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Seasonal and global NO_x production by lightning estimated from the Optical Transient Detector (OTD)

By STEPHEN W. NESBITT, RENYI ZHANG* and RICHARD E. ORVILLE, *Department of Atmospheric Sciences, Texas A&M University, College Station, Texas 77843-3150, USA*

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ABSTRACT

The Optical Transient Detector (OTD) lightning data for the 12-month period of 1996 are used to estimate the seasonal and global distributions of lightning-produced NO_x. The relatively small viewing footprint and the low detection efficiency of the OTD sensor and other difficulties require extrapolations of the OTD data to the actual global flash distributions. Furthermore, available measurements for the ratios of intracloud (IC) to cloud-to-ground (CG) flashes have been used to partition lightning counts for IC versus CG flashes from the OTD observations. The resulting lightning distributions are then used to calculate the global and seasonal production of NO_x, assuming a NO production rate of 6.2×10^{25} molecules for each CG flash and 8.7×10^{24} molecules for each IC flash. Consequently, we find that CG flashes produce more NO_x than IC flashes despite fewer CG flashes by a factor of 3 or more. NO_x production by lightning varies seasonally in accordance with the global lightning distribution, with the maximum production occurring in the Northern Hemisphere in the local summer. The latitudinal distribution of NO_x production exhibits a strong seasonal variation outside the tropics with the production occurring mainly in the summer hemisphere, whereas in the tropics the production is high throughout the year. The annual contribution to NO_x production by lightning is higher in the Northern Hemisphere than that in the Southern Hemisphere.

1. Introduction

Nitrogen oxides ($NO_x = NO + NO_2$) play a central rôle in atmospheric chemistry (Crutzen, 1970). In the troposphere and stratosphere, NO_x is closely related to the ozone chemistry via two separate processes. In regions of high NO_x concentrations ozone is produced photochemically in the cycling of NO to NO_2, which is facilitated by peroxy radicals formed during oxidation of carbon monoxide, methane, and other volatile organic compounds (VOCs), while in those with low NO_x concentrations ozone is catalytically destroyed (Seinfeld and Pandis, 1998). Nitrogen oxides are also intricately linked to the hydroxyl radical OH, a species which largely regulates the atmospheric oxidation potential (Logan et al., 1981). Reaction between NO_2 and OH leads to the formation of relatively stable nitric acid HNO_3, which can be removed from the atmosphere by precipitation and hence provides an important source of nitrate for the biosphere (Burns and Hardy, 1975). Also, since O_3 strongly absorbs the Earth's infrared radiation, knowledge of the global NO_x distribution is important for global climate studies (Ramanathan and Dickinson, 1979).

Nitrogen oxides are emitted into the atmosphere from natural and anthropogenic sources. Some important global sources of the primary NO_x include fossil fuel combustion, biomass burning, oxidation of atmospheric ammonia, and lightning (Prather and Logan, 1994; Houghton et al., 1995). In addition, the transport of NO_x from the strato-

* Corresponding author.
e-mail: zhang@ariel.tamu.edu

sphere and aircraft NO_x emissions could also be important sources in the upper troposphere (Strend and Hov, 1996; Brasseur et al., 1996). The production of NO_x by lightning has been the subject of numerous studies (Noxon, 1976; Chameides et al., 1977; Griffing, 1977; Levine et al., 1981; Liaw et al., 1990; Lawrence, 1995; Price et al., 1997a; Wang et al., 1998). Estimates of the global NO_x production by lightning vary considerably and lightning has been thought to have the largest uncertainty among the various NO_x sources (Lawrence et al., 1995; Price et al., 1997a).

To obtain an estimate of the global production of NO_x by lightning, several parameters need to be assessed and defined. These include the production of NO_x per joule of energy, the average energy dissipated per lightning flash, and the global lightning distribution. NO_x is thought to be produced primarily in the completely dissociated channel of a lightning flash through the recombination reactions of atomic oxygen and nitrogen (Zel'dovich and Raizer, 1966). The process involves "freezing out" a few % of NO_x as the temperature of the lightning channel decreases to about 3000 K. At that time, the volume of hot gas produced, which is related to the amount of energy deposited in the gas by the lightning flash, controls the amount of NO_x produced per joule of energy input. Other ambient factors may also influence the amount of NO_x produced per flash, including pressure, relative humidity, and the duration of the flash (which are different for different types of lightning) (Peyrous and Lapeyre, 1982; Stark et al., 1996; Wang et al., 1998). Hence the amount of NO_x produced by lightning may vary considerably with the physical characteristics of the lightning flashes. In addition, NO_x can also be produced by a mechanism involving ion-molecule reactions from ion and photon generation induced by lightning (Boldi, 1992).

