Production of lightning \( \text{NO}_x \) and its vertical distribution calculated from 3-D cloud-scale chemical transport model simulations

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Abstract

A 3-D cloud scale chemical transport model that includes a parameterized source of lightning NOx based on observed flash rates has been used to simulate six midlatitude and subtropical thunderstorms observed during four field projects. Production per intracloud (P_{IC}) and cloud-to-ground (P_{CG}) flash is estimated by assuming various values of P_{IC} and P_{CG} for each storm and determining which production scenario yields NOx mixing ratios that compare most favorably with in-cloud aircraft observations. We obtain a mean P_{CG} value of 500 moles NO (7 kg N) per flash. The results of this analysis also suggest that on average, P_{IC} may be nearly equal to P_{CG}, which is contrary to the common assumption that intracloud flashes are significantly less productive of NO than are cloud-to-ground flashes. This study also presents vertical profiles of the mass of lightning NOx after convection based on 3-D cloud-scale model simulations. The results suggest that following convection, a large percentage of lightning NOx remains in the middle and upper troposphere where it originated, while only a small percentage is found near the surface. The results of this work differ from profiles calculated from 2-D cloud-scale model simulations with a simpler lightning parameterization that were peaked near the surface and in the upper troposphere (referred to as a “C-shaped” profile). The new model results (a backward C-shaped profile) suggest that chemical transport models that assume a C-shaped vertical profile of lightning NOx mass may place too much mass near the surface and too little in the middle troposphere.
1. Introduction

The oxides of nitrogen, \((\text{NO} + \text{NO}_2 = \text{NO}_x)\), are important \(\text{O}_3\) precursors in the troposphere. Of the major sources of \(\text{NO}_x\) in the troposphere, lightning remains the source with the greatest uncertainty and is particularly important because it produces \(\text{NO}_x\) in the middle and upper troposphere where \(\text{NO}_x\) is longer lived and can be more efficient at producing ozone than in the boundary layer. The representation of lightning \(\text{NO}_x\) \((\text{LNO}_x)\) in three-dimensional (3-D) regional and global chemical transport models \((\text{CTMs})\) is critical to the models’ representation of ozone and other species such as \(\text{OH}\) [e.g. Stockwell et al., 1999, Labrador et al., 2004]. Labrador et al. [2005] found that both the magnitude of the global \(\text{LNO}_x\) source strength and its vertical distribution can substantially affect tropospheric trace gas concentrations in a global CTM. IPCC [2007] suggests a global \(\text{LNO}_x\) source of 1.1-6.4 Tg N yr\(^{-1}\) based on the work of Boersma et al. [2005]. However, Schumann and Huntrieser et al. [2007] have comprehensively summarized estimates of global \(\text{LNO}_x\) production and found the best estimate to be 5±3 Tg N yr\(^{-1}\).

In order to adequately represent the \(\text{LNO}_x\) source in global or regional models, the geographic distribution of flashes, average production of \(\text{NO}\) per flash, and vertical distribution of \(\text{LNO}_x\) following convection must be specified. A variety of schemes have been used to specify the horizontal distribution of flashes (e.g. using variables such as cloud-top height, upward cloud mass flux, convective precipitation, and CAPE as predictors). Allen and Pickering [2002] have evaluated their use in global 3-D CTMs. The production of \(\text{NO}\) per flash has also been examined using laboratory experiments, theoretical assumptions regarding the physics of lightning flashes, and observations obtained during field projects. Despite these efforts, a great deal of uncertainty remains...
regarding NO production on a per flash basis, as well as the relative production by intracloud (IC) and cloud-to-ground (CG) flashes. On the basis of previous studies, which suggested that IC flashes were less energetic than CG flashes (e.g. Holmes et al., 1971), many studies of lightning NOx production have assumed that \( P_{IC} \) is less than \( P_{CG} \).

Price et al. [1997] assumed that a CG flash produces approximately 1100 moles of NO and that an IC flash was one tenth as productive of NO as a CG flash in estimating global lightning NOx production.

However, a number of more recent studies have suggested that \( P_{IC} \) may be nearly as great as \( P_{CG} \). Gallardo and Cooray [1996] suggested that IC flashes may dissipate nearly as much energy as CG flashes and therefore \( P_{IC} \) may be on the order of \( P_{CG} \).

Supporting the Gallardo and Cooray [1996] hypothesis, a two-dimensional (2-D) cloud-scale modeling study by DeCaria et al. [2000] suggested that the \( P_{IC}/P_{CG} \) ratio is likely between 0.5 and 1.0 and a 3-D modeling analysis by DeCaria et al. [2005] narrowed this range to between 0.75 and 1.0. A study by Fehr et al. [2004] used a 3-D cloud-scale model simulation of a storm observed over Germany, and by comparing with lightning and aircraft observations, concluded that on average, an IC flash produced 40% more NO than a CG flash. Zhang et al. [2003] argued that IC flashes may dissipate 50-100% as much energy as CG flashes because they have a large number of return strokes which were neglected in the Price et al. [1997] calculations. Rahman et al. [2007] found that results from experiments with rocket-triggered lightning suggested that NOx production was associated with relatively long duration continuing currents, which may be greater in IC flashes than in CG flashes, leading to the implication that IC flashes may produce as much or possibly more NOx per flash than CG flashes. Recent estimates of energy dissipated by IC and CG flashes using electrical potential and charge density...
measurements by Maggio et al. [2008] also suggest IC flashes may dissipate as much or
more energy than CG flashes.

Pickering et al. [1998] presented vertical profiles of lightning NOx for use in 3-D
CTMs based on the results of 2-D cloud-resolving model simulations of seven convective
events. These simulations assumed the production scheme of Price et al. [1997]. NOx
produced by CG flashes was distributed in the simulated storms from the surface to the
-15°C isotherm while NOx produced by IC flashes was distributed from the -15°C
isotherm to the cloud top. Average profiles of LNOx mass computed for the midlatitude
continental, tropical continental, and tropical marine regimes showed peaks in mass near
the surface and in the upper troposphere, leading many CTMs to adopt a C-shaped
vertical distribution of LNOx mass.

