Indirect validation of tropospheric nitrogen dioxide retrieved from the OMI satellite instrument: Insight into the seasonal variation of nitrogen oxides at northern midlatitudes

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[1] We examine the seasonal variation in lower tropospheric nitrogen oxides (NOx = NO + NO2) at northern midlatitudes by evaluating tropospheric NO2 columns observed from the Ozone Monitoring Instrument (OMI) satellite instrument with surface NOx measurements (SouthEastern Aerosol Research and Characterization and Air Quality System) and current bottom-up NOx emission inventories, using a global model of tropospheric chemistry (GEOS-Chem). The standard (SP) and DOMINO (DP) tropospheric NO2 column products from OMI exhibit broadly similar spatial and seasonal variation, but differ substantially over continental source regions. A comparison of the two OMI tropospheric NO2 products with in situ surface NO2 concentrations and bottom-up NOx emissions over the southeast United States indicates that annual mean NO2 columns from the DP are biased high by 21%–33% and those from the SP are biased high by 27%–43%. The bias in SP columns is highly seasonal, 67%–74% in summer compared with −6% to −1% in winter. Similar seasonal differences exist between top-down and bottom-up NOx emission inventories over North America, Europe, and East Asia. The air mass factor largely explains the observed seasonal difference between the DP and SP, and in turn the seasonal SP bias. We develop a third product (DP_GC) using averaging kernel information from the DP and NO2 vertical profiles from GEOS-Chem. This product reduces to 5%–21% the annual mean bias over the southeast United States. We use the seasonal variation in the DP_GC to estimate the seasonal variation in the lifetime of lower tropospheric NOx against oxidation to HNO3 over the eastern United States. The effective NOx lifetime at OMI overpass time (early afternoon) ranges from 7.6 h in summer to 17.8 h in winter, consistent within 3 h of the simulated lifetime. GEOS-Chem calculations reveal that the seasonal variation in OMI NO2 columns largely reflects gas-phase oxidation of NO2 in summer with an increasing role for heterogeneous chemistry in winter.


1. Introduction

[2] Nitrogen oxides (NOx = NO + NO2) are key actors in air quality and climate change. NOx largely controls the production of tropospheric ozone, forms aerosol nitrate, and affects the abundance of the hydroxyl radical (OH). Nitrogen dioxide (NO2) is an indicator of surface air quality that is associated with mortality [Steib et al., 2003; Burnett et al., 2004; Samoli et al., 2006] and respiratory morbidity [Environmental Protection Agency (EPA), 2008]. The U.S. Environmental Protection Agency (EPA) has recently proposed to strengthen the primary NO2 national air quality standard [EPA, 2009]. Major sources of NOx are combustion, soils, and lightning. Gas-phase formations of HNO3 during daytime and N2O5-hydrolysis during nighttime are the dominant sinks of tropospheric NOx [Dentener and Crouse, 1993; Jacob, 2000]. NOx observations over broad spatial regions contain information needed to understand NOx sources and sinks.

[3] Tropospheric NO2 columns retrieved from satellite measurements have been used to evaluate chemical transport models [Velders et al., 2001; Martin et al., 2002; Lauer et al., 2002; van Noije et al., 2006], to examine spatial and
temporal patterns of NO$_x$ emissions [Leue et al., 2001; Beirle et al., 2003; Richter et al., 2004, 2005; van der A et al., 2006; Zhang et al., 2007; Boersma et al., 2008a; Kaynak et al., 2008], to provide top-down estimates of surface NO$_x$ emissions via inverse modeling [Martin et al., 2003a, 2006; Müller and Stavrakou, 2005; Zhang et al., 2007; Sauvage et al., 2007; Napelenok et al., 2008], to examine specific sources [Jaeglé et al., 2004, 2005; Boersma et al., 2005; Choi et al., 2005; Martin et al., 2007; van der A et al., 2008; Zhao and Wang, 2009], to infer NO$_x$ lifetimes [Schaub et al., 2007], and to estimate surface NO$_2$ concentrations [Lamsal et al., 2008]. These analyses, however, are affected by large discrepancies among contemporary tropospheric NO$_2$ retrievals [van Noije et al., 2006; Bucsela et al., 2008; Boersma et al., 2008a]. Assessments of retrieval quality using independent correlative measurements in a range of environments over all seasons are important for confidence in the accuracy and reliability of these analyses.

[4] Tropospheric NO$_2$ column retrievals from satellites have been evaluated with in situ NO$_2$ profile measurements from aircraft [Heland et al., 2002; Martin et al., 2004, 2006; Boersma et al., 2008b; Bucsela et al., 2008; Celarier et al., 2008] and NO$_2$ column measurements from ground-based instruments [Lambert et al., 2004; Ionov et al., 2008; Celarier et al., 2008; Brinksma et al., 2008; Kramer et al., 2008; Irie et al., 2008; Wenig et al., 2008]. Aircraft offer precise in situ measurements, but these campaign-based validation exercises are limited by sparse spatial and temporal sampling and by the need to extrapolate below the lowest measurement altitude [e.g., Bucsela et al., 2008]. Ground-based tropospheric NO$_2$ measurements from other novel techniques are yet to be thoroughly evaluated [Celarier et al., 2008]. Validation with in situ surface NO$_2$ measurements from dense networks of commercial molybdenum converter analyzers are complicated by interference in surface data [Winer et al., 1974; EPA, 1975; Grosjean and Harrison, 1985; Fehsenfeld et al., 1990; Ordóñez et al., 2006; Blond et al., 2007; Dunlea et al., 2007; Steinhacher et al., 2007; Lamsal et al., 2008]. Observations of “true” NO$_2$ from photolytic converter analyzers [Ryerson et al., 2000] offer an excellent opportunity to evaluate satellite retrievals. Collocated simultaneous photolytic and molybdenum measurements are valuable for quantifying the interference in molybdenum converter measurements.

[5] Bottom-up NO$_x$ emission inventories from some sources and regions remain quite uncertain, but elsewhere can provide a considerable level of knowledge through aggregation of information from diverse sources. In Canada and the United States, emission inventories provide quantitative estimates of emissions at national, state or provincial, and county levels for many source categories with medium to high level of confidence [NARSTO, 2005]. Western European emissions data compiled at the national level annually provide bottom-up emissions with uncertainties of 8%–23% [Vestreng et al., 2009]. The percent uncertainty in total continental emissions is lower than that for individual locations. The use of emission data for indirect validation benefits from a large domain coincident with satellite observations for a variety observational conditions.