A number of studies have been conducted to investigate the production of NO_x by lightning (Liaw et al., 1990; Biazar and McNider, 1995; Lawrence et al., 1995; Price et al., 1997a, b). For example, the concentrations of NO and NO_2 molecules from laboratory induced electrostatic discharges have been measured and related to the energy of the flash to yield the production of NO_x molecules per joule, with values ranging from $(2 \text{ to } 12) \times 10^{16}$ molecules J^{-1} (Biazar and McNider, 1995). These results are consistent with theoretical studies of the NO_x production of $(5 \text{ to } 17) \times 10^{16}$ molecules J^{-1} (Biazar and McNider, 1995). Also, field measurements of NO_x production have suggested a production of $(1 \text{ to } 30) \times 10^{26}$ NO_x molecules per flash (Biazar and McNider, 1995). When applying these results to actual lightning flashes in the atmosphere, however, there are several complicating factors. First, the characteristics of lightning, such as surface-to-volume ratio, voltage–current relationship, and thermal properties in laboratory and theoretical simulations may differ from real lightning flashes and hence may affect the estimates of NO_x production (Biazar and McNider, 1995). Also, intracloud (IC) flashes may have significantly lower energies than cloud-to-ground (CG) flashes and have a smaller NO_x production efficiency (Borucki and Chameides, 1984), since the amplitude of the radiation field for a typical CG flash in the 1–10 kHz range is much larger than that of an IC flash (Uman, 1987, p. 22). Furthermore, there is a considerable uncertainty concerning NO_x production by the corona sheath surrounding the lightning channel (Boldi, 1992). It should be noted that in a recent theoretical study Cooray (1998) found that, for a given amount of energy neutralization in the flash, a cloud flash dissipates more energy than a ground flash by a factor of approximately 2. Experimental data investigating this recent hypothesis have not yet been obtained.

The global lightning distributions used to estimate NO_x production have also varied significantly. Earlier studies estimating global NO_x production by lightning assume a constant lightning flash rate (Liaw et al., 1990), although a highly variable lightning flash rate has been inferred from satellite data and from ground-based lightning location systems (Orville and Spencer, 1979; Orville, 1994). These difficulties have lead to further studies using observed large-scale lightning data and estimated global lightning distributions. Biazar and McNider (1995) reported regional estimates of lightning production of NO_x using data from the National Lightning Detection Network (NLDN). In another recent study, Price et al. (1997a, b) have obtained the global and seasonal distributions of NO_x produced by lightning, based on a global lighting rate derived from the observed distributions of electrical storms and physical properties of lightning flashes along with constraints from the global atmospheric electric circuit.

In this study we report the global and seasonal distributions of NO_x production by lightning using data from the Optical Transient Detector (OTD). The OTD lightning data for the 12 months in 1996 were analyzed to derive the global and seasonal distributions of lightning. In addition, the OTD lightning data have been adjusted for IC and CG lightning flash ratios using measurements from Mackerras at al. (1998). The derived lightning distributions are then used to calculate the global and seasonal production of NO_x. We estimate the number of molecules of NO_x produced per lightning flash for CG and IC flashes based on the recent experimental study by Wang et al. (1998). They have reported detailed laboratory measurements of NO_x production by spark discharges as a function of dissipated energy, peak current, and pressure. Comparisons of global and seasonal NO_x production by lightning are made between our estimates and those from the most recently published results.

2. The Optical Transient Detector (OTD)

The long-term remote sensing of lightning on a global scale was made possible by the launch of the Optical Transient Detector (OTD) on the MicroLab-1 satellite in April 1995. The spaceborne lightning sensor was developed by the Marshall Space Flight Center in the 1980s for use as part of NASA's Earth Observing System (EOS) (Goodman et al., 1988; Christian et al., 1989). The OTD is the first long-term observer of lightning from space, with continuous observations since 1995. It can detect momentary changes in the optical scene that indicate the occurrence of lightning. The satellite was launched on 3 April 1995 into an orbital altitude of 710 km and an inclination of 70° (Christian et al., 1996). The satellite orbits the earth approximately once every 100 minutes. The OTD sensor has a 100-degree viewing angle that provides a $1300 \times 1300\ km^2$ viewing footprint. This allows viewing approximately 1/300 of the total surface area of the earth at a particular moment. The instrument has a spatial resolution of 10 km in the horizontal and a temporal resolution of 2 ms.

