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NO_x from lightning
2. Constraints from the global atmospheric electric circuit

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Abstract. The global atmospheric electric circuit can be used to constrain the total amount of NO_x produced by lightning (LNO_x). Since the global atmospheric electric circuit is regulated by global thunderstorm activity and, more specifically, global lightning currents, we use the global electric circuit to quantify and place limits on the total amount of energy available from lightning. Using a production rate of 10×10^{16} molecules NO/J, we have calculated the global LNO_x production on monthly, annual, and interannual timescales from 1983 to 1991. The 8-year mean production rate is found to be 13.2 Tg N/yr and agrees with the independent estimate derived in part 1 of this study (12.2 Tg N/yr), which is based on lightning physics and global lightning distributions. After considering the various uncertainties in these calculations, we conclude that the annual production rate of NO_x from lightning cannot be less than 5 nor more than 25 Tg N/yr.

1. Introduction

Nitrogen oxides (NO_x = NO + NO_2) in the troposphere play an important role in tropospheric chemistry, mainly through the production of tropospheric ozone [*Kroening and Ney*, 1962; *Crutzen*, 1970] and the regulation of OH concentrations [*Levy*, 1971; *Logan et al.*, 1981]. However, the relative importance of different sources of NO_x to the global budget is still highly uncertain, especially in regions adjacent to anthropogenic emissions of NO_x, although lightning and stratospheric injections appear to dominate remote regions. This paper uses the global atmospheric electric circuit to place limits on the amount of NO_x produced by lightning (LNO_x). This independent approach corroborates the first part of this study (*Price et al.* [this issue], hereinafter referred to as PPP1) in which we used lightning physics together with estimations of global lightning activity [*Price and Rind*, 1992, 1993] to calculate the production rate of lightning-produced NO_x (LNO_x) as a function of latitude, longitude, day, month, and year.

Previous studies of LNO_x concentrated mainly on determining the contribution of lightning to the global NO_x budget [*Noxon*, 1976; *Tuck*, 1976; *Chameides et al.*, 1977; *Levine et al.*, 1981; *Dawson*, 1980; *Hill et al.*, 1980; *Drapcho et al.*, 1982; *Peyrous and Lapeyre*, 1982; *Borucki and Chameides*, 1984; *Bhetonabhotla et al.*, 1985; *Franzblau and Popp*, 1989; *Liaw et al.*, 1990; *Sisterton and Liaw*, 1990]. These estimates used theoretical calculations, laboratory measurements, and field observations to extrapolate the amount of NO produced in a single stroke to a global mean rate, by typically using 100 flashes per second. Resulting LNO_x production rates vary by 2 orders of magnitude, from 1 Tg N/yr [*Levine et al.*, 1981] to 100 Tg N/yr [*Franzblau and Popp*, 1989] [Tg = 10^{12} g].

In this paper we introduce an entirely new approach to calculate this global value by using the Earth's global atmospheric electric circuit. The global electric circuit is regulated by thunderstorm activity and, more specifically, by lightning activity around the world. By using the global electric circuit to place an upper limit on the energy of global cloud-to-ground (CG) lightning, we can then place an upper limit on the NO_x production.

Section 2 discusses the general principles of the global atmospheric electric circuit. The globally integrated energy resulting from lightning is derived. In section 3 we discuss NO_x chemistry and present the global production rate of LNO_x on monthly, annual, and interannual timescales. In section 4 we discuss the uncertainties in this study and present our conclusions.

2. Global Atmospheric Electric Circuit

It is well known that thunderstorms are electrified, but it is less well known that the fair weather atmosphere is also electrified. In 1752, Lemonnier discovered that the air above the Earth had a persistent electrical field which, in fair weather conditions, is directed downward and has an average magnitude of 130 V/m [*Wormell*, 1953; *Chalmers*, 1967; *Israel*, 1971]. Because the permittivity of free space (ε_0) is 8.85×10^{-12} F/m, the charge on the Earth, as a result of this constant field, can be calculated.

$$Q = \varepsilon_0 V = 8.85 \times 10^{-12} \times 130 = 1.15 \times 10^{-9}\ \mathrm{C/m^2} \qquad (1)$$

which implies the Earth's surface has a total negative charge of 5.9×10^5 C. Because pure, neutral air at STP has a resistance of $5 \times 10^{13}\ \Omega$, which is an excellent insulator, it was originally believed that this charge was a permanent static feature of the Earth system. However, in 1887, Linss discovered that the atmosphere had a slight conductivity due to ions in the atmo-

