The impact of North American anthropogenic emissions and lightning on long-range transport of trace gases and their export from the continent during summers 2002 and 2004

Matus Martini,¹ Dale J. Allen,¹ Kenneth E. Pickering,² Georgiy L. Stenchikov,³,⁴ Andreas Richter,⁵ Edward J. Hyer,⁶ and Christopher P. Loughner¹

Received 2 April 2010; revised 10 December 2010; accepted 18 January 2011; published 7 April 2011.

We analyze the contribution of North American (NA) lightning and anthropogenic emissions to ozone concentrations, radiative forcing, and export fluxes from North America during summers 2002 and 2004 using the University of Maryland Chemical Transport Model (UMD-CTM) driven by GEOS-4 reanalysis. Reduced power plant emissions (NOₓ SIP Call) and cooler temperatures in 2004 compared to 2002 resulted in lower ambient ozone concentrations over the eastern United States. Lightning flash rates in early summer 2004 were 50% higher than 2002 over the United States. Over the North Atlantic, changes in ozone column between early summer 2002 and 2004 due to changes in lightning and meteorology exceeded the change due to emission reductions by a factor of 7. Late summer changes in lightning had a much smaller impact on ozone columns. In summer 2004, net downward radiative flux at the tropopause due to ozone produced from anthropogenic emissions ranged from 0.15 to 0.30 W m⁻² across the North Atlantic, while that due to ozone produced from lightning NO emissions ranged from 0.20 to 0.50 W m⁻². Enhanced lofting of polluted air followed by stronger westerly winds led to more net export of NOₓ, NOy, and ozone in early summer 2004 than 2002 despite reduced anthropogenic emissions. Ozone export fluxes across the eastern NA boundary due to anthropogenic emissions were factors of 1.6 and 2 larger than those due to lightning in 2004 and 2002, respectively. Doubling the NA lightning NO source increased downwind ozone enhancements due to lightning NO emissions by one third.


1. Introduction

North America is a major source of anthropogenic and naturally generated trace gases, and North American (NA) emissions affect trace gas mixing ratios over the North Atlantic, Europe and North Africa [Li et al., 2002]. A key trace gas for both chemistry and radiative balance of the troposphere is ozone (O₃). According to the Intergovernmental Panel on Climate Change (IPCC) [2007], tropospheric O₃ is the third most important anthropogenic climate gas. Major precursors of tropospheric O₃ are nitrogen oxides (NOₓ = NO + NO₂) from fuel combustion, soils and lightning. Surface precursors are rapidly transported upward via convection [Dickerson et al., 1987; Pickering et al., 1992, 1995] and detrained into the upper troposphere (UT) [Bertram et al., 2007] where concurrent lightning greatly enhances NOₓ [DeCaria et al., 2000, 2005; Zhang et al., 2003; Hudman et al., 2007]. The importance of the vertical distribution of O₃ and its precursors is emphasized by the fact that midtropospheric and upper tropospheric O₃ has larger radiative forcing efficiency [Lacis et al., 1990] than O₃ in the lower troposphere (LT). Therefore, O₃ resulting from lightning NOₓ and NOy transported upward in deep convection has the greatest consequences for the greenhouse effect [IPCC, 2007].

[3] The longer chemical lifetimes and greater wind speeds aloft can then lead to significant long-range transport (LRT) during which photochemical O₃ production occurs. On the other hand, the vertical mixing that occurs during convection over unpolluted regions can decrease the tropospheric O₃ column as high-O₃ air from the UT is transported down-
ward to levels where it is destroyed more quickly, and low-O$_3$ air that originated near the surface is deposited in the UT [Lelieveld and Crutzen, 1994].

[4] The measurements between 1 July and 15 August 2004 from the INTEX-A (Intercontinental Chemical Transport Experiment–Phase A) aircraft campaign over the contiguous United States and adjacent areas [Singh et al., 2006] and from coordinated IONS (INTEX Ozoneonde Network Study) ozonesonde launches [Thompson et al., 2007a, 2007b] showed that the NA UT was greatly influenced by both NO$_x$ from lightning (LNO$_x$) and surface pollution lofted via convection and contained elevated concentrations of peroxyacetyl nitrate (PAN), O$_3$, hydrocarbons and NO$_x$ [Singh et al., 2007; Cooper et al., 2006].

[5] Hudman et al. [2009] found that during the INTEX-A period the hemispheric tropospheric O$_3$ burden was enhanced with comparable contributions from anthropogenic and lightning NO emissions over North America. Choi et al. [2009] reported that LNO$_x$ has a greater impact on radiation via O$_3$ production than its anthropogenic counterpart (ANO$_x$) over North America. Modeling of the horizontal and vertical distribution of LNO$_x$ is highly uncertain. In the study by Hudman et al. [2007], the GEOS-Chem standard simulation greatly underestimated NO$_x$ in the UT. After increasing the lightning NO production to 500 mol flash$^{-1}$, GEOS-Chem simulated NO$_x$ was still low biased. Similarly, Bousser et al. [2007], Pierce et al. [2007], Fang et al. [2010], and Allen et al. [2010] underestimated upper tropospheric NO$_x$ using the MOCAGE, RAQMS, MOZART and GMI chemical transport models (CTMs) (all with different lightning schemes), respectively.

[6] We extend the previous work focused on NO$_x$ export from North America during the INTEX-A period in summer 2004 by estimating the climate implications (radiative effects), by contrasting the summer 2004 with a meteorologically different summer (2002) using the University of Maryland Chemical Transport Model (UMD-CTM) [Park et al., 2004a, 2004b]. Godowitch et al. [2008], using the Community Multiscale Air-Quality (CMAQ) model, showed that reduced NO$_x$ emissions from power plants [Frost et al., 2006; Kim et al., 2006] caused substantial decreases in NO$_x$ concentrations aloft (300–1100 m) and in ground level daily 8 h maximum O$_3$ between the summers 2002 and 2004. Sites downwind of the emission-rich Ohio River Valley (ORV) region (Pennsylvania, Ohio, West Virginia, Kentucky, Indiana and Illinois) experienced the greatest decreases in daily maxima of 8 h O$_3$ between 2002 and 2004. Interestingly, Godowitch et al. [2008] found that meteorological effects had greater impact on O$_3$ than those from emission changes over the region north of the Ohio River (Illinois, Indiana, Ohio, Wisconsin and Michigan). In particular, temperature and moisture parameters were considerably different in summer 2004 than 2002. Average maximum temperatures were substantially cooler in the northeastern United States, by as much as 3°C–5°C, during summer 2004 [Godowitch et al., 2008]. Meteorology over northeastern North America during summer 2004 was dominated by a persistent low pressure, and there were increased synoptic disturbances relative to summer 2002 [Thompson et al., 2007a, 2007b; Bükker et al., 2008]. The number of cold frontal passages over the northeastern United States was above average in summer 2004 [Fuelberg et al., 2007]. As we estimate later the change in LNO$_x$ emissions (due to more frequent lightning in summer 2004 than in 2002) is at least a factor of 2 larger than the change in ANO$_x$ emissions (due to power plant NO$_x$ reductions).

[7] In addition, we analyze the impact of the North American Monsoon. The monsoon region of the southwestern United States and northwestern Mexico does not have large ANO$_x$ emissions but has a large increase in LNO$_x$ emissions after the onset of the monsoon [Ridley et al., 1994]. Much of the LNO$_x$ becomes trapped in the UT above the Gulf of Mexico, the southern United States and Mexico—the major NA lightning region [Li et al., 2005; Cooper et al., 2006]—where conditions are favorable for O$_3$ production. On the basis of rainfall statistics over the southwestern United States (Arizona and New Mexico) and northwestern Mexico, 2004 is considered a weak monsoon year and 2002 is a near-normal or slightly weak monsoon year (daily climatology available at ftp://ftp.cpc.ncep.noaa.gov/precip/CPC_UNI_PRCP/GAUGE_GLB/).

[8] For both summers, we quantify the NA contribution to tropospheric O$_3$ by conducting sensitivity simulations with either anthropogenic or lightning emissions over North America shut off. In section 2, we describe the updated UMD-CTM, which has undergone major revision since Park et al. [2004a] and lightning simulations performed for this study. Section 3 includes model comparisons with aircraft, ozonesonde, satellite and ground-based measurements. We determine the model biases for O$_3$, NO$_x$ and other trace gases. We then discuss the summer-to-summer variability of lightning and the radiative impact of O$_3$ produced from NA anthropogenic and lightning emissions in the outflow region. The results are summarized in section 4.