The OTD detects lightning flashes by observing the neutral oxygen emission line at 777.4 nm (Christian et al., 1989), a consistently strong feature first identified in slitless spectra of lightning by Orville and Salanave (1970). "Flashes" are recorded by comparing the luminance of adjoining frames of OTD optical data. If the difference in the luminance is more than a given threshold value, an "event" is recorded. One or more adjacent events in the same 2 ms time frame are recorded as a "group". One or more groups in a sufficiently small time period (within approximately 330 ms and separated in space by no more than 0.05° latitude or longitude) are classified as a "flash". The amount of time a particular location on the earth's surface is viewed by the instrument is also recorded; the so-called "viewtime" is useful in calculating flash rates.

The OTD detects cloud-to-ground lightning flashes with an efficiency of about 45–70% and slightly higher for intracloud lightning (Boccippio et al., 2000). An overall value of 48%, however, is appropriate for the satellite sensor in 1996 (Boccippio, 2000, personal communication). The sensor also provides much better spatial (70°S to 70°N) and temporal coverage (with continuous observations since 1995) than any other spaceborne lightning detection instruments (Orville, 1982; Goodman and Christian, 1993). One of the disadvantages for OTD, however, is the relatively small viewing area ($1300 \times 1300\ km^2$). This deficiency requires extrapolation of the OTD data to obtain the actual global lightning distributions. In addition, the South Atlantic Anomaly (SAA), located in southern South America and the South Atlantic Ocean, further reduces the detection efficiency of the OTD in that area. The SAA is caused by a dip in the earth's Van Allen radiation belt, which interferes with the instrument as increased background noise. The SSA occupies an area of approximately $2.78 \times 10^7\ km^2$ and causes a loss of data in a region where mesoscale convection systems (MCSs) are often observed (Mohr and Zipser, 1996).

3. Data and methods

This study uses monthly OTD data from 1996 in an attempt to derive the seasonal variation of lightning and NO_x production. The data were obtained from the Global Hydrology and Climate

Center Lightning Research Team at NASA's Marshall Space Flight Center. The OTD flash data were gridded using the Read_OTD software provided by the Lightning Research Team. The software took the OTD raw observations and combined the flash data in 1.0° by 1.0° grid boxes for analysis. Anomalous data were simultaneously filtered out, including correction for the SAA, sun glint, and sensor malfunctions. The total number of flashes recorded in a grid box was divided by the total viewtime of the grid box to obtain an observed flash density for that location. These densities were then multiplied by the total time in the month to obtain a flash rate based on the observations. A correction for the detection efficiency of the satellite is needed to obtain a realistic estimation of global flash distributions. In this study, a value of 48% (Boccippio, 2000, personal communication) for the OTD detection efficiency was adopted in calculating the global distribution of lightning and NO_x production. After these corrections, we estimate a total lightning count of 1.88×10^9 lightning flashes for 1996.

Due to the OTD sensor's inability to differentiate between different types of lightning (i.e., IC versus CG flashes), an estimation of IC to CG flash ratio must be used to estimate the populations of each type. Mackerras et al. (1998) recently used data from the CGR3 (Cloud-Ground Ratio #3) instrument, which estimates the IC/CG ratio for flashes near the instrument. Observations from 11 stations between 59.9°N and 27.3°S over periods averaging several years were used to obtain the ratio. These data were grouped into three regions, with latitudes between 0°–20°, 20°–40°, and 40°–60°. A linear fit was applied to the data to obtain an estimate of the IC/CG ratio (R) for all latitudes, yielding an expression of $R = 0.051L + 4.55$ where L is the latitude. This ratio was applied to the OTD observations from each latitude range to obtain estimates of the total number of IC and CG flashes. This yielded 1.46×10^9 IC flashes and 4.21×10^8 CG flashes, or an average of 3.5 IC flashes for every CG flash. We note that there may be an underestimate of this ratio because of the inability of the CGR-3 instrument to detect low peak current IC flashes (Mackerras et al., 1998). The uncertainty in the obtained IC/CG ratio was estimated to be about 50% (Prentice and Mackerras, 1977; Mackerras et al., 1998).