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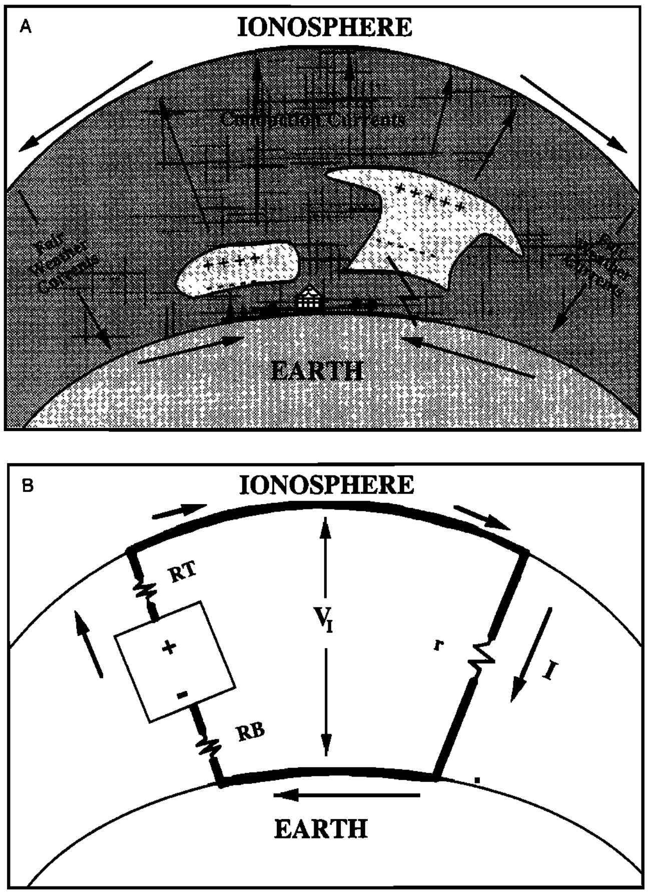

Figure 1. (a) Schematic representation of the currents flowing in the global atmospheric electric circuit. (b) Equivalent electric circuit showing the resistances in the circuit, the direction of the current and the power source.

sphere. This resulted in measurements of a fair weather atmospheric current of approximately 2×10^{-12} A/m^2 (1000 A globally) flowing from the atmosphere to the Earth's surface. This discovery resulted in a simple calculation indicating how long the Earth could maintain its negative charge.

$$t = \frac{Q}{I} = \frac{5.9 \times 10^5}{1000} = 590 \text{ s} = 9.8 \text{ min} \qquad (2)$$

Therefore in less than 10 min the Earth should lose its charge. Since this is obviously not the case, scientists proposed that there must be a generator that continuously replenishes the charge on the Earth's surface. *Wilson* [1920] was the first to suggest that the generator of this charge was related to global thunderstorm activity. A decade later, *Whipple* [1929] demonstrated that the diurnal fluctuations in the Earth's surface potential gradient observed over the oceans were well correlated with diurnal fluctuations in global thunderstorm activity.

With the discovery of the ionosphere in the 1920s the description of the global electric circuit started taking shape. The overall picture is that of a spherical capacitor formed by a conducting Earth, a conducting upper atmosphere, and a leaky dielectric in between [*Israel*, 1971] (Figure 1). Currents are generated in regions of thunderstorms and electrified clouds. The currents above thunderstorms flow upward toward the ionosphere. At altitudes of approximately 60 km the ionosphere is regarded to be an equipotential surface, since at these altitudes the conductivity is so large that potential gradients are very small [*Israel*, 1971]. Therefore the currents flowing upward to the ionosphere from above thunderstorms spread globally in the upper atmosphere and return to the Earth in regions of fair weather (Figure 1a). The equivalent electric circuit is shown in Figure 1b, where global thunderstorms represent the battery in the circuit. To prove that this atmospheric electric circuit is truly global, measurements of the air-Earth current and the potential gradient at the Earth's surface have been made simultaneously at different locations around the globe, and the agreement with each other is quite remarkable [*Muhleisen*, 1971; *Markson*, 1985].

It is important to realize that the energetic lightning strokes producing NO are only one fraction of the current in the global circuit. Thus knowledge of the electric circuit provides a strict upper limit to NO production. This paper endeavors to calculate that fraction of the current I in lightning strokes and hence an independent estimate of LNO_x production.

Atmospheric Currents

It is now well known that under fair weather conditions the mean current density at the Earth's surface is approximately 2×10^{-12} A/m^2, or 1000 A integrated over the globe [*Chalmers*, 1967; *Israel*, 1971; *Roble and Tzur*, 1986]. This fair weather conduction current is controlled by the intensity of electric currents generated in regions of thunderstorm activity (Figure 1a). The conduction current above individual thunderstorms is estimated to be of the order 1 A [*Blakeslee et al.*, 1989]. There are two main contributors to the global atmospheric currents: (1) cloud-to-ground lightning that brings primarily negative charge from the cloud to the ground and (2) point discharge or corona currents from pointed objects such as trees and buildings below electrified clouds. Point discharge occurs when electric fields of the order of kilovolts per meter at the surface below clouds result in exposed pointed objects going into corona. This implies that the local field near a conducting point reaches values necessary for ionization by collisions to occur. When the point is positively charged (in a negative potential gradient), as is the case underneath thunderstorms, electrons move toward the point and positive ions away. Therefore point discharge currents under thunderstorms further contribute to the negative charge of the Earth's surface.