2. Model Description

[9] The UMD-CTM was described in detail by Park et al. [2004a]; here we describe it briefly in terms of the experimental design. The horizontal resolution of the model is 2° × 2.5°. From the surface to 9.3 hPa, there are 14 sigma layers and 17 constant pressure layers with a sigma pressure, and there were increased synoptic disturbances relative to summer 2002 [Thompson et al., 2007a, 2007b; Bükker et al., 2008]. The number of cold frontal passages over the northeastern United States was above average in summer 2004 [Fuelberg et al., 2007]. As we estimate later the change in LNO$_x$ emissions (due to more frequent lightning in summer 2004 than in 2002) is at least a factor of 2 larger than the change in ANO$_x$ emissions (due to power plant NO$_x$ reductions).

[7] In addition, we analyze the impact of the North American Monsoon. The monsoon region of the southwestern United States and northwestern Mexico does not have large ANO$_x$ emissions but has a large increase in LNO$_x$ emissions after the onset of the monsoon [Ridley et al., 1994]. Much of the LNO$_x$ becomes trapped in the UT above the Gulf of Mexico, the southern United States and Mexico—the major NA lightning region [Li et al., 2005; Cooper et al., 2006]—where conditions are favorable for O$_3$ production. On the basis of rainfall statistics over the southwestern United States (Arizona and New Mexico) and northwestern Mexico, 2004 is considered a weak monsoon year and 2002 is a near-normal or slightly weak monsoon year (daily climatology available at ftp://ftp.cpc.ncep.noaa.gov/precip/CPC_UNI_PRCP/GAUGE_GLB/).

[8] For both summers, we quantify the NA contribution to tropospheric O$_3$ by conducting sensitivity simulations with either anthropogenic or lightning emissions over North America shut off. In section 2, we describe the updated UMD-CTM, which has undergone major revision since Park et al. [2004a] and lightning simulations performed for this study. Section 3 includes model comparisons with aircraft, ozonesonde, satellite and ground-based measurements. We determine the model biases for O$_3$, NO$_x$ and other trace gases. We then discuss the summer-to-summer variability of lightning and the radiative impact of O$_3$ produced from NA anthropogenic and lightning emissions in the outflow region. The results are summarized in section 4.

2. Model Description

[9] The UMD-CTM was described in detail by Park et al. [2004a]; here we describe it briefly in terms of the experimental design. The horizontal resolution of the model is 2° × 2.5°. From the surface to 9.3 hPa, there are 14 sigma layers and 17 constant pressure layers with a sigma pressure transition (at 177 hPa) near the tropopause. The UMD-CTM is driven by assimilated meteorological fields from version 4 of the Goddard Earth Observing System (GEOS-4) of the NASA Global Modeling and Assimilation Office. Specifically, we use the GEOS-4 CERES (Clouds and the Earth’s Radiant Energy System) reanalysis (http://gmao.gsfc.nasa.gov/research/merra/sci_archive/climate.php). Convection in GEOS-4 [Bloom et al., 2005] is represented by two parameterizations; deep convection follows Zhang and McFarlane [1995], while shallow convection is based on work by Hack [1994]. Moist convective transport in the UMD-CTM is parameterized using updraft, downdraft, entrainment and detrainment fields from the GEOS-4 CERES reanalysis. Turbulent mixing is calculated through a fractional mixing scheme [Allen et al., 1996]: during a CTM time step (15 min) 20% of the mass in each model layer within the BL is mixed completely throughout the BL. Stratospheric O$_3$ flux into the troposphere is controlled through the synthetic O$_3$ (Synoz) scheme [McLinden et al., 2000] as in work by Park et al. [2004a]. The Synoz-based flux is set to 475 Tg O$_3$ yr$^{-1}$ for both years following McLinden et al. [2000].
[10] We use the same chemical mechanism as in the work by Park et al. [2004a] but with updated rate constants based on work by the Jet Propulsion Laboratory [2006]. We implemented the parameterization of quantum yields to update the photolysis rates for acetone on the basis of work by Blitz et al. [2004]. The wet deposition scheme [Liu et al., 2001] includes contributions from scavenging in convective updrafts and rainout and washout from convective anvil and large-scale precipitation, and it allows for reevaporation.

[11] Table 1 identifies the modeling scenarios used to isolate the impacts of anthropogenic emissions, lightning and their summer-to-summer variability on \( \text{O}_3 \) concentrations. Initial conditions for \( \text{O}_3 \) were obtained from NASA’s Global Modeling Initiative Chemical Transport Model (GMI CTM) [Douglass et al., 2004] driven by meteorological input from the Finite Volume General Circulation Model (FVGCM) with several-year spin-up. Initial conditions for other species were obtained from a reduced \( 4° \times 5° \) simulation of 1985 with the UMD-CTM by Park et al. [2004a] in the troposphere and from the GMI CTM in the stratosphere. The meteorological fields from the FVGCM do not correspond to a particular year.

2.1. Anthropogenic Emissions

[12] In 1998, the U.S. Environmental Protection Agency (EPA) issued a regulation to reduce the interstate transport of \( \text{NO}_x \) and ground level \( \text{O}_3 \) in the eastern United States [Environmental Protection Agency, 2005]. This rule, commonly known as the \( \text{NO}_x \) State Implementation Plan (SIP) Call, became effective in 2003 and required substantial power plant \( \text{NO}_x \) emission reductions in 22 eastern states [Frost et al., 2006] with full implementation of controls to be completed by the summer 2004 \( \text{O}_3 \) season. In 2000, according to EPA’s National Emission Inventory (NEI) and the Emission Database for Global Atmospheric Research (EDGAR), U.S. power generation accounted for one quarter (1.5 Tg N) of national \( \text{NO}_x \) emissions (5.9 Tg N). Other major sources included road transport (1.9 Tg N), international shipping (0.6 Tg N) and air transport (0.3 Tg N).

[13] Global anthropogenic emissions in the model are as described by Park et al. [2004a] unless otherwise specified. Monthly power plant \( \text{NO}_x \) emissions from the United States are taken from Continuous Emission Monitoring System (CEMS). These direct measurements represent one of the most accurate parts of the U.S. emission database (http://www.epa.gov/airmarkets/emissions). All other anthropogenic emissions are from EDGAR 3.2 Fast Track 2000 (J. A. van Aardenne et al., The Edgar 3.2 Fast Track 2000 dataset (32FT2000), 2000, available at http://themasites.pbl.nl/images/Description_of_EDGAR_32FT2000(v8)_tcml61-46462.pdf) [Oliver and Berdowski, 2001; Olivier et al., 2005]. Because of EPA’s SIP Call, \( \text{NO}_x \) emitted from ORV power plants decreased on average by 50% between the summers 2002 and 2004. Overall, the \( \text{NO}_x \) SIP Call resulted in a 10% reduction in total \( \text{NO}_x \) emissions from the contiguous United States (CONUS).

[14] The power plant \( \text{NO}_x \) emissions are released from tall stacks (average stack height is 76 m) in plumes with considerable buoyancy (average release temperature is 117°C). Stack emissions of \( \text{NO}_x \) are injected into the second-lowest model layer. All other anthropogenic emissions are injected into the lowest model layer. In the UMD-CTM, the lowest levels are centered at approximately 50, 250, 600, 1100 and 1900 m above the local surface.

[15] We increase \( \text{ANO}_x \) emissions in eastern China by 15% above the 2000 EDGAR \( \text{NO}_x \) emissions for both summers since a large positive trend of tropospheric \( \text{NO}_2 \) was reported by Richter et al. [2005] and van der A et al. [2006] over the industrial areas in China. It should be noted that we hold all nonpower plant U.S. \( \text{NO}_x \) emissions constant between 2002 and 2004; we also hold non-U.S. \( \text{ANO}_x \) emissions of any type constant between the 2 years. The spatial distribution of the changes in surface \( \text{NO}_x \) emissions from summer 2002 to 2004 over the United States used in the UMD-CTM simulations is shown in the auxiliary material (Figure S1).