[6] Direct observation of the area-averaged NO$_x$ lifetime is difficult. Several previous estimates of the NO$_x$ lifetime are based on in situ observations in industrial and urban plumes [e.g., Spicer, 1982; Dommen et al., 1999; Nunnermacker et al., 2000; Ryerson et al., 2003]. Surface NO$_x$ emission inventories over northern midlatitudes exhibit little seasonal variation [Olivier et al., 2001]. Thus, the seasonal variation in tropospheric NO$_2$ columns provides information on the NO$_x$ lifetime [Schaub et al., 2007]. Retrieval errors must be minimized to reduce errors in the inferred lifetime.

[7] In this paper, we use in situ surface NO$_2$ measurements and current NO$_x$ emission inventories for indirect validation of satellite retrievals and then go on to estimate the NO$_x$ lifetime. Section 3 compares surface NO$_2$ concentrations inferred from the Ozone Monitoring Instrument (OMI) satellite instrument with in situ observations from photolytic and molybdenum converter analyzers. In section 4, top-down NO$_x$ emissions inferred from OMI observations are compared with bottom-up emissions over surface sites to understand the magnitude and temporal variation in satellite retrievals. The comparison of top-down and bottom-up emissions is extended to the entire domain of North America (Canada and the United States), Organisation for Economic Co-operation and Development (OECD) Europe, and East Asia. Differences between OMI NO$_2$ retrievals are examined in section 5. We then apply the OMI NO$_2$ data to estimate the NO$_x$ lifetime in section 6.

2. Observational Data

2.1. OMI Tropospheric NO$_2$ Column Retrievals

[8] The OMI aboard the Aura satellite provides measurements of solar backscatter that can be applied to retrieve tropospheric NO$_2$ with a spatial resolution of up to 13 × 24 km [Levett et al., 2006b, 2006a]. Aura was launched on 15 July 2004 into a Sun-synchronous polar orbit with a local equator crossing time of 13:45 in the ascending node.

[9] Two independent tropospheric NO$_2$ column data products from OMI observations are available. These are the OMI standard product (SP; version 1.0.5, collection 3) available from the NASA Goddard Earth Sciences (GES) Data Active Archive Center (http://disc.sci.gsfc.nasa.gov/data/datapool/OMI/) and the DOMINO product (DP) (version 1.0.2, collection 3) available from Tropospheric Emission Monitoring Internet Service (TEMIS) (http://www.temis.nl/). Both algorithms begin with the same slant column, determined by nonlinear least squares fitting of modeled spectrum to the OMI-measured attenuation spectrum in 405–465 nm window. The slant column represents the integrated abundance of NO$_2$ along the average photon path from the Sun, through the atmosphere, to the satellite. The two retrieval algorithms differ in the subsequent steps of tropospheric NO$_2$ column retrieval. Below, we briefly describe the two algorithms for collection 3, which include updates from Bucsela et al. [2006] and Boersma et al. [2007].

[10] The algorithm for the standard OMI NO$_2$ data product is described by Bucsela et al. [2006, 2008] and Celarier et al. [2008]. A 24 h history of slant column densities is used to correct for a cross-track anomaly in the level 1b irradiance measurements as reported by Dobber et al. [2008]. The stratospheric (background) NO$_2$ field is determined by applying masks over regions where tropospheric NO$_2$ column
abundances are high, smoothing in the meridional direction with a boxcar function, and conducting a zonal planetary wave analysis up to wave 2. The tropospheric air mass factors (AMFs) needed to convert the tropospheric slant columns into vertical columns are computed with the TOMRAD radiative transfer model [Bucsel et al., 2006] using a geographically gridded set of annual mean tropospheric NO$_2$ vertical profiles for late morning (09:00–12:00 local time) obtained from a GEOS-Chem simulation [Martin et al., 2003b], surface reflectivity from Global Ozone Monitoring Experiment (GOME) [Koelmaneijer et al., 2003], and cloud parameters from the OMI O$_2$–O$_3$ cloud algorithm [Acarreta et al., 2004]. For cloudy scenes, the below–cloud amount is derived by scaling the NO$_2$ profile to the retrieved tropospheric NO$_2$ column. The tropospheric NO$_2$ columns used in this study typically are about 5% higher than the “polluted” NO$_2$ columns over northern midlatitude continents.

[11] The DOMINO algorithm [Boersma et al., 2007] begins with the same NO$_2$ slant columns density processes for the standard product. Stratospheric NO$_2$ is derived by assimilating OMI NO$_2$ slant columns into a chemical transport model, TM4 [Dentener et al., 2003]. The tropospheric AMFs are computed as a function of the NO$_2$ vertical profile simulated by TM4 for the day and time of measurement and the vertically resolved sensitivity to NO$_2$ of the solar radiation backscattered to space (averaging kernels; Eskes and Boersma [2003]) determined with the DAK radiative transfer model [Stamnes, 2001]. The forward model parameters include cloud parameters based on the cloud model of [Acarreta et al., 2004], surface reflectivity from the TOMS and GOME measurements [Herman and Celarier, 1997; Koelmaneijer et al., 2003], and viewing geometry.

[12] The retrieved tropospheric NO$_2$ column is sensitive to the NO$_2$ profile shape ($X_k$) used in the calculation of the tropospheric AMFs. Hains et al. [2010] evaluated the NO$_2$ profile from the TM4 model used in the DP and found evidence that the NO$_2$ profiles in the TM4 model are insufficiently mixed throughout the boundary layer as a result of an implementation error in sampling the NO$_2$ fields [Huijnen et al., 2009]. NO$_2$ mixing ratios are more vertically uniform in the unstable mixed layer in GEOS-Chem than in TM4. The DP makes available averaging kernels ($A_k$) at each level k, which depend only on forward model parameters, when multiplied with the TM4-derived AMF (M) [Eskes and Boersma, 2003]. Following the recommendations of Eskes and Boersma [2003] and Boersma et al. [2004], we combine the DP $A_k$ with the NO$_2$ profile shapes ($X_k^{GC}$) from a GEOS-Chem–TM4 simulation described in Appendix A to remove the influence of TM4 (except for the temperature dependence of the NO$_2$ cross section). This yields a third data set, DP GC, which is calculated from each tropospheric slant column density ($\Omega_k$) and an AMF that depends on GEOS-Chem NO$_2$ profiles:

$$DP_{GC} = \frac{\Omega_k \sum_{k=1}^{2} X_k^{GC}}{M \sum_{k=1}^{2} A_k X_q^{GC}}$$

[13] The use of DP GC allows for a more consistent interpretation with GEOS-Chem. We correct in DP GC for the cross-track bias in tropospheric slant column densities. The bias was determined for each orbit using NO$_2$ slant column densities in the 5th to 95th percentile limits over less polluted areas (30°S–5°N) following the approach described by Celarier et al. [2008]. Correction of the cross-track bias decreases by ~5% the mean tropospheric NO$_2$ columns. The stratosphere–troposphere separation in DP GC remains unchanged from that for DP.