This paper has two primary objectives: (1) to summarize the results of 3-D cloud-
resolved storm simulations yielding estimates of NO production per flash and (2) to
update the vertical LNOx profile information of Pickering et al. [1998]. Six storms from
field projects conducted in Germany, Colorado, south Florida, and Kansas/Oklahoma
have been simulated using a 3-D cloud-scale chemical transport model (CSCTM) that
includes a parameterized source of LNOx. LNOx production per flash is estimated
individually for five of the six storms. In this study we present vertical distributions of
LNOx calculated from each of these 3-D simulations as well as average vertical profiles
for the midlatitude continental and subtropical events, which can be applied in regional
and global CTMs. Section 2 describes the methodology used in these studies, while
section 3 presents results from the individual storm simulations. Section 4 discusses the
results of the storm case studies and their application to global models and remote
sensing. Section 5 presents conclusions that may be drawn from this work.
2. Methodology

Storms from the Cirrus Regional Study of Tropical Anvils and Cirrus Layers -
Florida Area Cirrus Experiment (CRYSTAL-FACE; Ridley et al., 2004; Lopez et al.,
2006), European Lightning Nitrogen Oxides Project (EULINOX; Huntrieser et al, 2002),
Stratosphere Troposphere Experiment: Radiation, Aerosols and Ozone (STERAO; Dye et
al., 2000), and Preliminary Regional Experiment for STORM (PRE-STORM; Rutledge
and MacGorman, 1988) field projects were simulated. With the exception of the PRE-
STORM event, all of these storms featured measurements of chemical and
meteorological properties by research aircraft at anvil levels. The time, location, and
peak current of CG lightning occurrences in all storms were recorded by ground-based
systems, and during STERAO and EULINOX, total lightning activity (IC + CG) was
mapped by a VHF interferometer. In addition, all experiments included extensive
satellite and radar observations of storm development and evolution.

The dynamical evolution of each storm was simulated using a cloud-resolving
model and the temperature, wind, and hydrometeor fields were then used to drive the
offline CSCTM. For each storm, various LNO\textsubscript{x} production per flash scenarios were
simulated and model results were compared with in-cloud aircraft observations of NO\textsubscript{x}
through use of mean profiles, column NO\textsubscript{x} mass, and probability distribution functions of
simulated and observed NO\textsubscript{x} to determine the most appropriate scenario. At the end of
the CSCTM simulation, the mass of N fixed by lightning was calculated at each model
level, and the percentage of the total mass of LNO\textsubscript{x} was calculated for 1-km layers.

A detailed description of the CSCTM is found in DeCaria et al. [2005]. In this
version of the model, LNO\textsubscript{x} production is computed using observed IC and CG flash
rates and a specified scenario of P\textsubscript{IC} and P\textsubscript{CG} to calculate the mass of NO injected into the
cloud per time step. Both laboratory experiments (Wang et al., 1998) and theoretical considerations (Price et al., 1997) have pointed to a strong dependence of LNOK production on stroke peak current. Therefore, we have made initial estimates of PCG using these relationships because peak current data for return strokes are available from ground-based network observations of CG flashes. However, this assumption contributes to uncertainty in the results because recent work with rocket-triggered lightning (Rahman et al., 2007) has suggested that return strokes are not the primary NO-producing phase of a lightning flash. Field experimental results from TROCCINOX (Tropical Convection, Cirrus and Nitrogen Oxides Experiment) in Brazil (Huntrieser et al., 2008) have suggested a more minor dependence on stroke peak current.

The NO produced by CG flashes is distributed unimodally in the vertical, while the NO produced by IC flashes is distributed bimodally based on the vertical distributions of very high frequency (VHF) sources of IC and CG flashes presented in MacGorman and Rust [1998]. The two modes correspond to the two main charge centers in a typical thunderstorm cloud. The vertical distributions of IC and CG lightning channels used in the model are shown in Figure 2 of DeCaria et al. [2005]. The modes of the IC distribution are nominally set at the heights of the -15°C and -45°C isotherms. However, the vertical distribution of IC channels is modified as necessary in some storms by changing the upper mode isotherm to account for a higher or lower cloud top and to match the upper tropospheric peak in aircraft observations of NOx. At each model level, the lightning NO is distributed uniformly to all grid cells within the 20 dBZ contour computed from simulated hydrometeor fields. A passive version of the CSCTM includes only the transport of tracer species and production of lightning NOx. In this version, three types of NOx (pre-existing NOx, CG LNOx, and IC LNOx) are transported without
any chemical reactions and the results are used to estimate average NO$_x$ produced by IC
and CG flashes. Various production scenarios are specified and the model results
compared with in-cloud aircraft observations to determine a first estimate of the most
appropriate LNO$_x$ production scenario for the storm in question.

A version of the model that includes O$_3$ photochemistry is used to separate NO$_x$
into NO and NO$_2$ and obtain a final and best estimate of NO production by IC and CG
flashes. The chemical mechanism for the STERAO storms is described in DeCaria et al.
[2005]. In the CRYSTAL-FACE and EULINOX simulations, the chemical scheme is
identical to that described in DeCaria et al. [2005] with the exception that in these cases,
isoprene and propene chemistry was included. Initial profiles of ozone were constructed
using out-of-cloud aircraft observations, and when necessary to fill gaps, climatological
ozone profiles appropriate for the latitude of the storm in question. The CSCTM includes
a simple scheme to represent the influence of clouds on photolysis rates based on the
work of Madronich [1987] and fully described in DeCaria et al. [2005]. Clear sky
photolysis rates are calculated following Stamnes et al. [1988] using observed column
ozone amounts measured by the Total Ozone Mapping Spectrometer (TOMS) or, in the
case of the STERAO storms, ozonesondes launched from Boulder, Colorado.
Perturbations to clear sky photolysis rates are determined by cloud thickness with very
thick clouds (deeper than 5 km) resulting in photolysis rates multiplied by a factor of 2
above the cloud and 0.1 below the cloud base with a linearly interpolated degree of
enhancement at intermediate altitudes.

3. Results

3.1 Subtropical Events
The CRYSTAL-FACE experiment was conducted over South Florida in July, 2002 and two storms investigated during the campaign were simulated. The July 29 CRYSTAL-FACE storm was simulated using the NASA Goddard version of the non-hydrostatic PSU/NCAR (MM5) mesoscale model (Tao et al., 2003b) with a horizontal resolution of 2 km and vertical resolution of 0.5 km. At 1700 UTC (1300 LT) on July 29, 2002, a powerful thunderstorm developed along the west coast of Florida near Fort Myers. While the storm intensification and moved north along the coast, the area in and above the anvil was sampled by the NASA WB-57 research aircraft from 1845 to 2011 UTC at altitudes ranging from 12.5 to 13.8 km. The coastal convection later merged with convection originating near Lake Okeechobee. Figure 1 shows the time series of CG flashes recorded by the National Lightning Detection Network (NLDN) from 1700 to 2300 UTC. The July 29 storm was an exceptionally strong lightning producer with 4168 CG flashes recorded during this period. Maximum CG flash rates exceed 30 flashes per minute. These lightning flash rates and their relationship to NO observations from the WB-57 aircraft have been discussed by Ridley et al. [2004].