2.2. Lightning

[16] The annual \( \text{LNO}_x \) production is set to 5 Tg N yr\(^{-1}\), which is in the center of the currently accepted range of 2–8 Tg N yr\(^{-1}\) [Schumann and Huntrieser, 2007]. The lightning scheme follows Allen et al. [2010]. The \( \text{LNO}_x \) production is assumed to be directly proportional to lightning flash rate \( FR \) as

\[
FR = G \times L \times (z_{mmu} - z_{mmu_0})^\gamma,
\]

where \( z_{mmu} \) is GEOS-4 CERES upward cloud mass flux (at ~430 hPa). The lightning is thus collocated with the convective transport in the CTM. \( FR \) is set to zero for \( z_{mmu} < z_{mmu_0} \). We use \( z_{mmu_0} = 0.57 \) kg m\(^{-2}\) min\(^{-1}\) as in the work by Allen et al. [2010] with \( \gamma = 2 \), thus assuming that the \( FR \) is a quadratic function of \( z_{mmu} \); \( \gamma = 2 \) gives more

---

Table 1. The UMD-CTM Simulations With Different Sources of \( \text{NO}_x \) Emissions

<table>
<thead>
<tr>
<th>Simulation Name</th>
<th>Anthropogenic ( \text{NO}_x )^a</th>
<th>Lightning ( \text{NO}_x )^b</th>
<th>Period Simulated</th>
</tr>
</thead>
<tbody>
<tr>
<td>L0</td>
<td>CEMS 2004</td>
<td>OTD/LIS (240)</td>
<td>May–Aug 2004</td>
</tr>
<tr>
<td>L2 (doubled lightning)</td>
<td>CEMS 2004</td>
<td>NLDN-based (480)</td>
<td>May–Aug 2004</td>
</tr>
<tr>
<td>no NOx SIP Call</td>
<td>CEMS 2002</td>
<td>NLDN-based (240)</td>
<td>May–Aug 2004</td>
</tr>
</tbody>
</table>

^aEmission inventory used for the power plant sector for the contiguous United States (CONUS).

^bObserved flash rates used to adjust the model-calculated flash rates over the CONUS; lightning NO moles produced per flash over the CONUS are in parentheses.

^cNorth America is defined as Canada, the CONUS, Mexico, and the Gulf of Mexico.
realistic day-to-day variability in model-calculated flash rates, decreases biases and improves correlations with respect to observed flash rates than $\gamma = 1$. Using observations from the spaceborne Optical Transient Detector/Lightning Imaging Sensor (OTD/LIS) [Boccippio et al., 2002; Christian et al., 2003; Mach et al., 2007] and from the ground-based National Lightning Detection Network (NLDN) [Cummins et al., 1998; Orville and Huffines, 2001], we scale lightning flash rates (FR) globally ($G$) and locally ($L$) so the model flash rates per grid box match the NLDN and/or OTD/LIS observed data sets on a monthly basis (details in the work by Allen et al. [2010], who scaled FR to match the global OTD/LIS v2.2 climatology). In the vertical, we partition lightning NO emissions on the basis of the modeling studies of Pickering et al. [1998].

Table 1 shows three lightning simulations with the UMD-CTM.

\[17\] Table 1 shows three lightning simulations with the UMD-CTM.

\[18\] 1. In L0, total flash rates (FR) derived from convective mass fluxes are adjusted to match the flash rates observed by OTD/LIS from space. We use Low Resolution Monthly Time Series (LRMTS) in the region between 35°S and 35°N and Low Resolution Annual Climatology (LRAC) elsewhere (available at http://thunder.msfc.nasa.gov/data). Since month-specific LIS observations are available only south of 35°N, simulation L0 does not account for summer-to-summer variability of NA lightning poleward of 35°N.

\[19\] 2. In L1, in addition to the L0 approach, over the CONUS, the flash rates derived from convective mass fluxes are adjusted to match the monthly average NLDN-based IC (intracloud) + CG (cloud-to-ground) flash rates (details are below). L1 is called “standard simulation.”

\[20\] 3. In L2, in addition to the L1 approach, NO production per flash over the NA midlatitudes (25°N-50°N) is increased by a factor of 2 to 480 mol flash$^{-1}$, which nearly matches the estimates of Ott et al. [2010] derived from cloud-resolved modeling and of Hudman et al. [2007] used in their improved GEOS-Chem simulation of the INTEX-A period.

\[21\] When determining the NLDN-based IC + CG flash rates (simulations L1 and L2), we remove NLDN flashes with peak currents between 0 and 20 kA, since they are assumed to be IC in character [Biagi et al., 2007]. We only use data over the CONUS for scaling as the NLDN detection efficiency drops off rapidly beyond 300 km from shore. The NLDN underwent a system-wide upgrade during 2002 [Cummins et al., 2006]. The mean preupgrade detection efficiency over the CONUS was $\sim$85%. After this upgrade, which began in spring 2002, the NLDN had a detection efficiency of 90–95% over the CONUS. For summer 2004, we thus use a detection efficiency of 93%. In order to estimate the detection efficiency for summer 2002, we average the preupgrade value derived from Cummins et al. [1998, Figure 9] and postupgrade value of 93%. To obtain the total IC + CG flash rates, we multiply the detection efficiency–adjusted NLDN CG flashes by $Z + 1$, where $Z$ is the IC/CG ratio. Boccippio et al. [2001] constructed a 0.5° × 0.5° daily climatology of $Z$ ratios (not year specific), by using observations of NLDN CG flashes and OTD/LIS total (IC + CG) flashes. In our study, we smooth their $Z$ composite with a 7.5° moving boxcar, calculate the monthly averages and interpolate onto the 2° × 2.5° UMD-CTM grid. Before smoothing, we exclude grid boxes with $Z > 12$ as these values are anomalous [Boccippio et al., 2001].

\[22\] To compare the lightning sources in our simulations with other investigators, we summarize the lightning NO emissions over the CONUS and adjacent coastal areas during INTEX-A (1 July to 15 August 2004) in Table 2. Simulations L0, L1 and L2 yield LNO$_2$ emissions of 0.16 Tg N, 0.25 Tg N and 0.50 Tg N, respectively. Hudman et al. [2007, 2009], using a cloud top height–based flash rate scheme and assuming 520 NO mol flash$^{-1}$, obtained a LNO$_2$ emission of 0.27 Tg N over the same areas for that period. They noted that their flash rates were biased low with respect to NLDN-based flash rates (assuming an IC/CG ratio of 3). Adjusting for this bias, they obtained a best estimate of 0.45 Tg N for the lightning NO source; however, they did not use this in their model simulations. Jourdain et al. [2010], with their GEOS-Chem simulation with NLDN-based flashes and an assumed production of 520 NO mol flash$^{-1}$, obtained a source of 0.28 Tg N for July 2006. Extrapolating to 1.5 months gives 0.42 Tg N, which is close to the bias–adjusted estimate by Hudman et al. [2007] for 2004. Allen et al. [2010], using the GMI CTM, reported 0.17 Tg N in their standard simulation and 0.34 Tg N in their simulation with doubled lightning NO production (480 mol flash$^{-1}$). They scaled to OTD/LIS climatology rather than NLDN-based flash rates. The magnitude of lightning source in our standard simulation (L1) nearly matches the one used by Hudman et al., while the L2 source (0.50 Tg N) is close to their NLDN-based estimate of the source.
It is noteworthy that the 50% increase in CONUS LNO₃ emissions between 2002 and 2004 more than offsets the ANO₃ emission decreases due to the NOₓ SIP Call. By applying this 50% change to L1 and L2 sources above, we obtain estimates of 0.13 and 0.25 Tg N, respectively, for the LNO₃ emission changes from the same areas and time period as above. These estimated LNO₃ emission changes are at least a factor of 2 larger than the corresponding change of 0.06 Tg N in ANO₃ emissions due to the NOₓ SIP Call (the ANO₃ emissions from the CONUS were reduced from 0.57 Tg N to 0.51 Tg N) during the same time period. Of course the impact of the ANO₃ emission changes is most noticed near the surface while the impact of the LNO₃ emission changes is most important in the UT.

### 2.3. Biogenic Emissions

Isoprene emissions used in the UMD-CTM simulations come from monthly average hourly emissions calculated by the Model of Emissions of Gases and Aerosols from Nature (MEGAN) for the CONUS [Guenther et al., 2006]. One of the most important meteorological factors in determining the isoprene emissions is the temperature. Pacifico et al. [2009, Figure 4] show that a 1°C temperature change can increase isoprene emissions by 15% for standard conditions (25°C–35°C). Temperatures in the region of high isoprene emissions were similar during summers 2002, 2003 and 2004 (see Figure S2 in the auxiliary material). Outside this region, maximum temperatures in 2002 exceeded maximum temperatures in 2004 by 1°C–5°C likely leading to more emissions in 2002 than in 2004. Hoglefe et al. [2004], in an isoprene sensitivity simulation with CMAQ, showed that summertime 8 h O₃ changed by <3 ppbv at locations within the domain (the eastern and central part of the United States) when isoprene emissions were increased by 20%-50% corresponding to maximum temperature increases of 1.5°C–3.5°C. Nolte et al. [2008], in another isoprene sensitivity simulation with CMAQ, showed that summertime 8 h O₃ increased by 1 ppbv or less over most of the CONUS, when isoprene emissions were increased by 25%. Therefore, the use of the same isoprene emissions for 2002 and 2004 is likely to have only a minor impact on conclusions from this study.