For the NO_x production by lightning flashes, we have employed the most recent laboratory results of Wang et al. (1998). These authors suggest using the peak current in natural lightning to estimate the NO_x production rate. They have obtained detailed measurements of NO_x production by electric sparks with peak currents and ambient air densities similar to natural lightning flashes. They have constructed a simple model of the lightning flash to estimate the NO_x production from CG lightning. Their model assumptions included a lightning flash occurring in an ideal gas of a constant lapse rate, with a height of 6 km and a peak current of 36 kA. They assumed a flash with a multiplicity of 2.8 strokes per lightning flash and a tortuosity factor of 3.6 to account for the lightning channel branching and the non-straight channel discharge path. We have modified the model by Wang et al. (1998) to include the NO_x production from both IC and CG flashes. We use a production rate of 3.1×10^{25} NO molecules per flash with a tortuosity factor of 2.0 (Idone and Orville, 1988), corresponding to a production of 6.2×10^{25} molecules for each CG flash. The experimental data from Wang et al. is also used to create an IC flash model. Brook (1999, personal communication) suggests a representative length of an IC flash to be 50 km, while the peak current is assumed to be 4 kA, which falls within the range reported by MacGorman and Rust (1998). For simplicity, the flash is assumed to occur at a pressure of 600 hPa, which is a representative height for a typical IC flash. This yields a NO_x production of 8.7×10^{24} molecules per IC flash. This dual-flash type model is used here to estimate the global NO_x production.

4. Results

Based on the analysis of the OTD data, we estimate that there were a total number of 1.8×10^9 flashes in 1996. This value is consistent with the study by Christian et al. (1996) using OTD data between the months of September 1995 and August 1996, who report that about 1.2×10^9 lightning flashes may occur annually. The difference between these two studies can be explained, we suggest, by a combination of the uncertainties associated with the OTD data and the different time period. Our value is very close to the estimate of 2.05×10^9 flashes per year by Mackerras et al. (1998) who used satellite lightning observations by the Defense Meteorological Satellite Program (DMSP) and the Ionospheric Sounding Satellite-b (ISS-b) in addition to ground based observations by CGR3 flash counters. Our analyzed global and seasonal distributions of lightning are also consistent with those recently published by Christian and Latham (1998). Using the partitioning method described above, it is estimated that there are 1.46×10^9 IC flashes and 4.21×10^8 CG flashes in the lightning data set for 1996. This corresponds to an IC/CG ratio of 3.46:1. Partitioning the flashes and using the IC and CG production rates yield an IC production of 0.29 Tg N year^{-1} and a CG production of 0.61 Tg N year^{-1}, respectively. The ratio of 0.48 : 1 for the NO_x production by IC and CG flashes is explained by the lowered production by IC flashes despite greatly outnumbering their CG counterparts.

Fig. 1 shows the estimated NO_x production for IC and CG flashes in 1996. It is seen from this figure that the most NO_x is produced in the Northern Hemisphere local summer, i.e., in the months of June, July, and August. CG flashes produce more NO_x than IC flashes despite the latter occurring more than three times as frequently. Our estimated seasonal variation of lightning NO_x production is qualitatively consistent with the data reported by Price et al. (1997a). There is a 55-day bias in the data that is described by Boccippio et al. (2000). This is minimized in Fig. 1 by taking the 3 month average, effectively giving an average of NO_x production for 3 months.

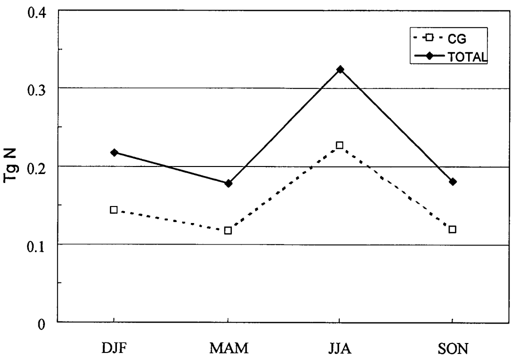

Fig. 1. NO_x production by IC and CG lightning in Tg N is shown quarterly (i.e., DJF, MAM, JJA, and SON) in 1996. The dashed line indicates contribution from CG flashes; the portion from the dashed line to the solid line corresponds to the contribution from IC flashes.