[14] The total error in the retrieval of tropospheric NO$_2$ columns arises from errors in the slant column density, in the stratosphere–troposphere separation and from the AMF calculation. The uncertainty due to spectral fitting is $0.75 \times 10^{15}$ molec cm$^{-2}$ [Boersma et al., 2007] and dominates the overall retrieval error over the oceans and remote areas. The uncertainty in the stratospheric slant column density is $0.15 \times 10^{15}$ molec cm$^{-2}$ for the DP [Boersma et al., 2007] and $0.20 \times 10^{15}$ molec cm$^{-2}$ for the SP [Bucsele et al., 2006]. AMF errors that arise from the incorrect assumptions on the surface reflectivity, aerosol, clouds, and NO$_2$ profile shape dominate overall retrieval error over continental source regions [Martin et al., 2002; Boersma et al., 2004, 2007; Wenig et al., 2008]. The estimated errors in the tropospheric NO$_2$ columns under clear-sky and cloudy conditions are ~30% and ~60%, respectively [Boersma et al., 2004]. The stripe removal may introduce additional bias [Celarier et al., 2008]. We exclude scenes with cloud radiance fraction [Boersma et al., 2004] exceeding 0.5 to reduce the retrieval errors. To reduce spatial averaging, we exclude the ground pixels at swath edges that correspond to a pixel size of more than 50 × 24 km$^2$.

2.2. Comparison of OMI NO$_2$ Retrievals

[15] Here, we compare OMI tropospheric NO$_2$ columns retrieved from the SP and DP algorithms. Figure 1 shows the seasonal area weighted average tropospheric NO$_2$ columns gridded to 0.1° × 0.1° from the SP (first row), DP (second row), and DP GC (third row) over North America for the year 2005. The three products exhibit similarities in their spatial distribution, with pronounced enhancements over major industrial and metropolitan areas. They have a broadly similar seasonal variation, with lower NO$_2$ columns over industrial source regions in summer than those in winter. Annual mean tropospheric NO$_2$ columns among the retrievals are well correlated ($r^2 > 0.95$, $N = 216,651$).

[16] The fourth row of Figure 1 shows the seasonal difference between the DP and SP tropospheric NO$_2$ columns. Significant differences of more than $5 \times 10^{15}$ molec cm$^{-2}$ are found over continental source regions. A clear seasonal difference is apparent. Over the domain of North America, the mean tropospheric NO$_2$ columns in the DP are 42% higher than those for the SP in winter and 22% lower in summer. Seasonal differences between DP and DP GC (bottom row) are typically within ±1 × 10$^{15}$ molec cm$^{-2}$. Similar seasonal differences are found for 2006.

2.3. In Situ Surface NO$_2$

[17] We attempt to understand these differences using hourly in situ measurements of NO$_2$ from two sources: The SouthEastern Aerosol Research and Characterization (SEARCH) network [Hansen et al., 2003] and the U.S. EPA’s Air Quality System (AQS) network [Demerjian, 2000]. There are a few complications in comparing satellite
observations with ground-based measurements. Satellite data represent observations that are averaged over a large field of view, covering several hundred square kilometers unlike local point measurements by ground-based instruments. Spatial inhomogeneity within a satellite ground pixel with larger NO2 concentrations at/near source regions often makes the measurements from a surface site non-representative [Brinksma et al., 2008]. To this end, we focus on the measurements in rural areas. Figure 2 shows the location of the rural stations. Mean tropospheric NO2 columns over these stations range over 2–6 \times 10^{15} \text{molec cm}^{-2}, well above the detection limit of the satellite measurements.

[18] NO2 measurements at SEARCH sites are made using photolytic converter analyzers, a technique that employs broadband photolysis of ambient NO2 followed by chemiluminescence detection of the product NO [Kley and McFarland, 1980; Ryerson et al., 2000]. This method uses wavelength filters to prevent the photolysis of other nitrogen-containing species and therefore offers almost interference-free NO2 measurements. The potential interferants, HONO...
and NO₃, have very low atmospheric concentrations during the day [Parrish et al., 1990; Ryerson et al., 2000]. Overall uncertainties for 1 h averages in NO₂ are estimated to be ±10% [Zellweger et al., 2000]. Here, we focus on three regionally representative sites: Oak Grove (OAK) in the state of Mississippi, Centreville (CTR) in Alabama, and Yorkville (YRK) in Georgia. The data from these stations are available for 1997–2006.

[19] The NO₂ measurement method of the EPA/AQS network relies on conversion of NO₂ to NO using a heated molybdenum catalytic converter followed by measurement of the resultant NO by chemiluminescence with ozone [EPA, 1975]. The molybdenum converter instrument responds not only to NO₂ but also to other reactive nitrogen species [Winer et al., 1974; EPA, 1975; Grosjean and Harrison, 1985; Demerjian, 2000]. The in situ NO₂ concentrations can be overestimated by more than 50% [Dunlea et al., 2007; Steinbacher et al., 2007; Lamsal et al., 2008]. Laboratory studies show that alkyl nitrates and peroxyacetyl nitrate (PAN) are converted to NO with efficiency greater than 92% [Winer et al., 1974; Grosjean and Harrison, 1985]. Interference from HNO₃ is difficult to estimate as it can deposit to and evaporate from the surfaces in the inlet manifold [Neuman et al., 1999; Dunlea et al., 2007]. On the basis of measurements at a Swiss site, Lamsal et al. [2008] estimated an effective conversion efficiency of ~35% for HNO₃ at OMI overpass time. Here, we use simultaneous measurements of surface NO₂ using molybdenum and photolytic converter analyzers at YRK to test the conversion efficiency of the molybdenum converter.