Lightning Currents

To calculate the contribution of cloud-to-ground (CG) lightning to the global electric circuit, one needs to know the frequency of global CG strikes and how much charge is deposited on the Earth per flash ($I = Q/t$). Since no global data sets of CG flash frequencies exist, a method has been developed to approximate global CG lightning distributions and frequencies using readily available satellite cloud data [*Price and Rind*, 1992, 1993; PPP1]. This method uses two parameterizations to calculate both total lightning frequencies and the fraction of the total lightning that is cloud to ground (see PPP1). The method utilizes global cloud data sets provided by the International Satellite Cloud Climatology Project (ISCCP) [*Rossow and Schiffer*, 1991]. The global distribution of lightning using this method is shown in our accompanying paper (PPP1, Plate 1). Using observed cloud data for the months of January and July 1988, the global mean simulated CG lightning frequencies for these months are 19 and 30 flashes/s, respectively. The intracloud lightning frequencies for these months are 52 and 71 flashes/s, implying that CG flashes make up approximately one third of the total global lightning frequencies.

It should be noted that intracloud (IC) flashes do not contribute to the currents in the global electric circuit. The IC flashes just tend to short-circuit the "batteries" in the circuit (see Figure 1b). However, intracloud flashes have much lower energies than CG flashes [*Holmes et al.*, 1971; *Kowalczyk and Bauer*, 1981; *Sisterton and Liaw*, 1990; PPP1], and therefore it is mainly the CG flashes that contribute to the NO_x production. The contribution of IC flashes to the NO_x budget are addressed later. This difference between CG and IC flashes has been overlooked by most previous researchers (see PPP1).

The mean charge deposited by a CG flash is an uncertain quantity. This quantity is normally derived by integrating over the current pulse ($Q = \int I\,dt$). In PPP1 it is shown how to theoretically calculate the charge Q, and expressions relating Q to the peak currents in CG return strokes were obtained. The charge deposited depends strongly on whether the flash has a return stroke with a continuing current component, which is a long period of low-intensity current flow. Between 40 and 50% of negative CG flashes have a continuing current component [*Kitagawa et al.*, 1962; *Brook et al.*, 1962; *Livingston and Krider*, 1978]. Following PPP1 the return strokes with continuing currents have an additional 22.5 C of charge transferred through the lightning channel. We assume a mean value of three strokes per negative flash, with 45% of them having a return stroke with a continuing current component. Hence for a negative flash

$$Q_- = 0.65(Q_1 + 2Q_s) + 0.45(Q_1 + 2Q_s + 22.5) \quad (3)$$

where Q_1 and Q_s are the charges deposited by the first and subsequent return strokes. For the observed mean peak current of 35 kA, $Q_1 = 11.1$ C, and $Q_s = 5$ C (PPP1). Therefore Q_- is taken to have a value of 33.3 C, in agreement with previously published observations [*Cianos and Pierce*, 1972; *Uman*, 1987]. It should be noted that positive CG flashes (primarily from high-altitude anvils to the ground) result in a net decrease in the fair weather current since positive flashes result in positive charge being deposited on the Earth's surface, opposite to negative flashes. Although studies show that positive lightning makes up only a few percent of the total CG lightning [*Orville*, 1994; PPP1], observations in the tropics indicate that the ratio may be as high as 10% [*Petersen and Rutledge*, 1992]. We adopt a global mean value of 5% for the fraction of positive CG lightning occurring around the globe. Even though positive discharges generally transfer larger amounts of charge to the Earth per stroke, we found 87% of positive flashes have only one return stroke (PPP1) with the remaining 13% having a total of two return strokes. Using a mean peak current of 61.4 kA for positive flashes, $Q_1 = 19.2$ C and $Q_s = 8.5$ C (PPP1), while a charge transfer of 22.5 C is assumed during the continuing current phase. The majority of positive flashes have a continuing curent portion [*Uman*, 1987]. Hence

$$Q_+ = 0.87(Q_1 + 22.5) + 0.13(Q_1 + Q_s + 22.5) \quad (4)$$

which is equal to 42.8 C for the above parameters. It is now possible to calculate the contribution of all CG lightning to the global electric circuit.

$$I = \frac{Q}{t} = Q_- f_- - Q_+ f_+ \quad (5)$$

The currents (I_L) for January and July 1988 are shown in Table 1 and include the contribution from the continuing current portion of the return stroke. However, for NO_x production the low-intensity continuing current portion of the return stroke is not of interest (see PPP1). Furthermore, since positive flashes also produce NO_x, we now need to add the absolute currents for the calculation of the NO_x production. Therefore the relevant global currents are $I_L^* = Q_-^* f_- + Q_+^* f_+$ where $Q_-^* = Q_1 + 2Q_s = 21.1$ C, and $Q_+^* = 0.87Q_1 + 0.13(Q_1 + Q_2) = 20.3$ C (Table 1).

Table 1. Values of different parameters used in calculating the NO_x production by lightning during January and July 1988. See text for definition of parameters.