The global distributions of lightning-produced NO_x are illustrated in Fig. 2 for the four seasons in 1996. The data are plotted in megagrams of nitrogen produced per 1.0° by 1.0° grid box, which is normalized by the cosine of the latitude in each box. Shown in Fig. 3 is the seasonal latitudinal distribution of NO_x production. The plots result from the OTD lightning distributions and, consequently, are in agreement with the result that more lightning occurs in the northern hemispheric summer in areas where more land area exists. It has been observed that continental convection accounts for most of the lightning observed worldwide due to the increased updraft speeds (increased instability). This accelerates the charge transfer in the updraft (Zipser, 1994). Marine convection, although occurring throughout the year (especially in the Inter-Tropical Convergence Zone or ITCZ), yields little lightning over the central Atlantic and Pacific (Orville and Henderson, 1984; Goodman and Christian, 1993).

The seasonal global NO_x distribution shown in Fig. 2 indicates that NO_x production is maximized where solar radiation is maximized during a particular time of the year, consistent with the global lightning distributions (Christian and Latham, 1998). There is NO_x production at higher latitudes during the northern hemisphere summer, based on the OTD lightning observations in those locations. Throughout the year the oceans remain relatively free of lightning because of the weak convection over the ocean and, consequently, the NO_x production is low.

Fig. 3 shows the latitudinal distribution of NO_x production and the contributions from IC and CG flashes to the total production. The plotted values are sums of the NO_x production along each 1.0° latitude bin. It is apparent in this figure that the dominant production areas in a given month are (a) along the ITCZ, which, depending on the season, contributes NO_x production between 10°S and 10°N, and (b) over sub-tropical and mid-latitude continental regions if a warm season is present during the month of consideration. During the southern hemisphere summer (December, January, and February), the area between 40°S and the ITCZ dominates the NO_x production by lightning. This is due to high lightning activity in South America and southern Africa. During the

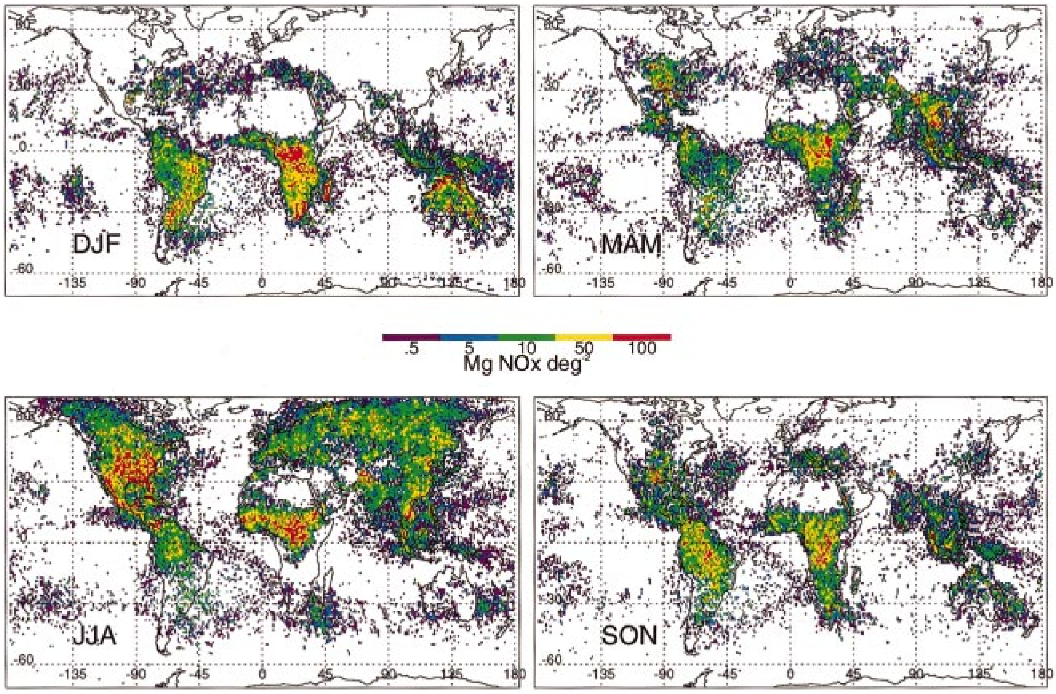

Fig. 2. Global distribution of lightning produced NO_x in the unit of Mg N per $1.0° \times 1.0°$ box, normalized to the area of an equatorial box by quarter.

northern hemisphere summer, the presence of land areas extending beyond 60°N latitude allows NO_x production rates to be significant near the Arctic Circle in June, July, and August. During the transition months from summer (winter) to winter (summer), NO_x production is largely equator-symmetric, with a slight bias towards more production in the Northern Hemisphere where more land areas receive solar radiation causing vigorous convection.