[20] Figure 3 compares the hourly average surface NO₂ measured by the two instruments during 13:00–14:00 local time over the period 1997–2006. The ratio of photolytic to molybdenum converter measurements, the blue line, gives the relative contribution of interfering species to the molybdenum converter measurements. The observed seasonal variation in the correction factor reflects the seasonal change in the relative contribution of HNO₃, PAN, and other organic nitrates to total reactive nitrogen species, with the largest contribution in summer. The red line indicates the monthly correction factor for 13:00–14:00 local time calculated from the GEOS-Chem simulation following the approach described by Lamsal et al. [2008], but assuming a 15% conversion efficiency for HNO₃. The GEOS-Chem-derived seasonal correction factors agree with measurements within 3% for all seasons except in winter, when the modeled correction factor is 16% higher than the measurements. Assuming an HNO₃ conversion efficiency of 35% improves the agreement in winter, but worsens the agreement in other seasons by 12%–17%. The correction factor for urban sites is closer to unity than the rural correction factors found here [Boersma et al., 2009]. We use local GEOS-Chem-derived correction factor to correct for the interference in the molybdenum converter measurements.

3. Comparison of In Situ Measurements With OMI-Derived Surface NO₂

[21] Here we conduct an indirect validation of cloud-free (cloud radiance fraction <0.5) OMI tropospheric NO₂ columns by comparison with coincident ground-based in situ NO₂ measured at 13:00–14:00.

3.1. Inferring Ground-Level NO₂ Concentrations From OMI

[22] We estimate ground-level NO₂ concentrations from OMI for comparison with the in situ measurements. We follow the approach of Lamsal et al. [2008] that combines information on the simulated NO₂ vertical profile with information from the satellite observations about the spatial variation of NO₂ concentrations in the boundary layer. Local NO₂ profiles coincident with the OMI observations are taken from the GEOS-Chem simulation.

[23] The ground-level NO₂ mixing ratio Ω is inferred from OMI tropospheric NO₂ columns Ω as follows:

\[
S = \frac{\nu}{\nu + \frac{1}{\Omega}} \times \Omega
\]

[24] The subscript “G” denotes GEOS-Chem. The symbol Ω represents the ratio of the local satellite NO₂ column to the mean satellite NO₂ column field over a GEOS-Chem grid. The simulated free-tropospheric NO₂ column Ω is taken as horizontally invariant over a GEOS-Chem grid, reflecting the longer NO₃ lifetime in the free troposphere. The satellite-derived surface NO₂ represents the mixing ratio at the lowest vertical layer (100 m) of the model.

[25] Equation (2) implicitly assumes that the tropospheric NO₂ column is dominated by the boundary layer concentrations. This assumption results in a spatial scalar less than Ω over regions where the boundary layer concentration is a small fraction of the tropospheric column, yielding the advantage of damping noise in NO₂ columns over regions where there is little NO₂.

3.2. Comparison With Photolytic Converter Measurements

[26] We compare the OMI-derived ground-level NO₂ concentrations with the photolytic converter measurements at three rural sites CTR, OAK, and YRK for 2005–2006.
Figure 4 presents the seasonal mean NO2 mixing ratio from in situ measurements and those derived from the OMI data. The seasonal variation of the OMI-derived NO2 mixing ratios is broadly consistent with the in situ measurements. However, the amplitude of the seasonal cycles differ. The seasonal mean NO2 concentrations for the in situ measurements decrease by a factor of 5.1 from the winter (maximum) to the summer (minimum), compared with factors of 2.7 for the SP, 4.8 for the DP, and 6.3 for the DP_GC.

Figure 4b shows the seasonal ratio of the OMI-derived to in situ NO2 concentration. Values are shown in Table 1. The annual mean bias is 27% for SP, 21% for DP, 43% for DP_GC. The ratio exhibits a strong seasonal variation for the OMI SP with a seasonal bias of 71% in summer and −5.6% in winter. The seasonal variations of the DP-derived and DP_GC-derived surface NO2 are more consistent with the in situ measurements. With the exception of summer, these results for OMI NO2 are consistent with the conclusions from earlier comparison of OMI tropospheric NO2 columns with ground-based and aircraft observations which indicate a bias of −30% to +40% in OMI retrievals [Boersma et al., 2008b; Brinksma et al., 2008; Bucsela et al., 2008; Celarier et al., 2008; Irie et al., 2008; Lamsal et al., 2008].

3.3. Comparison With Molybdenum Converter Measurements

Here, the satellite-derived surface NO2 concentrations are compared with the corrected molybdenum converter measurements at 8 rural sites over the United States for the years 2005-2006. Figure 5a shows the OMI-derived seasonal mean NO2 mixing ratios and those observed from the molybdenum converter instruments. The seasonal cycles of both the satellite-derived and in situ NO2 concentrations exhibit a winter maximum and summer minimum, similar to those over the SEARCH sites, providing confidence in the corrected data from molybdenum converter. However, the magnitude of the seasonal cycle again differs for the satellite products.

Figure 5b shows the seasonal average ratio of the OMI-derived surface NO2 and the corrected in situ measurements. Values are given in Table 1. The seasonal mean biases range from −4.5% in winter to 67% in summer for the SP, from 13% in spring to 43% in fall for the DP, and from −5% in summer to 30% in fall for the DP_GC. These seasonal biases are generally consistent with the comparison at the SEARCH sites, recognizing that differences with the SEARCH sites in part reflect different regions of comparison.

4. Seasonal Comparison Between Bottom-Up and Top-Down Emissions

We describe the approach to estimate NOx emissions from OMI tropospheric NO2 columns in section 4.2. The seasonal OMI-based top-down estimates are compared with seasonal bottom-up emission inventories in section 4.3.

4.1. Bottom-Up NOx Emissions Inventory

Table 2 and Figure 6 show the annual and seasonal mean, respectively, of NOx sources for North America, OECD Europe, and East Asia for the years 2005 and 2006 as implemented in the GEOS-Chem model (Appendix A).
The bottom-up inventories over these regions incorporate detailed source characterization as well as emission factors representative of country-specific emission rates \[ \text{NARSTO, 2005; Streets et al., 2006; Zhang et al., 2007; Vestreng et al., 2007} \]. Anthropogenic activities contribute >75% of total NO\textsubscript{x} emissions. For North America and OECD-Europe, the anthropogenic NO\textsubscript{x} emissions are dominated by on- and off-road engines and vehicles (\( \sim 55\% \)) followed by electric utilities (\( \sim 20\% \)), and industrial and residential combustion (\( \sim 20\% \)). The seasonal variation in area (e.g., on-road/non-road mobile, small industries) sources in the VISTAS emission inventory \[ \text{Morris et al., 2007} \] for the United States is <1%. Seasonal controls on power plant emissions drive the summer time reduction in anthropogenic NO\textsubscript{x} emissions \[ \text{Frost et al., 2006; Hudman et al., 2007} \]. Biogenic and pyrogenic emissions exhibit strong seasonal variation with the maximum emissions occurring in summer, but are a small fraction (<9%) of total surface NO\textsubscript{x} emissions.