Parameter	January 1988	July 1988
I_L, A	560	885
I_L^*, A	402	632
I_{PD}, A	473	502
I, A	1033	1387
R_T, Ω	2.782×10^5	1.797×10^5
R_B, Ω	6.586×10^5	4.974×10^5
R, Ω	9.37×10^5	6.773×10^5
V_I, kV	258	347
E_{CG}, J/s	1.514×10^{11}	2.705×10^{11}
$\mathbf{E}_{CG}$, J	7.97×10^9	9.02×10^9
E_{tot}, J/s	1.929×10^{11}	3.346×10^{11}
G, Tg N/yr	1.2	2.1

Point Discharge Currents

The point discharge current (I_{PD}) has been studied extensively by *Standler and Winn* [1979]. They estimated that when the electric field exceeds a few kilovolts per meter at the surface, point discharge is initiated resulting in an observed mean current of 10^{-9} A/m^2 below electrified clouds. Evidence exists that nonthunderstorm clouds can also be electrified, especially nimbostratus and stratus clouds [*Dvali*, 1959; *Chalmers*, 1967]. It also appears that often these clouds have similar charge structure in the clouds, resulting in negative charge near the base of the clouds and positive charge centers near the tops (Figure 1a). Very little data are available on electrified nonthunderstorm clouds. However, because of the long life and large areas covered by these clouds, they could potentially play a significant role in the overall point discharge currents that constitute the fair weather current. Although not an important source of NO_x, it is essential to consider this source of current in the global electric circuit. *Jacobson and Krider* [1978] have shown that as a result of objects on the Earth's surface going into corona, the electric field cannot increase above 10 kV/m. In fact, the point discharge current is more dependent on surface characteristics than the electric fields below cloud base. For this reason the point discharge currents below stratiform clouds are assumed to be of similar magnitude to those below deep convective thunderstorms. Although the point discharge current can be highly variable, depending on the surface type, we assume a mean global value of 10^{-9} A/m^2 under all electrified clouds [*Standler and Winn*, 1979].

To calculate the contribution of point discharge to the global currents, we need to know what area of the Earth is covered by electrified clouds. Since both deep convective clouds and low stratiform clouds (stratus and nimbostratus) are assumed to be electrified and therefore contribute to the currents flowing in the atmosphere (Figure 1a), we need to consider the area coverage of both cloud types. To establish the area coverage of electrified clouds, we analyzed global cloud data from the

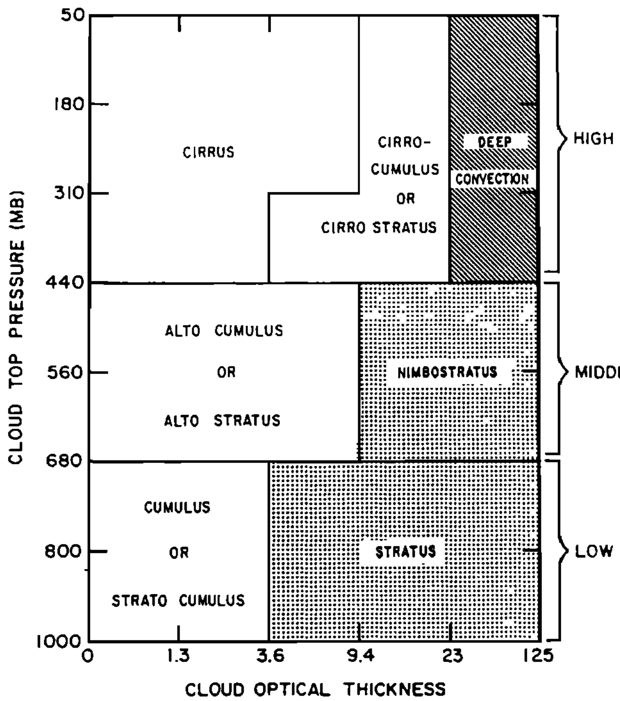

Figure 2. International Satellite Cloud Climatology Project cloud classification according to cloud top pressure and cloud optical depth. Lightning is assumed to occur only in deep convective clouds, while point discharge currents are assumed to be generated under all electrified clouds (shaded).

ISCCP data set mentioned above. The global cloud data set has a spatial resolution of approximately 5 km with global maps available 8 times per day from July 1983 to June 1991. Each 5-km pixel is described by two parameters: cloud top pressure (height) and cloud optical depth. Using these two parameters, one can differentiate between various types of clouds. However, because of uncertainties in determining cloud type at high latitudes (high solar zenith angle) the cloud data are ignored when the solar zenith angle is greater than 85°. This usually occurs at high latitudes in the winter hemisphere. The deep convective and stratiform clouds used in this paper are defined by their optical depths and altitudes in the atmosphere and are indicated by the shaded regions in Figure 2. It should be noted that over the oceans, very little lightning is observed [*Orville and Henderson*, 1986] and very little point discharge is expected [*Toland and Vonnegut*, 1977] due to the relatively smooth surface characteristics. Therefore only clouds over continental regions are considered to contribute point discharge currents to the global electric circuit. Furthermore, since visible radiances are used to obtain optical depth values to identify cloud type, this study considers only clouds during daylight hours. However, *Olapido and Mornu* [1985] have shown that over a 14-year period, tropical lightning activity in Nigeria is equally distributed between day and night. This also appears to be the situation in Darwin, Australia [*Williams and Heckman*, 1993].

The mean area coverage of continental deep convective clouds during January and July 1988 is 0.87×10^5 km^2 (January) and 1.15×10^5 km^2 (July), while for low stratiform clouds the area coverage is 3.86×10^5 km^2 (January) and 3.87×10^5 km^2 (July). The total area coverage of continental electrified clouds is therefore 4.73×10^5 km^2 (January) and 5.02×10^5 km^2 (July). Hence the global point discharge currents (I_{PD}) can be estimated (Table 1). This results in a total global circuit current ($I = I_L + I_{PD}$) of 1033 A during January 1988 and 1387 A during July 1988 (Table 1). These two values of conduction current generated in regions of storm activity represent a current density in the fair weather regions of the world of 2.03×10^{-12} A/m^2 (January 1988) and 2.72×10^{-12} A/m^2 (July 1988), in excellent agreement with observed values [*Chalmers*, 1967; *Israel*, 1971; *Roble and Tzur*, 1986]. It should be pointed out that the area coverage of low stratiform clouds may well be underestimated using the satellite observations due to overlapping of cloud layers in the atmosphere.