### 2.4. Biomass Burning

Biomass burning emissions south of 48°N were derived from the Global Fire Emissions Database Version 2 (GFEDv2) [van der Werf et al., 2006]. This data set prescribes emissions of total carbon as well as CO, CH₄ and NOₓ. For other species, the total carbon emissions are converted to dry matter burned assuming a biomass carbon fraction of 0.45. Emission factors from Andreae and Merlet [2001] are then applied to estimate nonmethane hydrocarbon emissions. Factors are provided separately for savannah/grassland, tropical forest, extratropical forest and agricultural burning. Poleward of 48°N, we use emissions derived from Boreal Wildfire Emissions Model (BWEM) [Kasischke et al., 2005] for summer 2002 and GFEDv2 emissions for summer 2004 (BWEM emissions for 2004 are unavailable). Land cover classification is derived from MODIS data [Hansen et al., 2000; Friedl et al., 2002].

### 2.5. Radiative Forcing Calculation

IPCC [2007] defines radiative forcing for tropospheric O₃ as the net downward flux (both the longwave and the much smaller shortwave contribution) at the tropopause due to the anthropogenic increase in tropospheric O₃ from preindustrial times; the global annual average present-day radiative forcing (stratospheric adjusted) due to tropospheric O₃ is +0.35 [–0.1, +0.3] W m⁻² as estimated by climate simulations. If the stratospheric temperatures are not adjusted, then the forcing is called the instantaneous radiative forcing. While the IPCC definition only considers anthropogenic changes, in general, both anthropogenic and natural O₃ contribute to instantaneous radiative forcing (i.e., reduction in the outgoing longwave radiation). In our study, we consider the instantaneous radiative forcing of O₃ produced from anthropogenic emissions and lightning NO emissions separately and compare their relative effects during long-range transport of trace gases from North America.

We calculate the longwave (980–1100 cm⁻¹ band) contribution of the net downward Radiative Flux at the tropopause for clear-sky conditions (for brevity we refer to this as RF) from O₃ enhanced by anthropogenic emissions and lightning. RF serves as a measure of the extra heat (in W m⁻²) input into the troposphere due to changes in O₃ (before stratospheric temperatures are adjusted to the radiative perturbation).

### 3. Results

In North America, O₃ concentrations and outflow are affected by both emission reductions and changes in...
meteorology [Godowitch et al., 2008]. To quantify the impact of changes in meteorology and associated lightning, we use the UMD-CTM to simulate the summers of 2002 and 2004. Because of the wide availability of observations (INTEX-A), we use the summer 2004 as a reference year to evaluate the model performance with regard to lightning and implementation of pollution controls (NOx SIP Call). We conduct three lightning simulations L0, L1 and L2 (Table 1) to account for current uncertainty in the simulation of lightning NO emissions and its relative role in the LRT of trace gases with respect to anthropogenic emissions.

3.1. Differences Between Summers 2002 and 2004

Large summertime flash rates over the CONUS enhance the NA UT and outflow region with NOx. Figure 1 shows the time series of NLDN-based total lightning over the CONUS in summer 2002 and 2004. Because of numerous thunderstorms in early summer 2004 (1 June to 17 July), lightning flash rates over the CONUS were about 50% higher compared to early summer 2002. In late summer (18 July to 31 August), total flash rates over the CONUS in 2004 were similar to those in 2002. Additionally, the onset of the North American Monsoon over the southwestern United States and northwestern Mexico for both years occurred in mid-July [Li et al., 2004; Gao et al., 2007]. Finally, there were contrasting patterns of vertical transport in early and late summer in the BL (Figure 2). In early summer, there was 10%-40% more convective lofting in 2004 than in 2002 over the ORV and much of the eastern, central and southern United States, with less lofting over New England. In late summer, there was less lofting over the central and southern United States in 2004, with more lofting over New England. Therefore, we break our analysis into two periods: early summer (1 June to 17 July) and late summer (18 July to 31 August).

Figure 3 shows GEOS-4 surface temperatures and winds at ~5.5 km above the local surface. A prominent feature of the circulation over the United States is the strong low-level jet transporting air and moisture from the Gulf of Mexico to the central United States up to ~45°N (not shown). At ~5.5 km, a strong anticyclone dominates the south-central and southwestern United States, consistent with 4 year climatology shown in Li et al. [2005]. The anticyclonic circulation has important implications for the fate of convective outflow over the United States, as we discuss later. In addition to the upper level anticyclone, the northward expansion of the subtropical Bermuda High in the late summer influences the winds along the east coast of the United States. In 2004, especially during early summer, enhanced westerlies over the eastern United States (Figure 3b), in combination with enhanced BL lofting (Figure 2b), promoted outflow of anthropogenic pollution from North America.

In order to compare lightning flash rates (IC + CG) observed from space and detected from the NLDN, we construct the time series shown in Figure 5. This comparison presents the sums over the CONUS south of 35°N as derived from NLDN and LIS observations. Both the NLDN and LIS time series agree that June and July of 2004 had increased flash rates with respect to 2002 in this region. However, we find that more lightning was observed by the NLDN network (after adjustment by the IC/CG ratios) than by the LIS sensor during summers 2002–2005. Similarly, Jourdain et al. [2010] found that NLDN-based flash...
rates (assuming an IC/CG ratio of 3) over the CONUS (25°N–50°N) in July 2006 were about 40% higher than OTD/LIS flash rates. Over the CONUS south of 35°N, the summertime IC/CG ratios average 3.17 (when the grid boxes are weighted by the CG flash rates during 2002–2004). While we do not have a reason to believe that IC/CG ratios are overestimated, if we decrease this mean summertime IC/CG ratio from 3.17 to 1.41, then the mean combined flash rates (IC + CG) derived from the NLDN would be consistent with the ones derived from the LIS. In our analysis, we exclude weak positive flashes (peak current <20 kA) from the NLDN data. It should be noted that removing only 0–10 kA flashes, as done by Boccippio et al. [2001], would require the summertime IC/CG ratios in this region to be decreased even more (to IC/CG = 1.24) for an agreement between NLDN- and OTD/LIS-based estimates of total flash rate. Therefore, model flash rates from simulation L1 (adjusted to NLDN data) exceed model flash rates from simulation L0 (adjusted to OTD/LIS) as shown in the auxiliary material (Figure S3) for early summer 2004.

To summarize, the LIS-derived flash rates are nearly a factor of 2 lower than NLDN-based IC + CG flash rates south of 35°N, suggesting either (1) a fraction of NLDN flashes with negative peak currents are actually IC flashes, (2) the climatological IC/CG ratios are overestimated, or (3) LIS flash rates are underestimated. The latter two possibilities could be caused by uncertainties resulting from temporal and spatial undersampling by LIS [Boccippio et al., 2001]. The uncertainties of lightning detection by LIS are discussed by Boccippio et al. [2002].

3.2. UMD-CTM Comparison With Observations

3.2.1. Comparison With DC-8 In Situ Measurements During INTEX-A

The INTEX-A field mission was conducted in summer 2004 (1 July to 15 August 2004) and focused on quantifying and characterizing the summertime inflow and outflow of pollution over North America and the western Atlantic [Singh et al., 2006]. INTEX-A was an important
component of the coordinated multiplatform atmospheric chemistry field program called ICARTT [Fehsenfeld et al., 2006]. Here we use observations from NASA’s DC-8 aircraft. [36] Regional lightning is the dominant source of UT NOx and can lead to O3 increases of 10 ppbv or more in the UT [e.g., DeCaria et al., 2005]. Deep convection and lightning were important factors during INTEX-A [Hudman et al.,

Figure 3. Mean GEOS-4 CERES surface temperatures and winds at ~5.5 km above the local surface for the period of (a) 1 June to 17 July 2004 and (c) 18 July to 31 August 2004 and the differences relative to 2002 for (b) early and (d) late summer.