Simulated convection along the coast began earlier than observed by approximately three hours, but a number of storm features were successfully reproduced, including cloud top height and the direction of storm movement. The transport of CO (initial boundary layer maximum) and O₃ (initial stratospheric maximum) were calculated by the CSCTM and compared with in-cloud observations using probability distribution functions (pdfs). The model overestimated the frequency of values in the upper end of the frequency distributions for both CO and O₃ at anvil levels, suggesting that both upward and downward transport in the model may be too strong. However, the intense lightning activity in the thunderstorm and extremely elevated NOₓ mixing ratios (up to 10
ppbv) observed in the anvil indicate that the lightning NO\textsubscript{x} source in this storm was extremely strong. As a result, errors in transport are unlikely to significantly affect the estimate of LNO\textsubscript{x} production per flash in this case.

Because the NLDN only recorded the occurrence of CG flashes during CRYSTAL-FACE, IC flashrates were estimated for the July 29 storm. NLDN flashes with positive peak current less than 10 kA are thought to be IC flashes [Cummins et al., 1998]. These flashes were removed from the NLDN observations to estimate CG flash rates. The percentage of recorded flashes with positive peak current less than 10 kA was calculated during both the July 29 storm and the month of July as a whole. The percentage of such flashes in the July 29 storm was larger by a factor of 2.5 than the percentage for the month of July which may indicate an enhancement of the IC/CG ratio in the July 29 storm over the climatological value. To account for this enhancement, the south Florida climatological value for the IC/CG ratio of 2 from Boccippio et al. [2001] was multiplied by 2.5 to estimate an IC/CG ratio of 5. The upper mode of the vertical distribution of IC flash channel segments was set to -45°C.

\( P_{\text{CG}} \) was estimated to be approximately 590 moles NO based on observed mean peak current (19 kA) and a relationship between peak current and energy dissipated from Price et al. [1997]. Various values of the \( P_{\text{IC}}/P_{\text{CG}} \) ratio were simulated and the results compared with aircraft NO\textsubscript{x} observations (observed NO + estimated NO\textsubscript{2}). NO\textsubscript{2} was estimated using NO and O\textsubscript{3} observations and the photostationary state assumption because no direct measurements of NO\textsubscript{2} were available. Following the work of Madronich (1987), who demonstrated that actinic flux and photodissocation could increase within clouds, NO\textsubscript{2} mixing ratios were calculated assuming both clear sky photolysis rates and rates enhanced by a factor of 2. The observed column mass of N in
NO\textsubscript{x} was calculated for the 1 km thick layer extending from 12.25 to 13.25 km by computing layer mean in-cloud NO\textsubscript{x} mixing ratios. Assuming that photolysis rates were enhanced in the cloud yielded a column mass of $6.6 \times 10^{-4}$ g N m\textsuperscript{-2} while assuming that photolysis rates were unaltered by the cloud yielded a column mass of $7.0 \times 10^{-4}$ g N m\textsuperscript{-2}. Table 1 shows the sensitivity of CSCTM-calculated column mass to the assumed P\textsubscript{IC}/P\textsubscript{CG} ratio. Assuming that an IC flash is on average 60\% as productive of NO as a CG flash yields the most favorable comparison with column mass of nitrogen estimated from aircraft observations when an IC/CG ratio of 5 is assumed.

Figure 2 shows the pdfs of observed and simulated in-cloud NO\textsubscript{x} assuming that P\textsubscript{IC} equals 50 and 60\% of P\textsubscript{CG} and an IC/CG ratio of 5. When compared with observed pdfs at both 12.5 and 13 km, the production scenario that assumes a P\textsubscript{IC}/P\textsubscript{CG} ratio of 0.5 compares more favorably than assuming a P\textsubscript{IC}/P\textsubscript{CG} ratio of 0.6. The pdfs show that the underestimation of the simulated column mass assuming a P\textsubscript{IC}/P\textsubscript{CG} ratio of 0.5 results from the inclusion of gridcells with background NO\textsubscript{x} concentrations as well as the underestimation of the distribution at 13 km between 2 and 6 ppbv. Based on the comparison of simulated and observed pdfs and computed column mass, it is estimated that in the July 29 CRYSTAL-FACE storm an IC flash on average produced 50-60\% as much NO as a CG flash while an average CG flash produced 590 moles NO. The assumption that an IC flash is one tenth as productive of NO as a CG flash significantly underestimated NO\textsubscript{x} when compared to column mass estimates calculated from in-cloud aircraft observations. When chemical reactions were simulated in addition to lightning NO\textsubscript{x} production and convective transport, a loss of NO\textsubscript{x} occurred due to conversion to reservoir species. The simulated column mass of N in NO\textsubscript{x} decreased by approximately 5\% from the values shown in Table 1. The P\textsubscript{IC}/P\textsubscript{CG} ratio of 0.6 was selected for the
subsequent calculations because it continued to provide the best comparison with the
column mass estimates derived from aircraft. It should be noted that the production
scenario discussed above was deduced assuming that the IC/CG ratio in this particular
storm was greater than the climatological IC/CG ratio for south Florida by a factor of 2.5.
Because many more weak positive flashes (which are believed to be IC flashes) were
recorded in this storm than was typical for the South Florida area during the month of
July, it is likely that the IC/CG ratio was elevated above the climatological value. If
instead the climatological IC to CG ratio of 2 is assumed, an IC flash must produce 50%
more NO than a CG flash to match aircraft observations.

It should be noted that the assumptions of IC/CG ratio, PCG value, and PIC/PCG
ratio contribute to uncertainty in the production scenario estimate. Figure 3 shows all the
possible production scenarios that yield NOx mixing ratios which would match observed
column mass when IC/CG ratios of 2 or 5 are assumed. The symbols on the curves show
our best estimates (PCG = 590 moles/flash with PIC/PCG at 0.6 and 1.5) based on the
observed mean peak current. Most literature estimates of PCG range from 200 to 1100
to 4 in the July 29 CRYSTAL-FACE storm. If PIC is assumed to equal PCG, then PCG
must be between 350 and 850 moles NO per flash depending on the number of IC flashes
which are assumed to have occurred. This analysis puts bounds on the uncertainty
associated with assuming a single production scenario. If the IC/CG ratio was known to
be 5 for this storm, the uncertainty would be reduced. PIC/PCG would be in the 0.3 to 1.8
range (assuming PCG is between 200 and 1100 moles NO per flash). The assumption that
IC and CG lighting are equally productive of NO on a per flash basis would yield a
production of 350 moles NO per flash. This analysis demonstrates the need for
observations of IC flashes in future experiments and more definitive information on the
relationship between peak current or other electrophysical variables and LNO_x
production.