Atmospheric Conductivity

The electrical conductivity of the atmosphere was first established by Linss in 1887. The conductivity is proportional to the number and mobility of ions, the mobility being defined as the velocity an ion would have in a field of 1 V/cm. Small ions, consisting of clusters of 10–30 molecules [*Israel*, 1971], have mobilities a few orders of magnitude larger than intermediate and large ions. For this reason the conductivity of the atmosphere is determined mainly by the concentration of small ions. The major source of ionization that maintains the electrical conductivity of the atmosphere below 60 km is cosmic radiation. For this reason the conductivity increases exponentially with altitude from the surface values of 10^{-14} mho/m to values of 10^{-10} mho/m at 60 km [*Israel*, 1971; *Volland*, 1982; *Makino and Ogawa*, 1984].

The columnar resistance (R_c) is defined as the resistance of a column of air of 1 m^2 cross section between two altitudes.

$$R_c = \int_{h_0}^{h_1} \frac{1}{\Lambda(z)}\, dz \qquad (6)$$

where $\Lambda(z)$ is the vertical profile of conductivity. The best fit to observations is obtained using an expression of the form

$$\frac{1}{\Lambda(z)} = \rho_1 e^{-\alpha_1 z} + \rho_2 e^{-\alpha_2 z} + \rho_3 e^{-\alpha_3 z} \qquad (7)$$

The values for α_1, α_2, and α_3 were first determined by *Gish* [1944] to be 4.527×10^{-3} m^{-1}, 3.75×10^{-4} m^{-1}, and 1.21×10^{-4} m^{-1}, respectively. The values for ρ_1, ρ_2, and ρ_3 differ in magnitude for different studies [*Gish*, 1944; *Israel*, 1971; *Volland*, 1984]. We use values of 5.17×10^{13} Ωm^2, 2.44×10^{13} Ωm^2, and 0.65×10^{13} Ωm^2, respectively, resulting in the global mean columnar resistance of the atmosphere between the surface and 60 km being approximately 1.3×10^{17} Ωm^2 [*Gish*, 1944; *Israel*, 1971; *Markson*, 1978; *Volland*, 1982, 1984; *Gringel et al.*, 1986; *Roble and Tzur*, 1986]. The columnar resistance does vary depending on location, season, and cosmic ray flux; however, since we are interested in the globally integrated mean value, the average value of 1.3×10^{17} Ωm^2 will be used. This corresponds to a global atmospheric resistance of approximately 250 Ω.

The global electric circuit can be represented by an equivalent electric circuit as shown in Figure 1b. The resistors in the circuit are represented by the resistance R_B of the air below cloud base, resistance R_T of the air above cloud top, and the fair weather resistance r between the ionosphere and the Earth's surface. Although point discharge currents contribute to the fair weather currents in the global electric circuit, only the lightning currents result in the high temperatures needed for NO_x production. If we assume the cloud base to occur at approximately 2 km, then by integrating (6), the columnar resistance between the surface and 2 km (R_B) is found to represent approximately 44% of the total columnar resistance and has a value of 5.73×10^{16} Ωm^2. The ISCCP data give the mean cloud top heights for deep convective clouds, which for January (July) 1988 is 7.8 km (8.8 km). Therefore the columnar resistance above these clouds (R_T) is 2.42×10^{16} Ωm^2 (2.07×10^{16} Ωm^2), representing 19% (16%) of the total columnar resistance.

In Figure 1b each thunderstorm represents an electric battery of potential 10^8–10^9 V [*Uman*, 1987], while R_B and R_T represent the sum of the resistances from all the individual storms around the globe. Since these storms are in parallel around the globe,

$$\frac{1}{R_{B,T}} = \sum_{i=1}^{n} \frac{1}{r_{B,T_i}} \qquad (8)$$

where r_{B,T_i} is the resistance below/above storm i.

Using the values for the area coverage of deep convective clouds only, we can now calculate the actual resistances in the global circuit resulting from thunderstorms. Once again we should point out that primarily continental clouds contribute to the global electric circuit. Very little lightning and point discharge occurs over the oceans. Assuming that deep convective clouds over continental regions have cloud bases at approximately 2 km, the columnar resistance above and below these clouds can be calculated (Table 1). These calculated values of R_B and R_T are well within the limits proposed by *Markson* [1978]. The resistance of the atmosphere in the fair weather regions of the Earth (r) is approximately 250 Ω, resulting in the total resistance ($R = r + R_T + R_B$) of the global electric circuit (Figure 1b) shown in Table 1.