Figure 4. The NLDN-based total (IC + CG) lightning flash rates from (left) 2002 and (right) 2004 over the CONUS during early summer (1 June to 17 July). For comparison with the UMD-CTM flash rates for early summer 2004, see Figure S3 in the auxiliary material.
Bousserez et al. underestimation and NO sources. Upper tropospheric OH is highly oxidized being too high to 10% [2008], –60% too low at 500–300 hPa and 80% too low above 300 hPa). NOy is underestimated by 20%–50% at 500–300 hPa and by 80% above 300 hPa. The simulation with doubled lightning NO production per flash (L2) decreases biases for both NO and NOy to 10%–30% at 500–300 hPa and to 60% above 300 hPa; NOy agrees well with measurements below 300 hPa. [39] NOy is overestimated in the LT by 15 ppbv, but this bias drops to 9.6 ppbv above 500 hPa. Doubling the lightning NO source (simulation L2) increases the bias to 12.3 ppbv. A 2–3 ppbv increase in UT NO resulting from a doubling of the LNOx source is also seen at IONS sites (Figure S4 in the auxiliary material). The largest impact is seen near (Houston, Texas, and Huntsville, Alabama) and downwind (Calif, Island, Virginia, and Sable Island, Nova Scotia) of frequent thunderstorms. The UMD-CTM also shows a considerable low bias of 20% for CO throughout the column compared to aircraft measurements. CO is not sensitive to different LNOx sources. Upper tropospheric OH is highly sensitive to LNOx, which can be seen in the clear separation of the L0, L1 and L2 profiles. Observations indicate that OH concentrations increase with altitude; this slope is best captured in the L2 simulation. Mean absolute values of bias above 500 hPa are 0.11 pptv and 0.07 pptv for L1 and L2, respectively. [40] HNO3 during INTEX-A was measured by the California Institute of Technology (CIT) and the University of New Hampshire (UNH). HNO3 is often depleted in the free troposphere because of scavenging during convection but can increase downwind of convection due to oxidation of NO2. HNO3 is highly sensitive to lightning; we see a larger change from L1 to L2 simulated profile than for PAN, consistent with Hudman et al. [2007] and Labrador et al. [2005]. Variability of HNO3 in the LT is larger than in the UT and is associated with variability of NOy. The simulated HNO3 is generally overestimated with respect to both the CIT (Figure 6) and UNH (not shown) data sets. The CIT observed about 40% more HNO3 above 500 hPa than the UNH, leading to better agreement with the model. HNO3 is overestimated likely because of NOx oxidation being too rapid or large removal being insufficient in the model or both. Overall, despite NOx underprediction, NOy is overpredicted below 300 hPa because both PAN and HNO3 are overestimated with respect to the in situ measurements. Most of NOy high bias above 500 hPa is due to PAN overestimation (by up to 0.2 ppbv and 0.3 ppbv in the L1 and L2 simulations, respectively). NOy underestimation and NOy overestimation could indicate a fundamental problem with the UT NOx chemistry. Henderson et al. [2010] evaluated seven different chemical mechanisms. They found that each mechanism overestimates the rate at which NOy is converted to NO2 (NOy → NO2), i.e., the rate at which NOy ages.

Figure 5. Total (IC + CG) lightning flash rates derived from NLDN ground and LIS spaceborne observations over the CONUS (land only) south of 35°N during 2002–2005. CG flash rates detected by the NLDN network (adjusted by the IC/CG ratios) are smoothed spatially (7.5° boxcar) and temporally (98 day window) and averaged for each month (indicated by the asterisks). Monthly LIS observations (LRMTS) were also smoothed with 98 day and 7.5° moving average.

Figure 6 compares simulated and measured mean vertical distributions of NO, O3, CO, HNO3, NOy, OH, PAN and NOx. First, we analyze the UMD-CTM biases from the standard simulation (L1). Simulated NO and NOy profiles are C shaped, reflecting the partitioning of LNOx in the vertical [Pickering et al., 1998] and the anthropogenic source near the surface. Biases are largest in the UT. NO is underestimated throughout the column (30%–60% too low at 500–300 hPa and 80% too low above 300 hPa). NOy is underestimated by 20%–50% at 500–300 hPa and by 80% above 300 hPa. The simulation with doubled lightning NO production per flash (L2) decreases biases for both NO and NOy to 10%–30% at 500–300 hPa and to 60% above 300 hPa; NOy agrees well with measurements below 300 hPa.
They also suggested several updates and fixes to various mechanisms to slow down this conversion rate.

[41] In summary, doubling the lightning NO production per flash reduces NO, NOx, and OH biases in the UT. However, it increases the biases for O3 and PAN slightly (by factors of 1.3 and 1.2, respectively) and for HNO3 and NOy substantially (factors of 2.8 and 2.0, respectively). In spite of increased O3 biases (by 2.7 ppbv above 500 hPa, L1 versus L2), the NOx profile from the L2 simulation agrees well with DC-8 measurements below 300 hPa but is low biased by 60% above 300 hPa. Because the lightning sources in L1 and L2 simulations bracket the emissions of other investigators (Table 2) and because of the mixed results from comparison with aircraft measurements during INTEX-A (NOx underestimated; NOy and O3 overestimated) as to which lightning source is most realistic, we complement the L1 results by examining the impact of doubled lightning NO production per flash (L2).

3.2.2. Comparison With SCIAMACHY Measurements

[42] The impact of reduced NOx emissions on NO2 columns in the ORV (the region dominated by power plants that had implemented controls) is evident from space [Kim et al., 2006]. Data from the high-resolution (30 × 60 km²) SCIAMACHY (Scanning Imaging Absorption Spectrometer for Atmospheric Chartography) instrument, onboard ENVISAT, became available in August 2002. It detects the sunlight reflected from the Earth or scattered in the atmosphere [Richter et al., 2005]. In nadir mode, SCIAMACHY...
observes the total NO$_2$ column from which the stratospheric column, as derived over the Pacific sector, is subtracted to get the tropospheric column. The measurements were screened to use only pixels with less than 30% cloud fraction.

In Figure 7, we determine whether changes in satellite-observed and model-calculated NO$_2$ columns (L1 simulation) are consistent with the updated emission inventories. We sample the UMD-CTM by following daily satellite tracks (ENVISAT overpasses the ORV at 0930–1000 local standard time). The UMD-CTM tropospheric NO$_2$ columns are calculated by integrating the columns from the surface to the GEOS-4 CERES tropopause. The UMD-CTM columns are interpolated in space and time to the SCIAMACHY pixels and times using the outputs at 1200 and 1800 UTC. We composite the observed and simulated columns onto a 0.54° × 0.70° grid, corresponding to approximately 60 × 60 km$^2$ (Figures 7a, 7b, 7d, and 7e). By temporally averaging the UMD-CTM output at this resolution (each grid box includes ~8 clear-sky days during August 2002 and ~6 clear-sky days during August 2004) we are able to obtain more detail than can be obtained from 2° × 2.5° UMD-CTM. However, the UMD-CTM even when averaged in this fashion is unable to resolve the maxima observed by SCIAMACHY over polluted urban areas (e.g., Chicago). The observations from SCIAMACHY show that major NO$_2$ plumes over the northeastern United States are of substantially smaller magnitude in 2004 than 2002, consistent with the emission reductions due to the NO$_x$ SIP Call. In August 2002, nearly one third of U.S. power plant NO$_x$ emissions were from the ORV region (larger box in Figure 7a), while in August 2004 they comprised less than one fifth due to implemented emission controls. CEMS data show that power plant NO$_x$ emissions from this region were reduced by ~50% between August 2002 and 2004. The observed NO$_2$ columns over the ORV were reduced by 22% on average from 2002 to 2004. A smaller observed reduction is expected because of transport from regions where emis-
The 8 h O₃ time series constructed from 155 AQS sites located in the ORV region (indicated from the sensitivity is in the bottom right corner of each plot. The UMD-CTM dots (Figures 7d and 7e). Reductions in observed columns were also seen over the northeastern United States (smaller box in Figure 7a), which is downwind of the ORV power plants. The modeled reductions in this region were 11%, while observed reductions were 20%. The difference in reductions between SCIAMACHY and the model in this region could indicate that NOₓ emissions from other sources also decreased between 2002 and 2004; however, this difference may also indicate that the medium-range transport of NOₓ is underpredicted by the UMD-CTM. Gilliland et al. [2008] noted that CMAQ underestimated the response of O₃ to changes in emissions partly because the transport of O₃ and its precursors was underestimated. Godowitch et al. [2008] in a simulation with CMAQ also underestimated the improvement in air quality between summers 2002 and 2004. In 2002, there was a 2 ppbv low bias whereas 2004 had a 4 ppbv high bias in 8 h O₃.

3.2.3. Comparison With Observations From Ground-Based AQS Sites

The AQS (Air Quality System) is an EPA database (http://www.epa.gov/ttn/airs/airsaqs) that provides ambient concentrations of air pollutants at monitoring sites, primarily in cities and towns. We use daily maximum 8 h O₃ (8 h O₃) as the metric for our comparisons, since it is important from a regulatory perspective. The 2008 National Ambient Air Quality Standard (NAAQS) for 8 h O₃ is 75 ppbv.