A vertical cross section of simulated NO_x through the core of the coastal storm at
the end of the 240 minute simulation is shown in Figure 4 (assuming P_{CG} = 590 moles
NO, P_{IC} = 354 moles NO, and an IC/CG ratio of 5). Maximum NO_x mixing ratios exceed
11 ppbv in the convective plume extending west from the Florida coast in the 10 to 12
km region. Figure 5 shows the vertical profile of the lightning NO_x mass as it is
introduced into the model domain, as well as its profile following convection from the
same simulation as Figure 4. The bimodal distribution of the profile of injected LNO_x
mass reflects the bimodal distribution of IC flash channel segments calculated by the
CSCTM. The upper mode peak is initially smaller in magnitude because the LNO_x is
distributed with a dependence on pressure as described in DeCaria et al. [2005]. Upward
transport during the storm results in LNO_x originally introduced into the model at
altitudes near the lower mode peak residing near the top of the cloud following
convection.

On July 16, 2002, an isolated convective system developed northwest of Miami
shortly after 1900 UTC (1500 LT) and was investigated as part of the CRYSTAL-FACE
project. Over the next few hours, the storm moved west across the Florida peninsula and
was extensively sampled by the WB-57 from 1936 to 2306 UTC at altitudes ranging from
9 to 15.5 km AGL. The storm was simulated using the Advanced Regional Prediction
System (ARPS) described in Xue et al. [2000; 2001] with a horizontal resolution of 2 km
and vertical resolution varying from 25 m near the surface to 0.5 km near the top of the
model domain at approximately 25 km. A number of different types of observations,
including radar reflectivity, were assimilated into the simulation. The simulated temporal
evolution of the storm matched observations well, as did storm size. The CSCTM was
used to calculate the transport of tracer species CO and O₃ and a comparison of model
results with anvil aircraft observations showed that the model adequately represented
transport within the storm.

Figure 6 shows the time series of flash rates recorded by the ground-based NLDN
from 1900 to 2300 UTC. In contrast to the July 29 CRYSTAL-FACE storm, the July 16
storm was a relatively weak lightning producer with only 301 CG flashes recorded during
this period and a maximum CG flash rate of 9 flashes per minute. The percentage of
weak positive flashes (peak current < 10kA) was calculated during the July 16 storm and
was over 20 times greater during the storm than for the month of July as a whole.

Because the flash rate during the storm represented too small a sample to reliably make a
large adjustment, IC flash rates were estimated from the observed CG flash rates and the
climatological IC to CG ratio of 2 for south Florida from Boccippio et al. [2001]. Based
on the mean peak current of CG flashes recorded by the NLDN for this storm (23 kA),
P_{CG} was estimated to be 700 moles of NO. In this simulation, the upper mode of the IC
flash channel distribution was set to -60°C. Several different values of the P_{IC}/P_{CG} ratio
were simulated and the results compared with observations. The assumption that on
average, an IC flash produces 75% as much NO as a CG flash yielded the most favorable
comparison with the column mass of N in NOₓ estimated from observations when
chemical reactions were not simulated. The simulation of chemistry led to a decrease in
NOₓ mixing ratios due to conversion of NOₓ to reservoir species such as HNO₃ and PAN.

In order to match aircraft observations, a P_{IC}/P_{CG} ratio of 0.9 was needed. Figure 7 shows
a vertical cross-section of NOₓ calculated assuming this production scenario taken
through the core of the storm after 180 minutes of simulation. Maximum NOx mixing ratios exceeding 5 ppbv are found at 6.5 km while lower concentrations are found in the upper part of the core and anvil.

Figure 8 shows the percentage of the mass of N in LNOx in each kilometer-deep layer after both the July 16 and 29 CRYSTAL-FACE storms. Following the July 29 storm, the maximum in the vertical mass distribution is found at anvil levels (~10 – 11 km). In the case of the July 16 storm, the maximum is found in the 6-7 km layer, coincident with the lower mode of the vertical distributions of the LNOx source in the CSCTM. A smaller peak is found in 9-10 km layer, the height of the upper mode of the distribution, and another peak at 12-13 km, near the top of the cloud. These vertical LNOx mass distributions are based on the assumed IC to CG ratios of 2 and 5 for the July 16 and 29 storms, respectively. Because IC to CG ratios may be highly variable and were estimated for these simulations, the results of a sensitivity test of the assumption of IC to CG ratios of 2 and 5 are shown for the July 16 storm in Figure 9a and for the July 29 storm in Figure 9b. For both storms, assuming an IC to CG ratio of 2 results in a slightly larger percentage of LNOx mass residing in the lower and middle portion of the cloud and a smaller percentage of LNOx mass near the cloud top (12-14 km for the July 16 case and 10-12 km for the July 29 storm).

3.2. Midlatitude Continental Events

The STERAO field project was conducted in June and July, 1996 over northeastern Colorado to study lightning NOx production and convective transport of chemical species. CG lightning activity was monitored by the NLDN, while total lightning activity, including both CG and IC flashes, was mapped by a VHF interferometer. Two storms observed during the STERAO field project were simulated.
and lightning NO\textsubscript{x} production per flash estimated in each. A similar analysis was conducted for one storm from the EULINOX field project conducted in southern Germany in July 1998. The fourth midlatitude storm simulated was from the 1985 PRESTORM experiment conducted over Kansas/Oklahoma.

All four midlatitude storms were simulated using the 3-D Goddard Cumulus Ensemble (GCE) model, which is described in Tao and Simpson [1993] and Tao et al. [2003a]. A description of the GCE simulation of the July 12 STERAO storm is contained in Stenchikov et al. [2005], while the results of the chemical transport model simulation are found in DeCaria et al. [2005]. Between 2000 and 2400 UTC (1400 and 1800 LT), 188 CG flashes and 2121 IC flashes were recorded by the NLDN and interferometer, respectively. Flash counts for the STERAO storms only include interferometer flashes with duration greater than 100 ms. Whether or not short duration flashes, which would not be recorded by some lightning detection systems, are productive of NO is an open question. DeCaria et al. [2005] estimated that $P_{CG}$ was 460 moles NO based on the mean peak current of 15 kA. Assuming that an IC flash was equally as efficient at producing NO as a CG flash yielded the best comparison with observations in terms of mean vertical profile shapes while a $P_{IC}/P_{CG}$ ratio between 0.75 and 1 compared most favorably with observed column mass.

On July 10, 1996, a multi-cellular thunderstorm organized in a northwest to southeast line developed near the Wyoming-Nebraska border at approximately 2100 UTC (1500 LT) and was observed as part of the STERAO campaign [Dye et al., 2000; Skamarock et al., 2000; 2003]. Research aircraft investigated the storm from 2237 to 0105 UTC. After 0115 UTC, the storm became unicellular with supercell characteristics. IC lightning activity dominated throughout the lifetime of the storm with only 77 CG
flashes and 3223 IC flashes recorded between 2201 and 0206 UTC. The University of North Dakota Citation aircraft observed maximum NO mixing ratios of 1 ppbv approximately 60 km downstream of the storm cores [Dye et al., 2000].