Given the above value of r and the previously calculated values of the conduction currents, we can also calculate the potential between the ionosphere and the Earth's surface (Figure 1b), known as the ionospheric potential (V_I) (Table 1).

$$V_I = Ir \qquad (9)$$

These values of the ionospheric potential agree well with observed values [*Markson*, 1976; *Muhleisen*, 1977; *Markson*, 1978]. To demonstrate the ability of our model using ISCCP cloud data to predict the fair weather current (I) and hence the ionospheric potential (V_I), three comparisons with actual V_I observations (R. Markson, personal communication, 1992) were made (Figure 3). The fluctuations in the predicted daily mean values of V_I are shown by the solid curve for the months of March 1986, May 1987, and September 1990. The available observed V_I data points are shown for the same period. It should be noted that the observations are taken at a specific time during the day and do not represent daily mean values. In fact, the diurnal variability (universal time) of V_I can be quite large, because of the diurnal variability of global thunderstorm activity. For example, on September 20, 1990, at 0310 UT the observed V_I was 170 kV, while at 2100 UT on the same day the observed V_I was 309 kV. Had the daily mean values of V_I been available, we would have expected a better agreement with the data points. Since our model uses optical depth values to determine different cloud types, the model can only predict V_I during daylight hours when optical depth values can be calculated from the visible radiances observed by the satellites.

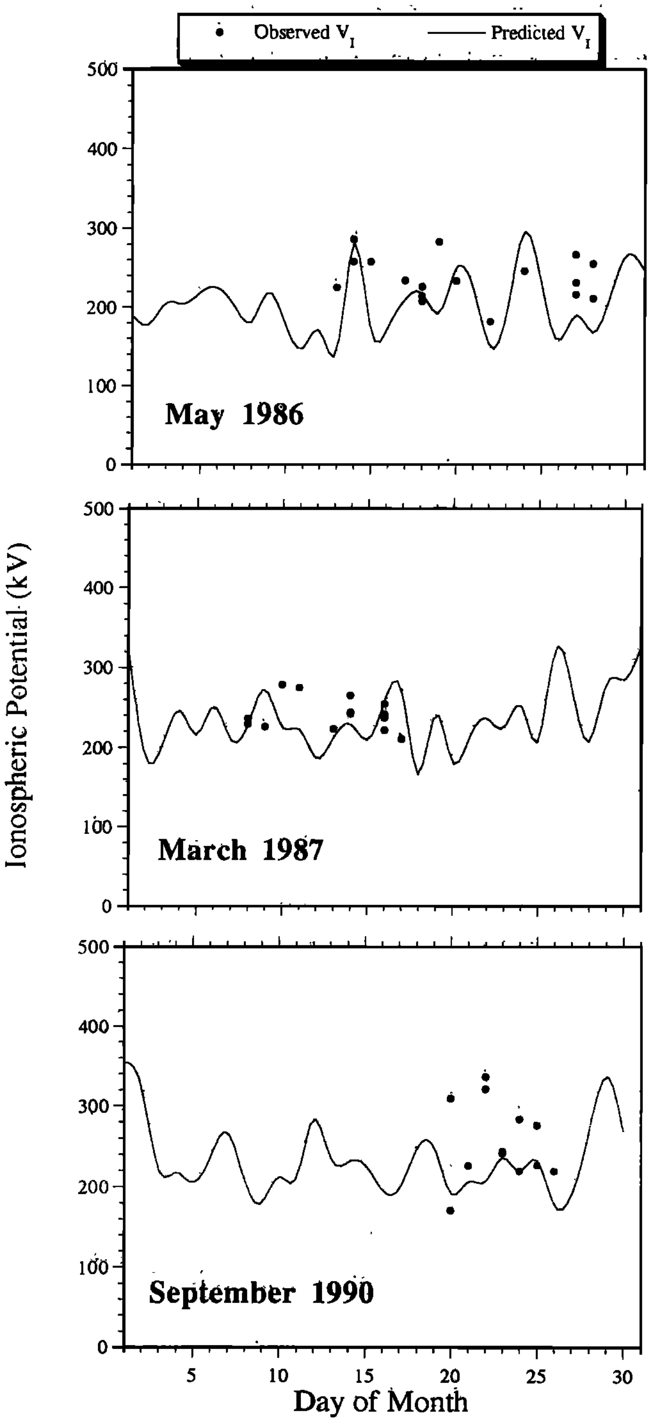

Figure 3. Modeled daytime ionospheric potential (V_I) compared with observed ionospheric potential during three different months (May 1986, March 1987, and September 1990).

Therefore at present we cannot use our model to predict V_I for a specific universal time during the diurnal cycle, since at any one time during the day, part of the globe is in darkness, and hence no ISCCP cloud data are available from that region. It may be possible to perform a more rigorous test for the predictability of this model against V_I if we can estimate the nighttime distribution of electrified clouds. In addition, the predicted V_I values are calculated using a constant value of the fair weather atmospheric resistance (250 Ω). This value varies with season, solar activity, aerosol loading, and time of day. It

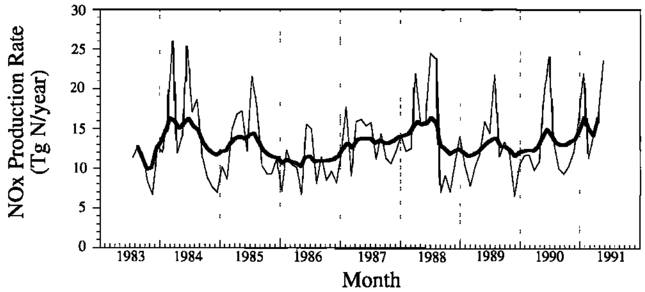

Figure 4. Monthly fluctuations in global LNO_x production from July 1983 to June 1991. The bold smoothed curve indicates the annual and interannual variability in the data.

is very likely that on the specific day the observations of V_I were made, the resistivity of the atmosphere was not 250 Ω. In fact, *Muhleisen* [1977] and *Roble and Tzur* [1986] both use a value of 230 Ω, while *Markson* [1978] used a mean value of 150 Ω and *Roble* [1991] uses a mean value of 300 Ω. The lack of fit can be explained by the variability of the atmospheric resistivity.