Figure 8 shows time series of 8 h O₃ from the ORV region. We see that the UMD-CTM captures well the periods with large day-to-day variability. Most of the variance ($r^2 > 0.5$) in summer 2002 and in late summer 2004 is explained by the model. In early summer 2004, observed day-to-day variability is smaller, and the UMD-CTM is unable to capture these subtle changes in surface O₃. It is likely that the correlation between simulated and observed 8 h O₃ might be improved if daily CEMS data were used in the model instead of monthly CEMS data. In the ORV, 8 h O₃ is simulated with mean high biases of 16.5 ppbv and 24.0 ppbv in summer 2002 and 2004, respectively. The difference between these biases is likely to decrease by up to 3 ppbv (see section 2.3) if isoprene emissions are allowed to respond to temperature variations. Despite this mean high bias, O₃ concentrations at numerous AQS sites were slightly underestimated during the highest O₃ episodes that occurred in summer 2002. Similarly, in the rest of the eastern United States (not shown), the UMD-CTM captures the O₃ variations reasonably well ($r^2 > 0.5$) with biases of 10–20 ppbv seen over the Great Lakes (Wisconsin and Michigan), New York State and New England and with 20–30 ppbv biases seen in the southern United States. Overprediction of surface O₃ in the eastern United States during summer is common in many CTMs. Reidmiller et al. [2009], as part of the Hemispheric Transport of Air Pollution project, 2007 (http://htap.org), showed that the mean multimodel (16 CTMs) bias was 10–20 ppbv. Some of the bias is due to the spatial averaging of emissions in a model grid box; dilution of NOₓ emissions to a $2^° \times 2.5^°$ grid leads to greater O₃ production than at finer resolutions [Sillman et al., 1990; Park et al., 2004b]. Additional uncertainty is introduced by the treatment of isoprene emissions (BEIS versus MEGAN) and isoprene-nitrate chemistry in chemical mechanisms.
Overall, the combined effects of changes in meteorology and emissions had a great impact on 8 h \(O_3\) concentrations in the northeastern United States. Observed 8 h \(O_3\) concentrations were reduced by 14 ppbv in the ORV on average from summer 2002 to 2004. Reductions of 7 ppbv were seen in the UMD-CTM (sampled at the locations of the AQS sites).

3.3. Ozone Enhancements From NA Anthropogenic Emissions and Lightning

We compare the relative effects of modeled \(O_3\) enhancements from NA anthropogenic emissions and NA lightning for summer 2004, focusing on long-range transport and continental outflow. Although not strictly true, because of the nonlinear response of \(O_3\) to \(NO_x\) emissions, the lightning (anthropogenic) enhancement is diagnosed as the difference between simulations with and without the \(LNO_x\) (anthropogenic) source. These results are then compared to similar simulations for summer 2002, allowing us to quantify the impact of changes in meteorology and NA lightning between summers 2002 and 2004 on long-range transport and continental outflow as well as the relative radiative impact.

Figures 9a, 9b, 9d, and 9e show the \(O_3\) enhancements from NA anthropogenic emissions and lightning in early summer 2004. Anthropogenic emissions produced the greatest \(O_3\) enhancements near the surface (up to 35 ppbv over the eastern United States, as seen in Figure 9a), whereas lightning had the greatest impact in the UT (up to 16 ppbv over the Gulf Coast and the western North Atlantic, as seen in Figure 9e). Hudman et al. [2009], using the GEOS-Chem, compared the \(O_3\) enhancements from NA anthropogenic emissions and lightning during INTEX-A. They also showed that the BL enhancements were mainly anthropogenic and that lightning had the greatest impact in the UT. Convectively lifted precursors and \(LNO_x\) enhanced the \(O_3\) production, especially at higher altitudes. We see similar enhancements as Hudman et al. [2009] over North America and the continental outflow, near-surface enhancements from anthropogenic emissions of 3–5 ppbv over western Europe, and UT (400–200 hPa) enhancements from lightning of 9–12 ppbv over the eastern subtropical Atlantic (with 9 ppbv contour reaching over Spain). In contrast with Hudman et al. [2009], we also examine the 2002 to 2004 variations in \(O_3\) enhancements from lightning (Figures 9c and 9f). From 2002 to 2004, there is an increase in the
contribution of lightning to eastern United States. \( O_3 \), both near the surface (Figure 9c) and in the UT (Figure 9f).

[50] Figure 10 shows the tropospheric \( O_3 \) columns during early and late summer 2004 and the enhancements from anthropogenic emissions and lightning NO emissions. In late summer 2004, the warm conveyor belt was especially active [Kiley and Fuelberg, 2006], enhancing the transport of anthropogenic \( O_3 \) along the U.S. east coast. In addition, stronger southerly winds relative to early summer (Figure 3c versus Figure 3a) pushed the anthropogenic and lightning plumes to more northern latitudes. Maximum anthropogenic enhancements were \( \sim 11 \) DU, which represented \( \sim 21\% \) of the total tropospheric column. Maximum lightning enhancements were \( \sim 9 \) DU (Figures 10c and 10f), which represented \( \sim 18\% \) of the total tropospheric column. Doubling the LNO\(_x\) source over North America in the UMD-CTM produces an additional 4 ppbv of \( O_3 \) in the UT (400–200 hPa) compared to lightning enhancements from L1 simulation, thus adding \( \sim 2 \) DU to the tropospheric column. Doubled lightning (L2) produces therefore \( \sim 11 \) DU, which is the same as produced from anthropogenic emissions. The relatively small increase from \( \sim 9 \) to \( \sim 11 \) DU, when going from 240 NO mol flash\(^{-1}\) to 480 NO mol flash\(^{-1}\) is due to the nonlinear response of \( O_3 \) enhancements to LNO\(_x\) emissions. Similarly, in downwind regions over the northern Atlantic and western Europe, the early summer \( O_3 \) enhancements in the L2 simulation exceeded the L1 enhancements by only 33% despite a doubling of LNO\(_x\) emissions from North America. In contrast, Wu et al. [2009] found no significant nonlinearity of \( O_3 \) response to ANO\(_x\) emissions in the downwind regions from North America.

[51] Shifting our focus to the summer-to-summer change, Figures 11a and 11c indicate substantial differences between 2004 and 2002 in \( O_3 \) enhancements due to lightning in the continental outflow, especially for early summer. Early summer 2004 lightning led to 2–6 ppbv more \( O_3 \) in the UT (400–200 hPa) over the subtropical North Atlantic, southern Europe and the Middle East when compared to 2002 (Figure 9f), enhancing the tropospheric column by 1.0–3.5 DU. Over the subtropical North Atlantic (20°N–45°N), increased NA lightning (and changes in meteorology) between early summer 2002 and 2004 explain about two thirds of the increase in tropospheric \( O_3 \) column between 2002 and 2004 (not shown). During late summer both years had similar lightning flash rates; however, meteorological conditions in 2004 were less favorable for \( O_3 \) formation [see
also Cooper et al., 2009; Allen et al., 2010] and led to 1–4 ppbv less O$_3$ in the UT over the eastern United States than in 2002 (not shown). However, the tropospheric column over the eastern Atlantic, Europe and northern Africa had up to 1.2 DU more O$_3$ from lightning in 2004 than 2002 (Figure 11c), reflecting more efficient transport over the Atlantic in both early and late summer 2004. Later in the summer (both years), the LIS sensor observed enhanced flash rates over Mexico, indicating the increased lightning activity and deep convection associated with the North American Monsoon [Li et al., 2004; Gao et al., 2007]. Note the intensification of the O$_3$ enhancement over Mexico and the convective outflow over the Gulf of Mexico in late summer (Figure 10c versus Figure 10f).

To compare the impact of increased NA lightning (and changes in meteorology) between 2002 and 2004 with the impact of emission reductions resulting from the NO$_x$ SIP Call, we did a sensitivity simulation with 2002 NO$_x$ emissions (when power plant emissions were not as tightly regulated) and 2004 meteorology and lightning. While decreases in surface layer O$_3$ over the eastern United States because of the NO$_x$ SIP Call were substantial (not shown), decreases in the tropospheric column were small (Figures 11b and 11d). Columns were reduced by <0.5 DU over the North Atlantic in both early and late summer (with the −0.1 DU contour reaching Spain, Italy and southern France). During the early summer in the region where the emission reductions (between 2002 and 2004) had the largest impact on O$_3$ column over the North Atlantic (30°N–50°N), the change in O$_3$ column due to changes in lightning and meteorology exceeded the absolute value of the change due to reduced anthropogenic emissions by a factor of 7. Differences in flash rates between 2002 and 2004 were much smaller in late summer. Consequently, the changes in O$_3$ column due to changes in lightning and meteorology were also smaller, and the change in O$_3$ column due to changes in lightning and meteorology was comparable to the change due to reduced ANO$_x$ emissions but opposite in sign.

