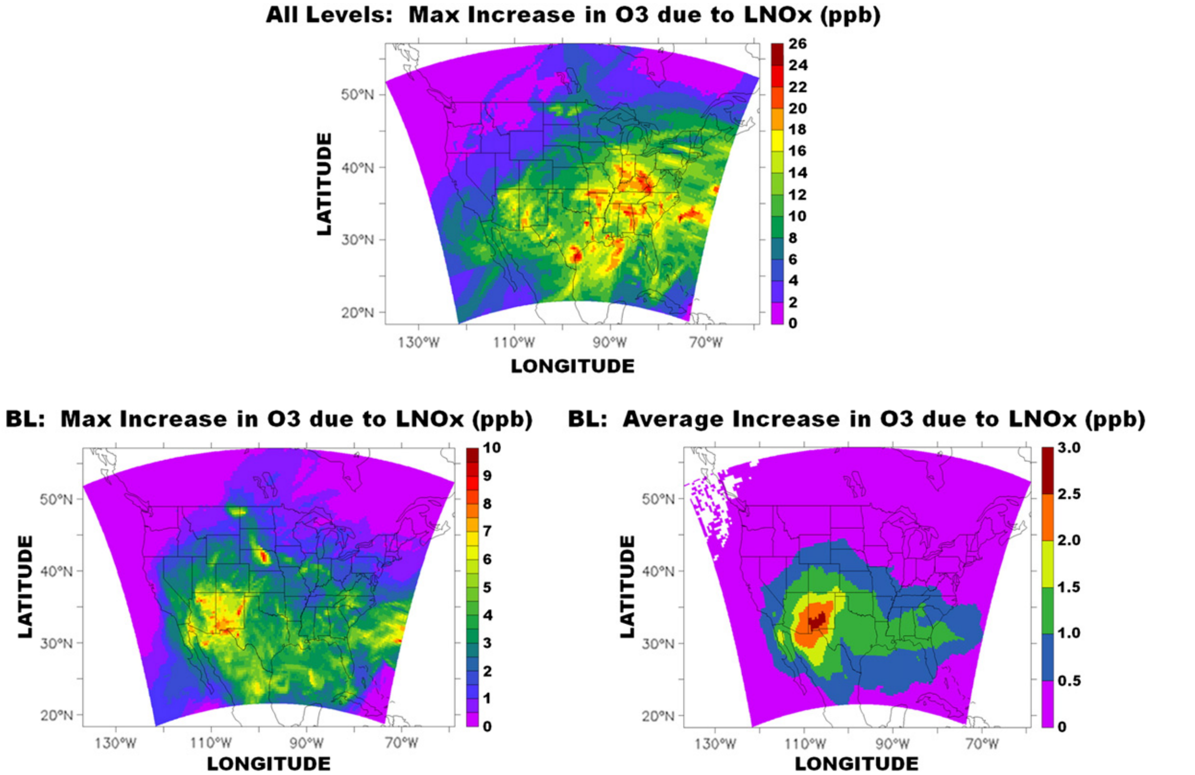

Fig. 3. Impact of lightning NO_x (LNO_x) on ozone concentrations. Top figure provides the maximum increase in ozone found when considering all levels, and the bottom two figures provide additional details for the boundary layer (BL).

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_x 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

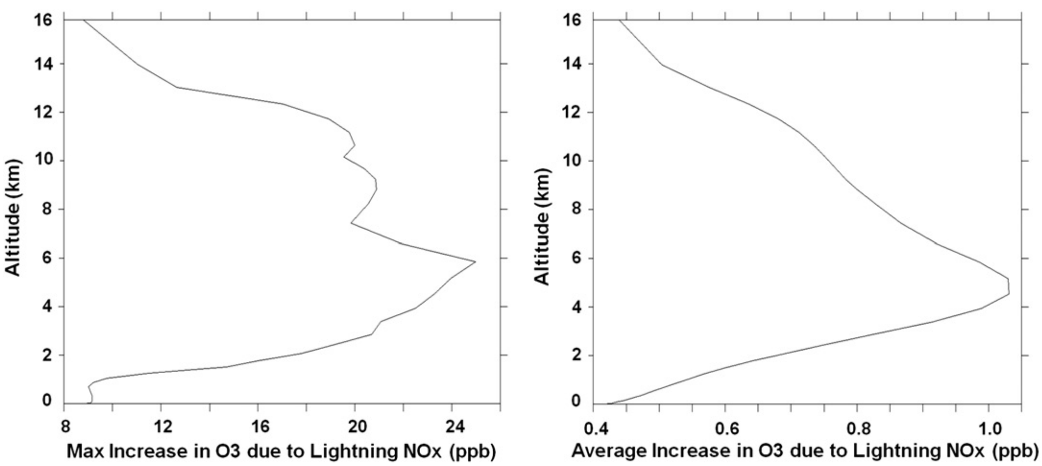

Fig. 4. Impact of lightning NO_x on ozone in the vertical. Left profile is the maximum increase in ozone found in each layer due to lightning NOx. Right profile is the average increase in each layer.

have continuing currents, as oppose to only 30% for negative polarity ground flashes).

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