The largest potential error in the V_I model results from the estimation of the area covered by nonthunderstorm electrified clouds that contribute to the point discharge current. We used the cloud types arbitrarily defined by their cloud top heights and their optical depths (Figure 2). Considering this uncertainty, it is actually quite remarkable how well the model agrees with the observations. Finally, the predicted V_I values do appear to be reproducing the variability found in the observed V_I data.

Energy

Although, ideally, we would like to calculate the energy from lightning using the lightning channel currents and conductivity (resistance), these parameters are very poorly known. In particular, the conductivity of a lightning channel can vary by 11 orders of magnitude during the first 5 μs of the discharge [*Yos*, 1963; *Uman and Voshall*, 1968; PPP1], which is a critical period for the NO_x production. For this reason we prefer to use the fair weather current and resistivity to infer the energy available from global lightning for the production of NO_x. The energy produced per unit time by CG discharges (Table 1) is simply given by

$$E_{CG} = (I_L^*)^2 R \qquad (10)$$

For the production of NO_x we are only concerned with the currents in the global electric circuit resulting from cloud-to-ground lightning, since point discharge does not appear to be important in the production of NO_x [*Sisterson and Liaw*, 1990]. Furthermore, we are only interested in the lightning current (I_L^*) that does not contain the low-intensity continuing current (see PPP1).

As mentioned previously, the lightning currents flowing in the global electric circuit are from CG discharges only. However, intracloud (IC) flashes also contribute to the total NO_x produced by lightning. As discussed in PPP1, IC flashes are assumed on average to have only 10% of the energy found in CG flashes. The average energy per CG flash ($\mathbf{E}_{CG} = E_{CG}/f$) is shown in Table 1. Therefore the total energy available from both cloud-to-ground and intracloud flashes can be calculated (Table 1).

$$E_{tot} = \mathbf{E}_{CG} \cdot f_{CG} + \mathbf{E}_{IC} \cdot f_{IC} = \mathbf{E}_{CG} \cdot f_{CG} + 0.1\mathbf{E}_{CG} \cdot f_{IC} = \mathbf{E}_{CG}(f_{CG} + 0.1 f_{IC}) \qquad (11)$$

3. Global Production of Lightning NO_x

As discussed in PPP1, we have adopted a mean value of 10 ± 5 × 10^{16} molecules NO/J for the production rate of NO_x. This estimate needs to be better quantified in future studies to reduce its uncertainty. However, using the mean value of P, 10 × 10^{16} molecules NO/J, we can now estimate global NO_x production (G) resulting from lightning using the formula

$$G = E_{tot} \cdot t \cdot P \cdot C \qquad (12)$$

where E_{tot} is the total energy available for the production of NO_x (J/s), t is the period of interest (s), P is the production rate (molecules NO/J), and C is a conversion constant equal to (14 g/mole)/(6.02 × 10^{23} molecules/mole) or 2.33 × 10^{-23} g/molecule. For January and July 1988 the monthly production rate of NO_x is 1.2 and 2.1 Tg N/month (Table 1), equivalent to an annual production rate of 14 Tg N/yr (January) and 24.6 Tg N/yr (July). As expected, the higher total available energy during July 1988 results in more NO_x being produced during July compared with January. In comparison, the production rates found using the method in PPP1 gave 12 Tg N/yr (January) and 18 Tg N/yr (July). Reasons for these differences will be discussed below.

Following the same procedure described above we have calculated the production rate of NO_x for all months during the 8 years of ISCCP data (1983–1991) (Figure 4). The monthly variability is shown together with a smoothed curve to indicate both seasonal and interannual variability in the NO_x production. On a monthly timescale the production rates vary between 5 and 25 Tg N/yr. Generally, the annual cycle shows maximum NO_x production during the northern hemisphere summer. The minimum lightning frequencies and hence NO_x production occur during 1986, which could possibly be related to the fact that 1986 was an El Niño year, when global circulation patterns and possibly thunderstorm patterns show large deviations from their climatological values. This interannual variability in lightning NO_x should directly impact tropospheric ozone since LNO_x is likely to be a major source of O_3 in remote regions (PPP1). Thus 1986 and similar El Niño/Southern Oscillation years may have lower than normal tropospheric ozone.