Lightning enhancements are primarily in the UT, where previous studies [e.g., Lacis et al., 1990] have shown...
O₃ to be most effective as a greenhouse gas. Choi et al. [2009], using the regional chemistry transport model REAM for the period of June–July 2005, showed that in the immediate convective outflow, the radiative effects of O₃ produced from LNOₓ were up to three times as large as those from anthropogenic emissions. In our analysis, we examine the larger-scale radiative impact (defined in section 2.5) due to O₃ produced from anthropogenic emissions (RF₁anthro) and from lightning (RF₁LNOₓ). Figure 12 shows that RF₁anthro ranged from 0.15 to 0.30 W m⁻² in the continental outflow across the North Atlantic, whereas the RF₁LNOₓ ranged from 0.20 to 0.40 W m⁻² (0.25–0.50 W m⁻² for doubled LNOₓ source) over the same area in early and late summer 2004. The RF₁LNOₓ also exceeded RF₁anthro over southern Europe and northern Africa in both early and late summer 2004. We find that, in early summer 2004, the RF₁LNOₓ/RF₁anthro ratio ranged from 0.3 at higher latitudes of the North Atlantic to 1.6 over the subtropical North Atlantic, with a maximum of 2.3 over the southern Gulf of Mexico (Figure 13). Doubling the LNOₓ source has the greatest impact on this ratio over the western subtropical North Atlantic, where the RF₁LNOₓ/RF₁anthro ratio increases from 1.6 to 2.1.

Figure 12. RF (calculated as described in section 2.5) for 2004 due to (a, d) North American anthropogenic emissions and (b, e) lightning as diagnosed by simulation L1 and the sensitivity simulations with respective sources turned off (Table 1). (c, f) Difference between 2004 and 2002 due to NA lightning. The values are (top) early summer (1 June to 17 July) mean and (bottom) late summer (18 July to 31 August) mean. Minima, averages, and maxima are listed above of each plot. Note a factor of 10 smaller units for RF in Figures 12c and 12f.

Figure 13. Early summer 2004 (1 June to 17 July) ratio RF₁LNOₓ/RF₁anthro as diagnosed by the standard simulation and sensitivity simulations with respective sources turned off (Table 1).
We see the largest impact from lightning after the onset of the North American Monsoon (Figure 12e), which is reinforced by the upper level anticyclone centered over Mexico [Cooper et al., 2009, Figure 2]. Although the RF$_{LNOx}$ is greater in late than early summer in the immediate convective outflow over Mexico and the Gulf of Mexico, it is slightly less over Europe and northern Africa in late summer 2004. This indicates that the convective outflow recirculated in this upper level anticyclone centered over Mexico in late summer, allowing more O$_3$ production over the southern United States and the Gulf of Mexico, as discussed by Li et al. [2005], prior to transport across the Atlantic.

The spatial pattern of summer-to-summer changes in RF (Figures 12c and 12f) is similar to that of summer-to-summer changes in the tropospheric O$_3$ column. RF$_{LNOx}$ was nearly a factor of 2 larger in early summer 2004 than 2002 in the NA outflow region. The impact of power plant reductions on RF (diagnosed from the sensitivity simulation with 2002 NO$_x$ emissions and 2004 meteorology and lightning) was much smaller than that seen in Figures 12c and 12f. The RF values over the North Atlantic decreased by <0.01 W m$^{-2}$ because of emissions reductions (not shown).

In early summer 2004, mean normalized RF per unit of added O$_3$ column, over the areas with enhancements exceeding 5 DU, is 0.027 W m$^{-2}$ DU$^{-1}$ due to NA anthropogenic enhancements and 0.047 W m$^{-2}$ DU$^{-1}$ due to NA lightning enhancements (average from L1 and L2 simulations). For comparison with previous studies we use Gauss et al. [2003], who used 11 different climate models to estimate the (longwave, clear-sky) normalized instantaneous radiative forcing. They gave a range of 0.042–0.052 W m$^{-2}$ DU$^{-1}$ for the global annual averages of normalized radiative forcing due to changes in tropospheric O$_3$ between 2000 and 2100. The annual average of normalized radiative forcing due to increasing anthropogenic emissions over the next century is predicted to be greater than that due to present-day NA anthropogenic emissions and is comparable with RF due to NA lightning NO emissions. Noteworthy is also Worden et al. [2008], who, using TES (Tropospheric Emission Spectrometer) measurements for cloud-free ocean conditions, obtained an estimate of 0.055 W m$^{-2}$ DU$^{-1}$ (annual mean from 45°S to 45°N) for the sensitivity to UT (500–200 hPa) O$_3$, thus providing an important observational constraint for both natural and anthropogenic O$_3$.

3.4. Import and Export Fluxes

We calculate the fluxes of NO$_x$, NO$_y$, CO, and O$_3$ across the western and eastern NA boundaries for early summer. These fluxes are summed along the longitudes 130°W (imports) and 65°W (exports) from simulation L1 for (a) 2004 exports (red solid), 2004 imports (red dashed), 2002 exports (blue solid), and 2002 imports (blue dashed) and (b) 2004 (red) and 2002 (blue) net exports. Vertically averaged fluxes (from the surface to 100 hPa) are listed in the bottom right corner of each plot. Fluxes across the northern and southern boundaries of NA are small and are not shown.

Figure 14. Early summer (1 June to 17 July) fluxes of NO$_x$, NO$_y$, CO, and O$_3$ across the western and eastern boundaries of North America (summed between 25°N and 60°N) at 130°W (imports) and 65°W (exports) from simulation L1 for (a) 2004 exports (red solid), 2004 imports (red dashed), 2002 exports (blue solid), and 2002 imports (blue dashed) and (b) 2004 (red) and 2002 (blue) net exports. Vertically averaged fluxes (from the surface to 100 hPa) are listed in the bottom right corner of each plot. Fluxes across the northern and southern boundaries of NA are small and are not shown.
2004; 2002 imports exceeded 2004 imports for each species. Since we held the Asian anthropogenic emissions constant for both years, the decreased imports (by ~30%) in 2004 compared to 2002 were mainly due to the weaker jet stream over the Pacific. For example the peak zonal winds at 225 hPa were 36 m s\(^{-1}\) and 32 m s\(^{-1}\) in 2002 and 2004, respectively, although it should be noted that the peak zonal winds do not represent the integrated effect of the entire wind field over the Pacific. The reduced imports seen in 2004 compared to 2002 motivate us to calculate the difference between exports and imports, hereafter referred to as the net exports. This method allows us to estimate the efficiency of photochemistry over North America by removing the differences in what is imported from what is photochemically produced or emitted over North America. \(O_3\) soundings at the west coast site of Trinidad Head, California, indicate that \(O_3\) imports are well simulated (Figure S4 in the auxiliary material shows a good agreement of ozonesonde-measured \(O_3\) profiles with model-calculated \(O_3\) profiles).

\[90\] \(NO_x\) and \(NO_y\) fluxes in this study are similar to those from Choi et al. [2008], in which the authors estimated imports and exports from North America in spring 2000 using the regional chemistry transport model REAM. They reported that in May 2000, the \(NO_x\) exports peak at \(4 \times 10^7\) mol d\(^{-1}\). In our study, \(NO_x\) exports peak at \(2.1-2.5 \times 10^7\) mol d\(^{-1}\) (in early summer 2002 or 2004, Figure 14a). This lower peak could be because of faster photochemical oxidation and slower wind speeds during summer. In addition, CEMS data show that \(NO_x\) emissions from the United States were greater in 2000 than 2002 or 2004. North America is a net source of pollution in summer (exports greater than imports throughout the troposphere); this is partially due to stronger westerlies over the western Atlantic than over the eastern Pacific (Figure 3). The total \(O_3\) exports (summed from the surface to 100 hPa) were factors of 2 and 1.4 larger than the total \(O_3\) imports in early summer 2004 and 2002, respectively, whereas in May 2000, the export-to-import ratio was close to 1 [Choi et al., 2008].

\[50\] Figure 14b indicates that the net exports were larger in early summer 2004 than in 2002. The areas to the left of the net export curves are proportional to the total mass exported from North America. \(CO\) was exported at higher altitudes in 2004 (Figure 14b) which along with enhanced westerlies (Figure 3) led to greater net export than in 2002. In order to determine if differences in biomass burning between 2002 and 2004 had a substantial impact on net exports, we reran the UMD-CTM for early summer 2004 using 2002 biomass burning emissions. Net \(CO\) exports increased by 9%; the impact on other species was smaller. Because of stronger westerlies, enhanced lightning \(NO\) emissions over North America in summer 2004 than in 2002 and a possible increase in \(O_3\) imported from stratosphere in 2004 (consistent with Thompson et al. [2007a]), net \(O_3\) exports were greatly enhanced in the UT compared to 2002.