5. Discussion

Using the OTD lightning data and the partitioned IC/CG production rates, we estimate an average global lightning flash rate of 57 flashes per second and an annual lightning NO_x production of 0.9 Tg N year^{-1}. A study by Kumar et al. (1995) used the data from the ISS-b satellite to estimate lightning produced NO_x distributions. That satellite recorded lightning by the radio wave emissions, which has a lower lightning detection efficiency than the optical method used by the OTD (Kumar et al., 1995). Nevertheless, the latitudinal distribution of lightning NO_x production reported by Kumar et al. exhibits a similarity to that displayed in Fig. 3. The study by Kumar et al. (1995) estimated a lightning NO_x production rate of 2 Tg N year^{-1}, which is somewhat larger than the value presented in this study. Our seasonal and global distributions of NO_x production estimated from OTD data are also consistent with those reported by Price et al. (1997a, b), although our estimated annual NO_x production is lower than their value (about 12 Tg N year^{-1}). Recently, Wang et al. (1998) used global flash rates of 30 and 100 flashes per second to estimate annual NO_x production rates of 2.5 and 8.3 Tg N year^{-1}, respectively. Their flash rates encompass the flash rate observation derived in this study, but their lightning model assumes that all flashes are of the CG type. This accounts partially for their higher NO_x production estimate compared to our study. Also, Wang et al. (1998) used a tortuosity factor of 3.6, which appears to be larger than that