The overall uncertainty in the seasonal variation in anthropogenic NO\textsubscript{x} emissions is expected to be <25% over OECD Europe \[ \text{Vestreng et al., 2009} \] and the United States (Christian Hogrefe, personal communication, 2008). The uncertainty in seasonal variation in power plant NO\textsubscript{x} emissions in the United States is fairly small due to the use of Continuous Emission Monitoring Systems (CEMS) \[ \text{Frost et al., 2006} \]. Biogenic and pyrogenic emissions exhibit strong seasonal variation with the maximum emissions occurring in summer, but are a small fraction (<9%) of total surface NO\textsubscript{x} emissions.

### Table 2. Average GEOS-Chem NO\textsubscript{x} Emissions Over North America, OECD Europe, and East Asia for the Years 2005–2006

<table>
<thead>
<tr>
<th>Source</th>
<th>North America</th>
<th>OECD Europe</th>
<th>East Asia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fossil fuel combustion</td>
<td>5.29</td>
<td>2.71</td>
<td>7.36</td>
</tr>
<tr>
<td>Lightning</td>
<td>0.70</td>
<td>0.09</td>
<td>0.27</td>
</tr>
<tr>
<td>Biomass burning</td>
<td>0.15</td>
<td>0.03</td>
<td>0.05</td>
</tr>
<tr>
<td>Soils</td>
<td>0.67</td>
<td>0.34</td>
<td>0.57</td>
</tr>
<tr>
<td>Biofuels</td>
<td>0.03</td>
<td>0.10</td>
<td>0.01</td>
</tr>
<tr>
<td>Aircraft</td>
<td>0.16</td>
<td>0.07</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Figure 5. Seasonal variation of NO\textsubscript{2} mixing ratios at rural EPA/AQS sites for 2005–2006. (a) Seasonal mean NO\textsubscript{2} mixing ratios from molybdenum converter measurements (filled circles) and those derived from the OMI SP (blue), DP (red), and DP_GC (green) tropospheric NO\textsubscript{2} columns (squares). In situ data are averaged over 13:00–14:00 local time and are corrected for interference using a GEOS-Chem simulation. Error bars in molybdenum converter measurements are calculated from errors in photolytic converter and the seasonal difference between photolytic and corrected molybdenum converter measurements. Error bars in the OMI-derived surface NO\textsubscript{2} represent errors in retrievals and in the GEOS-Chem NO\textsubscript{2} profiles. (b) Seasonal mean ratio of satellite-derived surface NO\textsubscript{2} concentrations from the SP (blue), DP (red), and DP_GC (green) to the in situ surface measurements.

Figure 6. Seasonal NO\textsubscript{x} emissions for 2005–2006 from surface sources over land of North America, OECD Europe, and East Asia for various source categories: fossil fuel combustion (FF), soil (SO), biomass burning (BB), and biofuel (BF).
4.2. Top-Down NO₂ Emissions Estimate

[35] We use the mass balance approach [Leue et al., 2001] as described by Martin et al. [2003a] to relate OMI tropospheric NO₂ columns (Ω) to surface NOx emissions (E):

\[ E = \frac{E_G}{\Omega_G} \times \Omega. \]  

(3)

[36] Here, ΩG is the tropospheric NO₂ column from the GEOS-Chem simulation sampled at satellite overpass time and based on the a priori emissions E_G. We adopt the improvement of Wang et al. [2007] to account for contributions from external and free-tropospheric sources such as lightning. These contributions were identified with a sensitivity simulation in which local land surface emissions are turned off and subtracted from both the retrieved and simulated NO₂ columns. We infer daily surface NO₂ emissions over coasts and continents. We take the uncertainty in the inversion to be 30% [Martin et al., 2003a]. The use of \( \frac{E_G}{\Omega_G} \) generally yields an effective NO₂ lifetime that accounts for local NO₂ chemistry and transport. However, because of spatial smearing [Palmer et al., 2003], the grid average NO₂ column in part reflects nearby NO₂ emissions. We considered the approach by Toenges-Schüller et al. [2006] and Boersma et al. [2008b] to account for the emissions from adjacent grid cells:

\[ E_{ij} = \frac{E_{Gi}}{\sum_{m=1}^{N} \sum_{n=1}^{M} K_{ij} \Omega_{Gi,\text{adj}}} \times \frac{E_{Gj}}{\Omega_{Gj}} \times \Omega_{ij}, \]  

(4)

with the kernel K defined as \( \frac{1}{p+8} \begin{bmatrix} 1 & 1 & 1 \\ 1 & p & 1 \\ 1 & 1 & 1 \end{bmatrix} \). The correlation between the smoothed bottom-up emissions and the corresponding GEOS-Chem tropospheric NO₂ columns is maximum with the smoothing parameter \( p > 1000 \); therefore, application of equation (4) is unnecessary here.

4.3. Comparison

[37] Here we compare the satellite-derived emission estimates with the bottom-up inventories. Given that the inter-retrieval differences exceed the uncertainty in the bottom-up inventories, we interpret here the differences between top-down and bottom-up emissions for insight into retrieval biases. We first focus on the area where the three SEARCH sites are located.

[38] Figure 7 presents the ratio of seasonal total top-down and bottom-up surface NO₂ emissions over the SEARCH domain specified in Figure 2. Mean biases are in Table 1. The seasonal mean DP-based emissions are 24%–38% higher and the DP_GC-based emissions are 2.9%–34% higher than the a priori. The seasonal mean SP-based emissions are within 1% of the a priori in winter but 74% higher in summer. The seasonal biases in satellite retrievals inferred from bottom-up surface NO₂ emissions and in situ surface measurements (Figure 4) generally agree to within 15%. Similar seasonal discrepancies provide confidence in both methods of indirect validation. Small differences between the two approaches could arise from the different domains, in the observation period, and by seasonal non-linearity between the surface NOₓ emissions and the corresponding NO₂ column [Kunhikrishnan and Lawrence, 2004]. We extend the emissions comparison to larger geographic areas over the entire domain of North America, OECD Europe, and East Asia.

[39] Figure 8 shows the spatial variation of regional bottom-up and top-down NOₓ inventories of land surface emissions. Both top-down and bottom-up inventories exhibit broad similarity in their spatial pattern. However, pronounced differences in the magnitude of NOₓ emissions are observed.