\[60\] Despite reduced \(NO_x\) emissions due to the \(NO_x\) SIP Call and cooler temperatures (Figure 3b) in 2004 relative to 2002, simulations with the UMD-CTM show greater anthropogenic exports in 2004 than in 2002 (Figure 15a). This was likely due to an efficient transport mechanism from North America: enhanced convective lofting over polluted areas (Figure 2b) and stronger westerlies (Figures 3b and 3d). Similarly, the exports of \(NO_x\), \(NO_y\), and \(O_3\) due to lightning \(NO\) emissions in 2004 greatly exceeded those seen in 2002 (Figure 15).

\[60\] Because of lofted pollution from the BL, \(NO_x\) exports peaked in the UT in both years. \(NO_x\) exports due to anthropogenic emissions peaked in the LT. Increased lightning activity and stronger UT westerlies over the CONUS in early summer 2004 resulted in a factor of 2 greater \(LNO_y\) exports than in 2002. In early summer 2004, anthropogenic emissions explain about 28% and 41% of the net \(NO_x\) and \(NO_x\) column exports, respectively, while lightning explains about 49%–67% and 34%–49% (the lower estimates corresponding to production of 240 \(NO\) mol flash\(^{-1}\) and the upper estimates corresponding to production of 480 \(NO\) mol flash\(^{-1}\)). The remaining 5%–23% of the net \(NO_x\) and 10%–25% of the net \(NO_x\) is from other \(NO_x\) sources (biomass burning emissions and soil release) and the contribution from the north and south into North America. \(O_3\) exports due to anthropogenic emissions were a factor of 1.6 larger than those due to \(LNO_x\) emissions in 2004 (54 \(\times 10^{10}\) \(O_3\) mol d\(^{-1}\) compared to 33 \(\times 10^{10}\) \(O_3\) mol d\(^{-1}\)). However, in a sensitivity simulation with doubled \(LNO_x\) source, this ratio decreases to 1.2 (\(O_3\) exports due to lightning increased by 33% to 44 \(\times 10^{10}\) \(O_3\) mol d\(^{-1}\)). This is consistent with the earlier result.
where doubled LNO\textsubscript{3} source over North America increased the lightning enhancements by \(\sim 33\%\) in downwind regions compared to lightning enhancements from LNO\textsubscript{3} source in the standard simulation. In 2002, anthropogenic emissions contributed twice as much to the net O\textsubscript{3} export as lightning.

4. Summary

This study illustrates the importance of interannual variations in meteorology and associated lightning for the variability of long-range transport and continental outflow. We conducted several simulations of summers 2002 and 2004 with the UMD-CTM driven by meteorological fields from the GEOS-4 CERES reanalysis. Summer 2004 had reduced power plant NO\textsubscript{x} emissions in the Ohio River Valley (resulting from the NO\textsubscript{x}, SIP Call), more lightning, relatively cool temperatures and frequent synoptic disturbances over the contiguous United States compared to summer 2002. We used 2004 as a reference year to evaluate the UMD-CTM due to the valuable measurements that were obtained over the eastern United States and western North Atlantic during the INTEX-A science mission. Summer 2004 revealed great decreases in observed O\textsubscript{3} concentrations over the northeastern United States, especially downwind of the Ohio River Valley, the region with a high number of power plants that had implemented NO\textsubscript{x} controls. The satellite observations from SCIAMACHY clearly detected NO\textsubscript{x} column decreases in this region.

We also conducted several lightning sensitivity simulations. We assumed the lightning flashes are proportional to the square of convective mass fluxes and constrained to match the observations from OTD/LIS and from the NLDN. We found an inconsistency between LIS- and NLDN-based total flash rates over the CONUS south of 35\(^\circ\)N: more lightning was observed by the NLDN network (after adjustment by the IC/CG ratios) than by the LIS sensor. For agreement between these two data sets, the summertime IC/CG ratios over this region would have to be decreased by a factor of 2.

Like other global and regional CTMs, O\textsubscript{3} in the UMD-CTM is overestimated by 15–25 ppbv at the surface and by up to 12 ppbv in the upper troposphere (500–200 hPa) compared to aircraft and ozonesonde measurements. We found that the simulation with doubled lightning NO production (480 mol flash\(^{-1}\)) agrees best with observed NO\textsubscript{x}; however, it increases the upper tropospheric high bias for O\textsubscript{3} by \(\sim 3\) ppbv. Because of these mixed results, we complement the results from the standard simulation with the results from the simulation with doubled lightning NO production per flash. In the Ohio River Valley, the UMD-CTM showed similar reductions (19\%) of tropospheric NO\textsubscript{x} column as observed by SCIAMACHY (22\%) between August 2002 and 2004, consistent with the emission reductions due to the NO\textsubscript{x}, SIP Call. Simulations with the UMD-CTM showed reduced O\textsubscript{3} concentrations at the surface between the summers 2002 and 2004; however, these reductions were 50\% less than those seen in AQS observations.

Lightning over the United States greatly enhances the North American outflow of O\textsubscript{3}. In early summer 2004, North American anthropogenic emissions produced the greatest O\textsubscript{3} enhancements near the surface (up to 35 ppbv over the eastern United States), whereas lightning had the greatest impact in the upper troposphere (up to 16 ppbv for the standard and 20 ppbv for doubled LNO\textsubscript{x} source, over the Gulf Coast and the western North Atlantic). After the onset of the North American Monsoon, the impact of lightning was even greater (up to 18 ppbv for the standard and 22 ppbv for doubled LNO\textsubscript{x} source). RF (defined as net downward radiative flux at the tropopause for clear-sky conditions) of 0.15–0.30 W m\(^{-2}\) due to O\textsubscript{3} produced from anthropogenic emissions was seen in the continental outflow across the North Atlantic, extending to Europe and northern Africa, while RF due to O\textsubscript{3} produced from lightning NO emissions was 0.20–0.40 W m\(^{-2}\) (0.25–0.50 W m\(^{-2}\) for doubled LNO\textsubscript{x} source) over the same areas in early and late summer 2004. Lightning flash rates in early summer 2004 were 50\% higher than in 2002 over the contiguous United States. RF due to lightning was nearly a factor of 2 larger in early summer 2004 than 2002 in the North American outflow region. The normalized RF per unit of added O\textsubscript{3} column was 0.027 W m\(^{-2}\) DU\(^{-1}\) for anthropogenic enhancements and 0.047 W m\(^{-2}\) DU\(^{-1}\) for lightning enhancements. This is because of stronger radiative forcing efficiency of an upper tropospheric perturbation.

Sensitivity simulation with reduced emissions due to the NO\textsubscript{x} SIP Call showed that the impact of emission reductions (between 2002 and 2004) on O\textsubscript{3} column over the North Atlantic (30\(^\circ\)N–50\(^\circ\)N) was a factor of 7 smaller than the impact of changes in lightning and meteorology in early summer. Late summer changes in lightning had much smaller impact on O\textsubscript{3} columns.

Large differences between the two summers in horizontal winds and convection greatly modulated the changes in O\textsubscript{3} concentrations. Simulations with the UMD-CTM show that despite reduced emissions due to the NO\textsubscript{x} SIP Call and cooler temperatures in 2004 relative to 2002, more O\textsubscript{3} was exported from North America in 2004 due to anthropogenic emissions than in 2002 because of enhanced lofting of polluted air from the boundary layer (in early summer) followed by stronger westerly winds over the main NO\textsubscript{x} source region in the eastern United States. O\textsubscript{3} exports across the eastern NA boundary due to anthropogenic emissions were factor of 1.6 larger than those due to lightning in 2004. However, the simulation with doubled lightning source reduces this ratio to only 1.2 indicating nonlinearity. Doubling the North American lightning NO source increased downwind O\textsubscript{3} enhancements due to lightning NO emissions by one third.

Acknowledgments. This work was funded under NASA grants NNG04GD32G and NNG06GE01G (Interdisciplinary Science Investigation) and under NASA grant NNG06GB52G from the Tropospheric Chemistry Program. Model simulations have been conducted at NCICS at NASA Goddard Space Flight Center. We thank the INTEX-A science team for the aircraft measurements and Anne Thompson for IONS measurements. The NLDN data were collected by Vaisala, Inc., and archived by NASA Marshall Space Flight Center. OTD/LIS data were processed by NASA Marshall. We thank Owen Cooper for the IC/CG ratios prepared by Dennis Boccioppio. We thank Arlene Fiore and two anonymous reviewers for their helpful comments. We also thank Ross Saltawitch and Amanda Evans for their revisions and comments.

References
Allen, D. J., R. B. Rood, A. M. Thompson, and R. D. Hudson (1996), Three-dimensional radon 222 calculations using assimilated meteorolog-