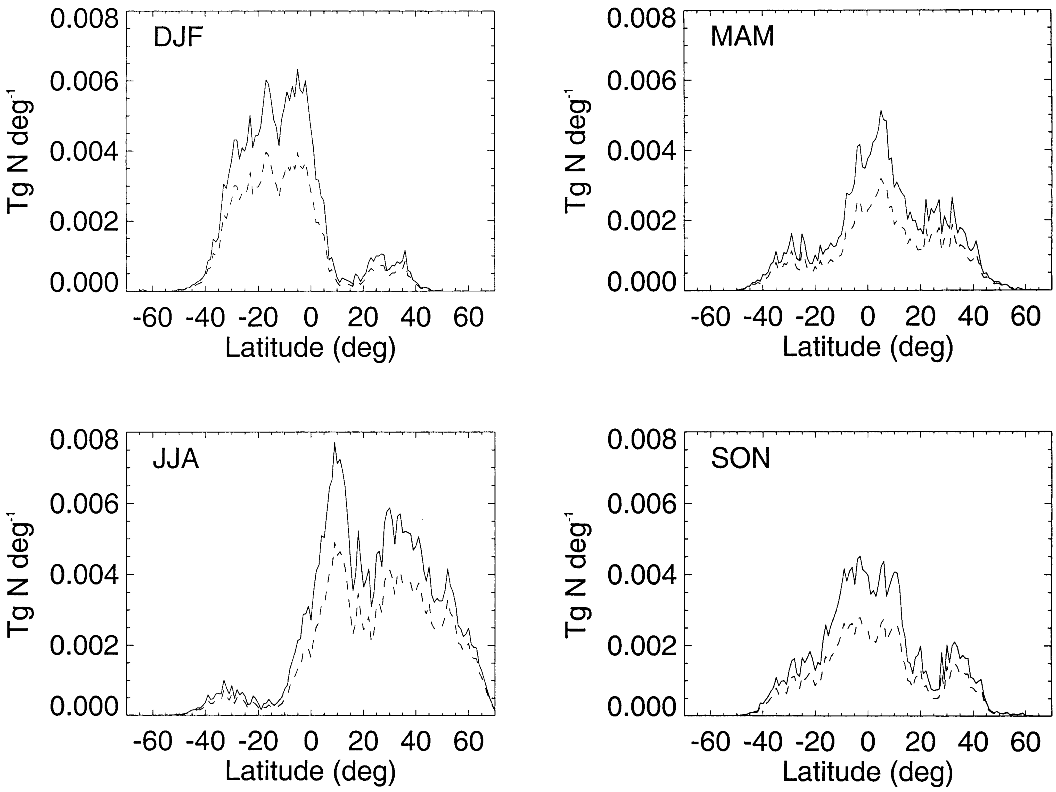

Fig. 3. Quarterly latitudinal distribution of lightning produced NO_x (presented in Tg N per 1.0°). Dashed lines indicate contribution from CG flashes; the portion from the dashed lines to the solid lines corresponds to the contribution from IC flashes.

measured in typical natural lightning occurring in Florida (Idone and Orville, 1988). The Florida tortuosity values, we realize, may not be representative of global values, but to our knowledge, are the only measurements available.

There are several uncertainties in the estimate of global NO_x production made in this study, due to uncertainties associated with the OTD detection efficiency, the IC/CG ratio, and the experimental data in the NO production per flash. For example, in this study we have adopted the laboratory data recently published by Wang et al. (1998) and calculated the NO production of 6.2×10^{25} and 8.7×10^{24} molecules for each CG and IC flash, respectively. This yields a global NO_x production rate of 0.9 Tg N year^{-1}. For the same OTD lightning data analyzed in our work, this value of the annual global NO_x production can vary considerably if values suggested in other literature for the NO production per flash are used. For example, Price et al. (1997a) estimate the production of 6.7×10^{26} and 6.7×10^{25} NO molecules for each CG and IC flash, respectively. Those values will lead to 6.6 Tg N year^{-1} for the CG flash and 2.3 Tg N year^{-1} for the IC flash, using our presently analyzed OTD data. The annual global production rate of 8.8 Tg N year^{-1}, therefore, is nearly an order of magnitude higher than that estimated using the data from Wang et al. (1998). In addition, we estimate an uncertainty of 50% for the OTD lightning data, when comparing our total flash number from OTD to those available in the literature (Christian et al., 1996; Mackerras et al., 1998). This results in an uncertainty of 50% in the annual global NO_x

production. For the IC/CG flash ratio, which has an uncertainty of 50% (Prentice and Mackerras, 1977; Mackerras et al., 1998), we estimate that the uncertainty in the global NO_x production would be about 35% due to this ratio. In addition, the lightning model we have adopted from Wang et al. (1998) is not very sensitive with respect to the estimate of the peak current value for the IC and CG flashes. For example, for an intracloud flash of 4 to 10 kA peak current, the NO production varies by less than 50%. Hence, the largest uncertainty in estimating the global NO_x distribution is associated with the estimate of the NO_x production by each lightning flash depending on the model used.

6. Conclusions

In this work, we have used the OTD lightning data to estimate the seasonal and global distributions of lightning-produced NO_x. The OTD data for the 12-month period of 1996 were analyzed to obtain the global and seasonal distributions of lightning and were partitioned between IC and CG flashes. The resulting global lightning distributions from OTD were then used to calculate the global and seasonal production of NO_x. NO_x production by lightning varies seasonally in accordance with the global lightning distribution, with the maximum production during the northern hemisphere summer. The latitudinal distribution of NO_x production also exhibits a seasonal variation with a maximum in the tropic region.

The OTD data are perhaps the best available satellite lightning measurements for the estimate of global NO_x production by lightning, and this paper represents the first attempt for such an application. The recent launch of the Lightning Imaging Sensor (LIS) aboard the Tropical Rainfall Measuring Mission (TRMM) satellite (Simpson et al., 1988) further improves the lightning detection due to its significantly improved flash detection efficiency, although the spatial coverage of the LIS is much smaller (35°S to 35°N) than that of the OTD. We are currently analyzing both OTD and LIS lightning data on a multiple year basis for better characterization of the global and seasonal lightning distributions.

Our study suggests that the largest uncertainty in estimating the global NO_x production using the satellite lightning data is associated with the estimation of the amount of NO production by lightning flashes, which should be better defined by further laboratory, theoretical, and field studies. Also, the implementation of a geostationary lightning detection device will allow a quasi-constant hemispheric view of lightning flash rates for improved quantification of global distribution of lightning.

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