The GCE model with a horizontal resolution of 2 km and 0.5 km vertical resolution was used to simulate the July 10 STERAO storm. The GCE and CSCTM simulations were included in a cloud-chemistry model intercomparison study described in Barth et al. [2007]. Both the magnitude and height of the simulated peak updraft velocity compared well with observations. Convective transport was evaluated by comparing simulated CO and O$_3$ mixing ratios with observations obtained during two across-anvil transects. While the simulation underrepresented transport during the first transect, mixing ratios in the later transect were reproduced well by the CSCTM simulation, indicating that convective transport was adequate after an initial spin-up period.

Simulated storm speed and cloud top heights compared favorably with radar observations. For the simulations of the July 10 STERAO and July 21 EULINOX storms, the parameterization of LNO$_x$ production was modified to simulate individual flashes. The method is fully illustrated in Ott et al. [2007]. Each flash is simulated by selecting grid cells at random from an area of the domain centered just downwind of the maximum updraft, which is similar in size to the area where lightning flashes typically occurred. The downwind location was chosen based on plots of radar reflectivity and flash location in Höller et al. [2000] and Dye et al. [2000] that show the majority of lightning activity occurring slightly downwind of the core updraft region. The number of grid cells included in a flash at each level is determined by vertical distributions adapted from the Gaussian distributions calculated in the original bulk method of LNO$_x$ parameterization described in DeCaria et al. [2005]. Simulations of both the July 10
STERAO and July 21 EULINOX storms using both the original and modified LNOx parameterizations show that the difference in parameterization produces little change in the vertical distribution of LNOx following convection. The upper mode of the IC flash channel distribution was set to -50°C for the July 10 STERAO storm.

In the July 10 STERAO storm, P_{CG} was estimated to be approximately 390 moles based on the observed peak current (13 kA) of CG flashes. Assuming a P_{IC}/P_{CG} ratio of 0.5 matched in-cloud aircraft observations well when chemical reactions were not considered. When chemical reactions were simulated, the P_{IC}/P_{CG} ratio was increased to 0.6 to match observations. Figure 10 shows a vertical cross section of calculated NOx through the core of the southernmost cell in the line of thunderstorms at the end of the 180 minute simulation. NOx mixing ratios exceed 2.8 ppbv at 3.5 km above the surface but are only ~1 ppbv in the anvil region.

The EULINOX field project was conducted in central Europe in June and July 1998 in order to study lightning NOx production over Europe. In addition to two research aircraft, the project included observations of CG lightning activity from the ground-based lightning detection system known as BLIDS (Blitz Informationsdienst von Siemens).

One storm from the EULINOX project, which occurred on July 21, 1998 over southern Germany, was simulated using the GCE model. The storm developed as a single cell and after an initial period of intensification split into two distinct cells. The northernmost cell became multicellular in structure and was observed to decay rapidly, while the southern cell strengthened and developed supercell characteristics. The southern cell produced 360 CG and 2565 IC flashes between 1640 and 1900 UTC (1840 and 2100 LT), while the northern storm produced 289 CG and 815 IC flashes. The GCE simulation succeeded in reproducing a number observed storm features, including the cell-splitting. A full
description of the GCE and CSCTM simulations is provided in Ott et al. [2007]. Based on the mean peak current (12 kA) of CG flashes, $P_{CG}$ was estimated to be 360 moles NO. The upper mode of the IC flash channel distribution was set to -45°C in this simulation. Several different values of $P_{IC}$ were simulated, and the scenario in which $P_{IC}$ is equal to $P_{CG}$ was found to compare most favorably with observations, though observed column mass was underestimated by 10%. In order to match observed column mass, the $P_{IC}/P_{CG}$ ratio needed to be increased to 1.15.

In addition to the STERAO and EULINOX storms, the June 10-11 squall line observed during the PRE-STORM project was simulated using the GCE model. The June 10-11 squall line has been documented extensively [e.g. Johnson and Hamilton, 1988; Rutledge et al., 1988] and has previously been simulated using the 2-D version of the GCE [Tao et al., 1993]. In this case, the horizontal resolution of the 3-D GCE was 1.5 km and vertical resolution varied from approximately 0.25 km near the surface to slightly more than 1 km near the top of the domain at 21.4 km. During PRE-STORM, the occurrence of CG lightning flashes was recorded by the National Severe Storms Laboratory's Lightning Location Network. Based on a time series of positive and negative CG flash rates from Nielsen et al. [1994], approximately 6500 CG flashes occurred during the storm's lifetime. Observations of total lightning activity were unavailable, so the climatological IC/CG ratio of 3 for the region [Boccippio et al, 2001] was assumed to estimate IC flash rates. The upper mode of the IC flash channel distribution was set to -45°C. No observations of the chemical environment of the squall line anvil are available. Therefore, it was not possible to estimate a production scenario for IC and CG flashes as in the other five storms. Instead, the average value of $P_{CG}$
calculated over the five other storms (~500 moles NO per flash) was used along with an estimate of \( P_{IC} \) that was 85% of \( P_{CG} \) or 425 moles of NO.

Figure 11 shows the vertical distribution of the mass of N in LNO\(_x\) for the four midlatitude continental storms. The distributions for the four storms all reflect the double peaked distribution of LNO\(_x\) produced by IC flashes in the model. There is variation between the simulations in the dominant mode of the lightning distributions. In the EULINOX and PRESTORM storms whose IC to CG ratios were on average 5 and 3, respectively, a higher percentage of LNO\(_x\) mass is found near the height of the lower mode of the IC distribution, which is also the mode of the CG distribution. In the July 10 and July 12 STERAO storms, which had average IC to CG ratios of 33 and 8 during the time periods simulated, a greater percentage of LNO\(_x\) mass resides near the height of the upper mode of the IC vertical distribution following convection. In addition to the IC to CG ratio, the dominance of the modes is likely affected by storm dynamics and the timing of IC and CG flashes in relation to the evolution of the storm.