[40] Figure 9 shows the ratio of seasonal area-averaged top-down and bottom-up NOₓ emissions over North America, OECD Europe, and East Asia. The ratio ranges from 0.97 to 2.03 for the SP, from 1.32 to 1.66 for the DP, and from 1.10 to 1.49 for the DP_GC. The overall comparison is generally consistent with the conclusions for the Eastern United States (Figures 4–7). For the SP the difference is smallest in winter and largest in summer. The seasonal variation in the DP top-down emissions is similar to the bottom-up. The bias versus the bottom-up is reduced significantly with the top-down estimates based on the DP_GC. We recommend using the DP_GC product for quantitative applications of the OMI NOₓ data.

5. Synthesis of Indirect Validation Across Multiple Methods

[41] Sections 3 and 4 presented consistent results of satellite-derived surface NO₂ versus the surface measurements (Figures 4 and 5, Table 1) and top-down versus bottom-up emission inventories (Figures 7 and 9, Table 1) that together indicate a seasonal bias in the satellite retrievals. Retrievals of tropospheric NO₂ columns are affected by the air mass factor and the removal of the stratosphere. Here we examine the relative contribution of each component to the observed difference between the DP and SP.

[42] We first calculate the difference between the DP and SP tropospheric NO₂ columns that arises from the stratosphere-troposphere separation. The change in the tropospheric vertical column \( \Delta \Omega_{\text{v, trop}} \) arising from the stratosphere-troposphere separation is the difference in the stratospheric slant columns \( \Omega_{s, \text{strat}} \) in the two retrievals divided by the tropospheric air
mass factor $M$. The SP stratospheric slant columns ($\Omega_{\text{strat}}^{\text{SP}}$) are calculated from the stratospheric NO$_2$ vertical columns and the SP stratospheric AMFs. We use values of $M$ from only one retrieval algorithm to isolate the effect of the stratosphere:

$$\Delta \Omega_{v,\text{strat}}^{\text{DP} - \text{SP}} = \frac{\Omega_{v,\text{strat}}^{\text{DP}} - \Omega_{v,\text{strat}}^{\text{SP}}}{M^{\text{DP}}}. \quad (5)$$

Figure 10 (left) shows the seasonal difference between the DP and SP tropospheric NO$_2$ columns due to their different AMF calculations for the stratosphere-troposphere separation. The stratospheric NO$_2$ slant columns in the two products generally agree to within $\pm 1 \times 10^{15}$ molec cm$^{-2}$. The effect on the troposphere can be larger at northern midlatitudes due to lower air mass factors. The seasonal difference at northern midlatitudes due to the stratosphere-troposphere separation can be opposite in sign to the difference in Figure 1.

The difference between the DP and SP tropospheric vertical NO$_2$ columns caused by their different AMF can be calculated by applying their respective AMFs to the same tropospheric slant columns:

$$\Delta \Omega_{v,\text{AMF}}^{\text{DP} - \text{SP}} = \frac{\Omega_{v,\text{AMF}}^{\text{DP}}}{M^{\text{DP}}} - \frac{\Omega_{v,\text{AMF}}^{\text{SP}}}{M^{\text{SP}}}. \quad (6)$$

Figure 10 (middle) shows the AMF-induced difference in the tropospheric NO$_2$ columns. Differences are largest at northern midlatitudes, and smallest over ocean. At northern midlatitudes in winter, spring, and fall DP AMFs are lower than SP AMFs, leading to larger DP tropospheric NO$_2$ columns. The sign reverses in summer when DP AMFs exceed SP AMFs. The OMI Science Team understands that

Figure 9. Seasonal mean ratio of area-averaged top-down surface NO$_x$ emissions to bottom-up emissions over (left) North America, (middle) OECD Europe, and (right) East Asia. Error bars represent uncertainty in bottom-up inventories, in the inversion, and in OMI retrievals. Bars are colored as in Figure 7.
these differences arise in part from the use of annual mean NO2 profiles in the SP algorithm. A future SP algorithm is being developed to use monthly varying NO2 vertical profiles to better account for seasonal variation in free-tropospheric NOx and in mixed-layer depths. Other sources of AMF differences arise from difference in terrain pressures [e.g., Zhou et al., 2009], radiative transfer algorithms, and surface reflectivity used in the two products. The existing difference in surface reflectivities of >0.02 [Bucsela et al., 2008] between the two algorithms can have significant effect in polluted areas with low reflectivities [Martin et al., 2002; Boersma et al., 2004; Hains et al., 2010].

[46] Figure 10 (right) shows the combined effect of the difference in the stratosphere-troposphere separation and air mass factors to the observed difference between the two products. The effect of the air mass factor is partially compensated by the effect of the stratospheric correction. Consequently, most regions of the world exhibit little change. However, pronounced seasonal differences remain over the industrial regions, with the DP being higher than the SP in winter. The sign and magnitude of the combined differences largely explain the observed seasonal differences between the two products shown in Figure 1.

6. Seasonal Variation in NOx

[47] In situ and OMI-derived surface NO2 concentrations exhibit a distinct peak in winter, with a minimum in summer (Figures 4 and 5). Three factors that could drive this seasonal variation are NOx emissions, the NO/NO2 ratio, and the NOx lifetime. Figure 6 shows that the seasonal variation in NOx emissions does not explain the observed seasonal change in NO2 concentrations. Seasonal variation in the NO2/NOx ratio at SEARCH sites during OMI overpass time is <10%. Velders et al. [2001] recognized that the seasonal variation in tropospheric NO2 columns is driven by the NOx lifetime. An inspection of the seasonal variation in the tropospheric NO2 columns, coupled with the weak seasonal variation in emissions, indicates that the NOx lifetime at northern midlatitudes varies by about a factor of two. Schaub et al. [2007] applied SCIAMACHY NO2 columns to infer the NOx lifetime over Switzerland, where NOx emissions are well known. We extend their approach here over the eastern United States.

[48] Tropospheric NO2 columns observed by OMI at time \( t_{\text{OMI}} \) reflect previous NOx emissions emitted at time \( t_i \) that decay exponentially with effective NOx lifetime \( \tau \). We calculate the effective NOx emissions \( E_{\text{eff}} \) preceding OMI observations as the weighted average with weights \( w_j = \exp \left(-t_{\text{OMI}} - t_i\right)/\tau \). This relationship allows inference of \( \tau \) from OMI observations (Ω):

\[
\tau = \beta \times \frac{\Omega}{E_{\text{eff}}},
\]

where \( \beta \) is the ratio of tropospheric NOx to NO2 columns obtained from the GEOS-Chem model. Because \( E_{\text{eff}} \) itself depends on \( \tau \), we find the solution iteratively. We apply the
calculation to the DP_GC product, for which the validation indicated the greatest confidence. As recommended by Eskes and Boersma [2003] and Boersma et al. [2004], the use of DP_GC also has the benefit of allowing a consistent interpretation since NO2 profiles used in the retrieval are from the same model used for the interpretation. We limit our calculation to polluted (winter NO2 columns >2 x 10^{15} molec cm^{-2}) areas of the eastern United States where the columns are dominated by the lower troposphere.