4. Applications for large-scale models and remote sensing

4.1 Vertical distribution of lightning NO\(_x\) mass

We have presented results from the simulations of six thunderstorms using the 3-D CSCTM. Figure 12a shows the average vertical distribution of the mass of N in LNO\(_x\) calculated by averaging the case studies in the subtropical regime and Figure 12b shows the average vertical distribution for storms in the midlatitude regime overlaid with the vertical distribution calculated by Pickering et al. [1998]. Both plots are overlaid with smooth curves fit to the regime average. Table 2 lists the percentages of LNO\(_x\) mass in each 1-km layer taken from the smoothed curves. In both regimes on average, only a small percentage of LNO\(_x\) resides in the boundary layer following the convective event.
A greater percentage of LNO\textsubscript{x} remains in the middle and upper troposphere where the LNO\textsubscript{x} was originally produced. These “backward C-shaped” average vertical distributions are in marked contrast to the C-shaped profiles presented in Pickering et al. [1998] based on 2-D cloud-resolving model simulations where a significant percentage of LNO\textsubscript{x} mass was transported to the boundary layer and relatively little LNO\textsubscript{x} mass was found between 1.5 and 6.5 km after convection concluded. Our results are similar to those from recent 3-D cloud models with explicit electrophysics. For example, Zhang et al. [2003a] found a maximum in NO\textsubscript{x} at mid-levels along with a secondary maximum at anvil levels indicating that a large portion of the LNO\textsubscript{x} remains within the cloud near the levels of its production. It should also be noted that our simulations indicate a small percentage of mass (~1%) remains above the tropopause following convection, which results from overshooting transport of lightning NO\textsubscript{x} produced at lower altitudes. Individual modeling groups who implement these profiles may want to consider scaling these profiles so that mass is not directly injected into the stratosphere because most convective parameterizations used in larger-scale models do not produce overshooting cloud tops. Implementation of the profiles should involve scaling them to calculated cloud top height on an individual grid cell basis.

Assuming the density profile of the standard atmosphere, the total mass of lightning NO\textsubscript{x} was averaged over the EULINOX and STERAO storms. That amount of NO\textsubscript{x} distributed uniformly over a 200 km by 200 km region (typical of a global model grid cell) using the average midlatitude profile shown in Table 2 corresponds to a maximum increase in NO\textsubscript{x} mixing ratios of ~145 pptv between 7 and 9 km immediately following convection (~2 km higher than the maximum of the lightning NO\textsubscript{x} mass distribution). Because the lifetime of NO\textsubscript{x} increases with altitude, lightning NO\textsubscript{x} will be
converted to reservoir species such as PAN and HNO$_3$ more rapidly in the 7-9 km layer than at higher altitudes. As the time after convection increases, the maximum increase in NO$_x$ mixing ratios due to lightning would be seen at higher altitudes, which is consistent with the C-shaped profile of NO$_x$ typically observed in the troposphere. Downward transport from the stratosphere also contributes to the upper tropospheric maximum in observed NO$_x$ mixing ratios, while the maximum near the surface results from emissions from surface sources such as fossil fuel combustion and soil.

The impact of assuming the vertical distributions of lightning NO$_x$ mass presented here has been calculated using NASA's Global Modeling Initiative (GMI) combined stratosphere-troposphere (Combo) CTM. The Combo CTM is detailed in Ziemke et al. [2006] and Duncan et al. [2007]. The tropospheric chemical mechanism includes 80 species and 300 reactions to simulate O$_3$-NO$_x$-hydrocarbon chemistry [Bey et al. 2001]. Lightning is assumed to produce 5 TgN yr$^{-1}$. Horizontal distribution of lightning NO$_x$ is determined by the locations of parameterized deep convection (as indicated by the upper tropospheric values of cloud mass flux) in the meteorological fields from the Global Modeling and Assimilation Office's GEOS-4 Data Assimilation System that are used to drive the Combo CTM. Flash rates are scaled such that on a regional and monthly basis they match those from the OTD/LIS climatology (Allen et al., 2009).

Two one-year simulations were produced by the Combo CTM. The first used the vertical profiles of lightning NO$_x$ from Pickering et al. [1998] while the second simulation used the vertical profiles of lightning NO$_x$ shown in Figure 12a and b for the midlatitude and subtropical regimes. Because no tropical thunderstorms were simulated with the cloud and chemistry models, a hypothetical tropical distribution (Figure 12c) was constructed by extrapolating the subtropical profile to a higher tropopause regime.
Test runs of the GMI Combo CTM revealed that this profile performed well in regions dominated by marine convection, but in tropical continental areas the Pickering et al. [1998] profile yielded better results for upper tropospheric ozone compared with ozonesonde data. Therefore, in tropical continental regions the Pickering et al. [1998] profile, modified by removing the boundary layer maximum and redistributing this mass between 4 and 11 km, was used. The tropical profiles are also provided in Table 2.

Figure 13 shows the zonal mean change in NOx and O3 in January and July when the profiles shown in Figure 12 are used instead of the Pickering et al. [1998] profiles. Because these profiles place less NO in the upper troposphere, NOx decreases above 10 km with decreases over 100 pptv found over the southern hemisphere in January and over the northern hemisphere in July. The decrease in NOx in the upper troposphere, which results from using the modified vertical profiles of lightning NOx mass, also causes a small decrease in ozone throughout much of the troposphere. The largest decrease in ozone is ~10 ppbv in July at 15 km and 30°N.

4.2. NO production

A best-fit production scenario of P_{IC} and P_{CG} has been estimated by comparing in-cloud aircraft observations with model output for the five storms where in-cloud aircraft observations were available. Figure 14 shows the production scenarios estimated for these five storms as well as the production scenario from Price et al. [1997], which was used in calculating the vertical profiles of LNOx mass presented in Pickering et al. [1998] and has been used in many global CTMs. In all cases, P_{CG} was estimated to be less than the 1100 moles per CG flash given in Price et al. [1997]. In addition, in all cases the ratio of P_{IC} to P_{CG} was greater than the commonly assumed value of 0.1 presented by Price et al. [1997]. Over the five storms simulated, the average estimated P_{CG} was 500 moles NO.
per flash or 7 kg N per flash (range of 360 to 700 moles per flash or -5 to 9.8 kg N per flash). Assuming $P_{IC}/P_{CG}$ ratios in the middle of the estimated uncertainty ranges for the July 29 CRYSTAL-FACE, July 12 STERAO, and July 21 EULINOX storms yields an average $P_{IC}/P_{CG}$ ratio of 0.93, corresponding to 465 moles NO. The median peak current (16.5 kA for negative flashes and 19.8 kA for positive flashes, which account for 10.9% of the total) of the North American Lightning Detection Network (NALDN) presented in Orville et al. [2002] corresponds to a $P_{CG}$ value of 508 moles NO when using the Price et al. [1997] relationship between peak current and energy dissipated, which agrees well with our estimate of 500 moles NO per CG flash. Therefore, the cases we have simulated appear to be representative of midlatitude and subtropical lightning. Assuming the average production scenario over the five storms presented, an average global IC to CG ratio of 3 (the same as estimated for the continental United States by Boccippio et al., 2001), and a global flash rate of 44 flashes s$^{-1}$ [Christian et al., 2003] yields a global lightning NO source of 8.6 Tg N yr$^{-1}$.

Estimates of the global lightning NO source have ranged from 2-20 Tg N yr$^{-1}$ [IPCC, 2001]. This range has been narrowed in recent years. IPCC [2007] recommends a 1.1-6.4 Tg N yr$^{-1}$ range, though a more comprehensive review has specified the range to be 2-8 Tg N yr$^{-1}$ [Schumann and Huntrieser, 2007]. This review considered all of the methods of estimating LNO$_x$ production: global model estimates constrained by various observations, cloud-resolved modeling studies, aircraft measurements, laboratory experiments, and theoretical estimates. Our estimate of 8.6 Tg N yr$^{-1}$ lies near the upper end of the recently established range of global estimates. It is unlikely that our estimate is larger than values in this range due to the global extrapolation. Because of satellite observations of total lightning activity from instruments such as the Optical Transient
Detector (OTD; see Christian et al., 2003), uncertainty in the global flashrate has been greatly reduced. Perhaps more likely it is due to the fact that our average production scenario was calculated using data from only midlatitude continental and subtropical storms. No tropical thunderstorms were simulated in this analysis. Because 78% of lightning flashes occur between 30°S and 30°N [Christian et al., 2003], further investigation of the properties of tropical lightning flashes and their production of NO is needed. Based on analysis of data from the TROCCINOX experiment in Brazil, Huntrieser et al. [2008] suggest that tropical flashes (shorter, possibly due to low vertical wind shear) produce less LNOₓ than subtropical or midlatitude flashes (longer, possibly due to greater wind shear). If this hypothesis holds true throughout the tropics, inclusion of tropical events into our average production scenario will decrease this average value. Tropical event simulations are currently underway.

Several modeling studies have assumed a production scenario similar to the mean scenario presented here where both IC and CG flashes produce on average approximately 500 moles NO per flash. Hudman et al. [2007] simulated NOₓ over the United States during the ICARTT campaign using the GEOS-Chem CTM and found that assuming a production per flash of 500 moles NO instead of the default GEOS-Chem value of 125 moles NO improved the comparison with upper tropospheric aircraft observations. Cooper et al. [2006] simulated LNOₓ production and transport over North America during the same period using the FLEXPART model and assumed IC and CG flashes produce 460 moles NO (based on the DeCaria et al. [2005] results for the July 12 STERAO storm) and a 2-day lifetime for upper tropospheric NOₓ. Resulting ozone enhancements were estimated with a box model. The results showed a good agreement between simulated NOₓ and DC-8 aircraft observations and between simulated ozone
enhancements and observations from commercial aircraft and ozonesondes. Jourdain et al. [2009] found that assuming a production per flash of 520 moles NO (rather than 260 moles NO) in GEOS-Chem simulations of ozone over the United States substantially reduced the model’s bias relative to TES observations. Choi et al. [2008] compared results from a regional CTM with tropospheric NO\textsubscript{2} columns from OMI and tropospheric O\textsubscript{3} columns derived from a combination of OMI and MLS data and found that the model, assuming IC and CG flashes produce 500 moles NO, was able to reasonably reproduce the spatial distribution of the satellite observations.

4.3 NO\textsubscript{2} in the vicinity of electrified storms

NO\textsubscript{2} profiles appropriate for regions dominated by NO\textsubscript{x} from lightning are useful for improving satellite retrievals of NO\textsubscript{2} column amounts in such environments. The air mass factor used in converting satellite-measured slant columns to vertical columns of NO\textsubscript{2} is highly dependent on the NO\textsubscript{2} profile shape. NO\textsubscript{2} profiles from the version of the CSCTM that includes chemical production and loss have been used to examine the structure of this species in the CRYSTAL-FACE, STERAO, and EULINOX storms.

Mean vertical profiles of NO\textsubscript{2} after convection are shown in Figure 15. The profiles were calculated over a 40 by 40 km area positioned in the convective core region of the model domain. The July 29 profile shows extremely elevated NO\textsubscript{2} mixing ratios exceeding 2 ppbv from 5 to 7.5 km, while the July 16 profile maximizes at only 0.7 ppbv at 9.5 km. The disparity in profiles is due to the large difference in flash rates in the two storms with over 4000 CG flashes recorded by the NLDN in the July 29 storm, and only 301 CG flashes recorded in the July 16 storm. Of the midlatitude storms, the vertical profile of NO\textsubscript{2} from the EULINOX storm (with both high flash rate and pollution inflow)
is much larger than in either of the STERAO storms with a maximum of nearly 3 ppbv at 5.5 km.

In addition to NO\textsubscript{2} profiles, we have also used these simulations to estimate partial columns of NO\textsubscript{2} that a satellite may be able to observe in the upper portion of a convective cloud. Vasilkov et al. [2008] compared cloud-top pressures retrieved in the UV wavelengths by the Ozone Monitoring Instrument (OMI) aboard the Aura satellite with those retrieved by IR measurements from MODIS aboard Aqua. A comparison of both cloud-top pressure products with CloudSat radar observations indicate that OMI may be able to measure NO\textsubscript{2} as far down as 400 to 600 mb in the presence of deep convective clouds. Partial NO\textsubscript{2} columns were calculated for our storms of interest by averaging 2-km model output over 13 km by 24 km areas equivalent to OMI's nadir footprint and integrating the column from 400 mb to the tropopause. The results are shown in Figure 16. The July 29 CRYSTAL-FACE and July 21 EULINOX storms show the greatest degree of enhancement, which is consistent with the NO\textsubscript{2} profiles shown in Figure 15. In the July 29 CRYSTAL-FACE storm, the region of highly elevated NO\textsubscript{2} columns extends over 100 km. Table 3 shows the sensitivity of the peak and background NO\textsubscript{2} columns to the choice of column depth. The peak values indicate the maximum partial NO\textsubscript{2} column amounts over an OMI grid box area (13 km by 24 km) in the storm anvil or core regions, while the background values indicate the mean partial NO\textsubscript{2} column amounts outside of the storm region. These data should be useful in providing a range of values of tropospheric column NO\textsubscript{2} that may be compared to retrievals over convective clouds from such instruments as OMI.