Figure 11 shows the monthly average lifetime of NOx at 13:00–14:00 h in the lower troposphere. The lifetime exhibits strong seasonal variation with a maximum in winter and a minimum in summer. The monthly mean effective lifetime ranges 6.7–19.5 h for OMI and 6.4–16.7 h for GEOS-Chem. The seasonal mean lower tropospheric NOx lifetimes presented here are consistent with the estimates of Schaub et al. [2007] over Switzerland from SCIAMACHY and of Beirle et al. [2003] over Germany from GOME, with the exception in summer. Previous studies based on measurements in power plant and industrial plumes report a large spatial variability (1.5–6.4 h in summer) [Spicer, 1982; Nunnermacker et al., 1998, 2000; Dommen et al., 1999; Stillman, 2000; Ryerson et al., 2003]. The in situ based estimates are expected to be lower than the area-averaged NOx lifetimes derived from OMI because of influence from free tropospheric NOx on the OMI calculation.

The loss of NOx mainly occurs through the formation of HNO3 by the reaction of NO2 with OH and by aerosol uptake of NO2, NO3, and N2O5. We examine their relative contribution for insight into the chemical mechanism that controls the seasonal variation of the NOx lifetime and OMI NO2 columns. Figure 12 presents the time-averaged fraction of total NOx loss to HNO3 contributed by the two chemical mechanisms as simulated with GEOS-Chem. The fraction of HNO3 formed by gas-phase reaction of NO2 with OH ranges from 85% (winter) to 99% (summer) during OMI overpass time and from 25% (winter) to 73% (summer) diurnally averaged. The uptake of NO2, NO3, and N2O5 by aerosols is more effective for nighttime formation of HNO3 and accounts for <1% during 13:00–14:00 LT and 26% on daily average in summer. The chemistry controlling the effective NOx lifetime inferred from OMI lies between these two extremes. Both extremes indicate that gas-phase chemistry controls the effective NOx lifetime in summer. However, in winter the diurnally averaged curve is more appropriate as the effective NOx lifetime approaches 24 h. The effective NOx lifetime inferred from OMI in winter reflects a larger influence from heterogeneous chemistry.

7. Conclusion

We examined the seasonal variation of lower tropospheric NOx at northern midlatitudes using surface NO2 measurements, bottom-up inventories of surface NOx emissions, tropospheric NO2 column retrievals from the OMI satellite instrument, and a global model of tropospheric chemistry (GEOS-Chem). Tropospheric NO2 columns retrieved from OMI using the standard (SP) and DOMINO (DP) algorithms exhibit similar spatial variation (r^2 = 0.9) over North America, but pronounced differences in their seasonal variation.

Tropospheric NO2 retrievals are sensitive to assumed NO2 profile shapes. We used averaging kernel information available from the DP to effectively replace the a priori profiles from TM4 by NO2 profiles from a GEOS-Chem simulation and produce a third data set (DP_GC). NO2 mixing ratios in the GEOS-Chem simulation are more vertically uniform within the unstable mixed layer, in contrast with NO2 mixing ratios in the TM4 simulation, which are more sharply peaked near the surface. We applied an improved destriping algorithm to correct for the cross-track bias in the DP_GC.

We indirectly validated OMI tropospheric NO2 columns with surface NO2 measurements by applying coincident GEOS-Chem NO2 profiles as a transfer function. The satellite-derived surface NO2 was compared with the photolytic (SEARCH) and molybdenum converter (EPA/AQS) measurements at rural sites in the United States. Coincident photolytic and molybdenum converter measurements in the southeast United States (YRK) were used to estimate an effective HNO3 detection efficiency of 15% for OMI overpass time. NO2 measurements from molybdenum converter analyzers were corrected for interference using coincident simulated values of HNO3, PAN, and alkyl nitrates from GEOS-Chem. The seasonal average of the photolytic and...
corrected molybdenum converter measurements agree to within 1%, with the exception in winter. The seasonal variation of the satellite-derived surface NO2 and surface measurements is broadly consistent, but differs in the seasonal amplitude. The mean seasonal difference between satellite-derived surface NO2 and photolytic measurements ranges from −5.6% (winter) to 71% (summer) for the SP, from 12% (spring) to 33% (summer) for the DP, and from −5.5% (summer) to 18% (winter) for the DP_GC. A comparison with the corrected molybdenum converter measurements yields consistent seasonal discrepancies.

[54] We indirectly validated the satellite retrievals of tropospheric NO2 columns with well-established seasonal bottom-up surface NOx emission inventories for the south-eastern United States. The bottom-up emissions exhibit little seasonal variation and have an uncertainty of 25% at the regional scale. The GEOS-Chem model was used to infer from OMI NO2 top-down estimates of NOx emissions. Over the SEARCH sites, the seasonal mean biases between OMI and bottom-up emissions range from −1% (winter) to 74% (summer) for the SP, from 24% (spring) to 38% (fall) for the DP, and from 2.9% (summer) to 34% for the DP_GC. The larger inter-retrieval difference in top-down emissions than that in bottom-up emissions permits the evaluation of the retrievals rather than bottom-up emissions through this approach. The seasonal biases in top-down emissions are similar to those between in situ and satellite-derived surface NO2, providing confidence in both indirect validation techniques. We recommend using the DP_GC product for quantitative applications of the OMI NO2 data.

[55] We extended the comparison between top-down and bottom-up annual mean surface NOx emissions to North America, OECD Europe, and East Asia. The SP top-down inventory is higher than the bottom-up inventory by 45% over North America and 62% over East Asia and OECD Europe, with the largest difference (75%–100%) in summer. The DP-based emissions are higher than the bottom-up emissions by 39% over North America, 52% over OECD Europe, and 49% over East Asia. The DP_GC-based top-down inventory is 10%–38% higher than the bottom-up inventory over the three regions.

[56] We assessed the contribution of the stratosphere-troposphere separation and air mass factors to the observed difference between the DP and SP tropospheric NO2 columns. The effect of the different stratospheric NO2 columns on the tropospheric columns is generally small (<1 × 1015 molec cm−2). However, this difference can dominate in the tropics and over oceans. The contribution of air mass factors is more important over continental source regions where it generally causes a larger seasonal variation in DP than in SP. The lack of seasonal variation in the SP a priori is a key reason for the seasonal differences in air mass factors.

[57] The seasonal variation in OMI NO2 columns is primarily driven by seasonal variation in the NOx loss rate at northern midlatitudes, where NOx emissions exhibit little seasonal variation. We exploited this information to estimate the seasonal NO2 lifetime from OMI NO2 observations. The resultant monthly average tropospheric NO2 lifetime over the eastern United States is 6.7–19.5 h, in close agreement by 3 h of the lifetime calculated from the GEOS-Chem model. We use the GEOS-Chem model to calculate that the effective NOx lifetime observed by OMI is driven by the formation of HNO3 by gas-phase reaction of NO2 with OH in summer, with an increasing role for heterogeneous chemistry in winter. Observation of the seasonal variation in NO2 from other satellite instruments such as GOME-2 with overpass times earlier in the day will be more strongly influenced by aerosol processes.

[58] The work presented here serves as indirect validation of satellite products. On the basis of this analysis, we recommend switching from annual to monthly NO2 profiles in the SP algorithm, using a stripe correction in DP, reconsidering the boundary layer mixing scheme used to generate NO2 profiles, reevaluating the stratosphere-troposphere separation algorithms, moving toward a common surface reflectivity database, and following the example of DP that all solar backscatter trace gas products make averaging kernel (or scattering weight) information available so that profile assumptions can be removed. A higher resolution simulation may better capture sharp horizontal gradients in the a priori NO2 profile in the boundary layer. Direct validation of satellite observations with in situ and ground-based measurements over wide geographic regions over an extended period of time will be valuable for further understanding of seasonal processes. Replacement of molybdenum converter analyzers with “true” NO2 capability would better address compliance needs in light of the EPA’s proposed NO2 standard, contribute to air quality research, and facilitate satellite validation.

Appendix A: The GEOS-Chem Model

[59] GEOS-Chem is a global three-dimensional model of tropospheric chemistry driven by assimilated meteorological data available from the Goddard Earth Observing System at the NASA Global Modeling and Assimilation Office (GMAO). The model has recently been applied to interpret a variety of NOx observations [Martin et al., 2006, 2007; Hudman et al., 2007, 2009; Sauvage et al., 2007; Boersma et al., 2008a, 2009; Lamsal et al., 2008; Zhang et al., 2008]. GEOS-Chem simulations generally agree to within 30% of measured NOx, HNO3, and PAN over eastern North America [Martin et al., 2006; Hudman et al., 2007; Singh et al., 2007].

[60] Here we use version 8-01-04 (http://acmg.seas.harvard.edu/geos/) of the model for simulation at 2° × 2.5° using GEOS-4 meteorological fields. The GEOS-4 data have 55 vertical levels between surface and 0.1 hPa and a temporal resolution of 6 h. Data for surface variables and mixing depths are given every 3 h. There are about 16 levels in the troposphere, including five levels below 2 km. The chemical time step in the model is 1 h.

[61] The model includes a detailed simulation of tropospheric ozone-NOx-hydrocarbon chemistry as well as of aerosols and their precursors. The aerosol and gaseous simulations are coupled through the formation of sulphate and nitrate, the HNO3/NO3 partitioning of total inorganic nitrate, heterogeneous aerosol chemistry including uptake of N2O5 by aerosols [Jacob, 2000; Evans and Jacob, 2005], and aerosol effects on photolysis rates [Martin et al., 2003b].

[62] The global NOx emission inventory in GEOS-Chem has been recently updated [van Donkelaar et al., 2008]. Canadian emissions are based on the CAC inventory (http://
www.ec.gc.ca/pdb/cac/) for 2005. Mexican emissions are based on BRAVO [Kalnins et al., 2005] for 1999. We update here the fossil fuel NO\textsubscript{2} inventory for the United States, OECD Europe, and East Asia. Anthropogenic emissions over the United States are based on the VISTAS inventory (http://www.vistas-sesarm.org) for the year 2002. Diurnal variations are based on the EDGAR inventory [Olivier et al., 2001]. Weekly variation is based on the U.S. EPA National Emissions Inventory for 1999 (http://www.epa.gov/chief/net/1999inventory.html). We scale the VISTAS 2002 emissions to the year of simulation (i.e., 2005 and 2006) according to source- and state-specific emission trends available from the U.S. EPA. The scale factors are monthly and include regulated changes in emissions. We update the European inventory to EMEP for 2005. The East Asian emissions (http://www.cger.uiowa.edu/EMISSION_DATA_new/data/intex-b_emissions/) are for the year 2006, with monthly variation based on the work of Zhang et al. [2007].

[63] Other NO\textsubscript{X} sources are biomass burning, soil, and lightning. Biomass burning emissions are from a climatological inventory with seasonal variability estimated using Along Track Scanning Radiometer (ATSR) fire counts [Duncan et al., 2003]. Diurnal variation in biomass burning emission is based on hourly fire counts over central America detected by the Geostationary Operational Environmental Satellite (GOES-4) for 2002 as described by Boersma et al. [2008a]. Soil NO\textsubscript{X} emissions are computed as a function of vegetation type, precipitation, temperature, fertilizer usage, and leaf area index [Yienger and Levy, 1995; Wang et al., 1998]. All surface emissions are distributed vertically in the unstable mixed layer [Martin et al., 2003b]. Emissions of NO\textsubscript{X} from lightning are linked to deep convection following the parameterization of Price and Rind [1992] with vertical profiles taken from Pickering et al. [1998]. The midlatitude lightning NO\textsubscript{X} source is 1.6 Tg N yr\textsuperscript{-1} following Martin et al. [2006] and Hudman et al. [2007]. The spatial distribution of lightning flashes is scaled to OTD-LIS following Sauvage et al. [2007] and L. Murray et al. (manuscript in preparation, 2010). Nitric oxide emissions from aircraft are based on the monthly mean emission inventory compiled by Baughcum et al. [1996]. The cross-tropopause NO\textsubscript{X} flux calculated from N\textsubscript{2}O oxidation in the model stratosphere [Bey et al., 2001] contributes 0.1 Tg N yr\textsuperscript{-1} as NO\textsubscript{X} and 0.4 Tg N yr\textsuperscript{-1} as HNO\textsubscript{3}.

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