5. Conclusions
Simulations of six midlatitude and subtropical thunderstorms occurring during four field projects have been conducted using the CSCTM, which includes a parameterized source of LNO\textsubscript{x}. In order to estimate LNO\textsubscript{x} production per flash in each storm, different scenarios of P\textsubscript{IC} and P\textsubscript{CG} were specified in the model, and the results compared with in-cloud aircraft observations of NO\textsubscript{x}. By comparing column mass and probability distribution functions of the observed and simulated storms, the most appropriate production scenario was estimated for each storm. The results suggest that P\textsubscript{IC} may be nearly the same as P\textsubscript{CG}. A frequent assumption that P\textsubscript{IC} is equal to one tenth P\textsubscript{CG} resulted in a significant underestimation of LNO\textsubscript{x} in all five simulations where anvil observations were available. We echo the recommendation of Ridley et al. [2005] for use of comparable values of P\textsubscript{CG} and P\textsubscript{IC}. The Ridley et al. [2005] recommendation was partly based on one of the cases presented here. Our similar results for four additional cases strengthen this recommendation. The mean P\textsubscript{CG} obtained from the five case simulations is 500 moles NO per flash (range 360 to 700), which, when extrapolated globally, yields an estimate at the high end of the currently accepted range. This may result from the absence of tropical flashes in this analysis.

Vertical profiles of the percentage of LNO\textsubscript{x} mass in each 1-km layer after the convection show very little LNO\textsubscript{x} mass near the surface with the majority of LNO\textsubscript{x} remaining in the mid- and upper troposphere in a “backward C-shaped” profile. Global and regional CTMs that have adopted C-shaped vertical profiles of LNO\textsubscript{x} mass may be underestimating the amount of LNO\textsubscript{x} in the mid- troposphere and overestimating the amount near the surface. Global models which are changed to represent equivalent per flash production by IC and CG lightning may require a change of the global LNO\textsubscript{x} source strength to reasonably reproduce NO\textsubscript{x} observations in the middle and upper troposphere.
Changes in the vertical placement of LNO\textsubscript{x} in CTMs may significantly alter distributions of species such as O\textsubscript{3} and OH.

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Table 1. Calculated column mass of N in NO\textsubscript{x} in the July 29 CRYSTAL-FACE storm assuming an IC/CG ratio of 5

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<th>$P_{CG}$ (moles NO per flash)</th>
<th>$P_{IC}/P_{CG}$ (IC/CG = 5)</th>
<th>$P_{IC}/P_{CG}$ (IC/CG = 2)</th>
<th>Column Mass (g N m\textsuperscript{-2})</th>
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Table 2. Average Profiles of LNOx Mass in Percent

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Figure 1. Time series of CG flash rates detected by the NLDN from 1700 to 2300 UTC (1300 and 1900 LT) for the July 29 CRYSTAL-FACE storm.
Figure 2. Pdfs of simulated and observed NO\textsubscript{x} at 12.5 km (a) and 13 km (b) for the July 29 CRYSTAL-FACE storm. Solid (dashed) line shows observed values assuming clear sky (cloud enhanced) photolysis rates. Dashed (dot-dashed) line shows simulated values assuming P\textsubscript{IC}/P\textsubscript{CG} of 0.5 (0.6).
Figure 3. Relationship between $P_{CG}$ and the $P_{IC}/P_{CG}$ ratio necessary to match the column mass of N computed from aircraft observations. Solid (dashed) line shows the relationship when an IC/CG ratio of 2 (5) is assumed. Plus signs indicate the production scenarios when $P_{CG}$ is assumed to be 590 moles NO per flash based on observed mean peak current.
Figure 4. Vertical cross-section of simulated NO\textsubscript{x} in the July 29 CRYSTAL-FACE storm (assuming P\textsubscript{CG} = 590 moles NO, P\textsubscript{IC} = 354 moles NO, and an IC/CG ratio of 5) at 240 minutes.
Figure 5. Vertical distributions of the percentage of LNO\textsubscript{x} mass per kilometer injected into the cloud and following convection for the July 29 CRYSTAL-FACE storm (assuming \(P_{\text{CG}} = 590\) moles NO, \(P_{\text{IC}} = 354\) moles NO, and an IC/CG ratio of 5).
Figure 6. Time series of CG flash rates detected by the NLDN from 1900 to 2300 UTC (1500 to 1900 LT) for the July 16 CRYSTAL-FACE storm.
Figure 7. Vertical cross-section of simulated NO$_x$ through the core of the July 16 CRYSTAL-FACE storm assuming $P_{CG} = 700$ moles NO and $P_{IC} = 630$ moles NO at 180 minutes.
Figure 8. Vertical distributions of percentage of LNOx mass per kilometer following convection for two simulated subtropical storms.
Figure 9. Vertical distributions of the percentage of LNO₃ mass per kilometer following convection for (a) the July 16 and (b) the July 29 CRYSTAL-FACE simulations assuming IC to CG ratios of 2 and 5.
Figure 10. Vertical cross-section of simulated NO$_x$ through the core of the southern cell of the July 10 STERAO storm assuming P$_{CO}$=390 moles NO and P$_{IC}$=234 moles NO at 180 minutes.
Figure 11. Vertical distributions of percentage of LNO$_x$ mass per kilometer following convection for four simulated midlatitude continental storms.
Figure 12. Average vertical distribution of percentage of LNO\textsubscript{x} mass per kilometer following convection (solid) for the (a) subtropical and (b) midlatitude continental regimes. Dashed line shows polynomial fit. Midlatitude continental profile from Pickering et al. [1998] (dash-dot) is also shown in (b). Hypothetical tropical marine profile (c) is based on extrapolating the subtropical average profile to a higher tropopause regime while the tropical continental profile was constructed using the Pickering et al. [1998] profile with the boundary layer maximum removed and that mass redistributed into layers from 4 to 11 km.
Figure 13. Zonal mean change in NOx (pptv) and O3 (ppbv) in January and July resulting from using the lightning NOx profiles in Figure 11 instead of the profiles from Pickering et al. [1998].
Figure 14. Estimated lightning NO$_x$ production scenarios for the July 16 CRYSTAL-FACE (C, 7/16), July 29 CRYSTAL-FACE (C, 7/29), July 10 STERAO (S, 7/10), July 12 STERAO (S, 7/12), and July 21 EULINOX (E, 7/21) storms. The bars in the 7/29 CRYSTAL-FACE, 7/12 STERAO, and 7/21 EULINOX storms indicate the estimate uncertainty. The Price et al., [1997] and Fehr et al. [2004] production scenarios are indicated by asterisks, as is the estimated value of P$_{CG}$ calculated assuming the NALDN median peak current from Orville et al. [2002].
Figure 15. Average vertical profiles of NO$_2$ mixing ratio in the convective core region following simulated subtropical storms (a) and midlatitude storms (b).
Figure 16. Partial NO$_2$ columns ($10^{14}$ molecules cm$^{-2}$) from the tropopause to 400 hPa for CRYSTAL-FACE, STERAO, and EULINOX simulated thunderstorms.