Figure 4 should be compared with the equivalent figure from PPP1 (Figure 6). Although the mean annual values appear to be fairly similar in the two studies, the annual and interannual fluctuations are larger in this study using the global electric circuit. In the present study (PPP2) there are more free parameters that are allowed to vary from day to day and month to month. In PPP1 the total energy is calculated using $E = QV$ where V is constant throughout the study and Q is allowed to vary. Here the energy is calculated using $E = I^2R$ where both I and R can vary according to the frequency of lightning and the area covered by electrified clouds. Furthermore, the energy is proportional to I^2, whereas in PPP1 the energy is a linear function of the current I. It is therefore understandable that the method presented here would show larger variability compared with the method in PPP1.

By summing up the contribution from each month, we obtain the annual production rate for the seven complete years of the ISCCP data (Table 2). The annual mean production rates vary from 10.3 to 14.7 Tg N/yr with a global mean annual production rate of 13.2 Tg N/yr. Once again the range in these values is larger than those obtained in PPP1, as explained above. However, the annual mean value for the eight years is in excellent agreement with that found using the method in PPP1 (12.2 Tg N/yr).

Table 2. Annual production of LNO_x from 1984 to 1990

	1984	1985	1986	1987	1988	1989	1990	Mean
NO_x production, Tg N/yr	14.7	13.3	10.3	13.5	14.6	12.5	12.8	13.2

4. Discussion and Conclusions

In this study we use the global atmospheric electric circuit to estimate the total available energy from lightning for the production of NO_x. The lightning currents flowing in the global electric circuit are generated only by cloud-to-ground (CG) lightning. However, as discussed in part 1 of this study (PPP1), we have shown that intracloud (IC) lightning has only 1/10 the energy of CG lightning and therefore does not contribute significantly to the NO_x production. Nevertheless, we have included the contribution of IC flashes to the NO_x production in our calculations.

To calculate the energy available from lightning using the global electric circuit, it is necessary to calculate the lightning currents and the global resistances in the global electric circuit ($E = I^2R$). To do this, we needed to calculate the global frequency of CG lightning and the global area coverage of thunderstorms, which were done using the ISCCP cloud data sets. When the total energy deposited in CG strokes was derived, we applied a mean NO_x production rate (10×10^{16} molecules NO/J) to calculate the global NO_x production on monthly, annual, and interannual timescales. The annual cycle appears to maximize in the northern hemisphere summer, with 1986 (an El Niño year) indicating below-average NO_x production. The annual mean production rate was found to be 13.2 Tg N/yr, with a range of 10.3–14.7 Tg N/yr.

The production rate of 13.2 Tg N/yr is in reasonable agreement with many previous studies; however, we believe this is purely fortuitous. Many of the previous studies have made two incorrect assumptions that tend to cancel each other. First, the energy per flash in previous studies has been underestimated (see PPP1), possibly because of the fact that often the total energy in a lightning flash is derived from the optical energy that represents less than 1% of the total energy [*Borucki and Chameides*, 1984]. Second, the global frequency of NO_x-producing flashes has been overestimated in previous studies. Although there appear to be of the order of 100 flashes per second around the globe, 70% of these flashes are intracloud discharges, each with possibly 10% of the NO_x-producing power of CG flashes. These two negating effects appear to have resulted in previous studies arriving at global estimates of LNO_x production similar to the values obtained in this study.

There are a number of other possible sources of uncertainty in our study which need to be identified. Although the global calculations of lightning frequencies using the ISCCP data have been shown to be in good agreement with observations [*Price and Rind*, 1992], there are problems with the available observations of global lightning used for verification. The detection efficiencies of the satellite-based sensors are uncertain [*Turman and Edgar*, 1982], and the observations are made at only a few specific local times during the day [*Orville and Henderson*, 1986]. It is therefore difficult to know with certainty how well we are simulating global lightning distributions.

There is great need for better global lightning data. In particular, the differentiation between CG and IC flashes needs to be further studied. The relationship used to derive the fraction of cloud-to-ground lightning in a thunderstorm may need refining in the future as more lightning data become available. Because of the difference in energies of CG and IC flashes it is important to determine the fraction of global lightning that is intracloud. The energy of IC flashes is assumed to be only 1/10 that of CG flashes. More work needs to be done on intracloud discharges to determine how important they are in producing NO_x.

All the empirical relationships used in the global simulations of lightning presented in this paper were derived using lightning data mainly from the United States. These relationships may be different in other regions of the globe. In addition, to calculate the current flowing in the global circuit as a result of CG lightning, we had to derive a mean value for the charge deposited in a lightning flash. On the basis of observations in the United States we arrived at a value of 33 C for a negative flash and a value of 43 C for a positive flash. These values may also not be globally representative, even though they agree with observations from other locations around the globe.

For the NO_x calculation using the global circuit, we also needed to know the area of thunderstorms around the globe. This information is obtained from the ISCCP data products, which has an arbitrary definition of deep convective clouds based on cloud top pressure and cloud optical depth. Changes in this definition could result in changes in the total area covered by thunderstorms as defined by the ISCCP data set. This would result in a change in the resistances calculated in the global electric circuit, hence influencing the total energy assumed to go into LNO_x production.

The primary remaining uncertainty is the production rate of NO_x per unit energy. In this paper we have not tried to improve this estimate, which is rather uncertain. The production rate may vary with altitude along the lightning channel, energy density, and atmospheric water vapor content, and it is not clear how the production rate may vary as the total energy changes. Is the production of NO_x linearly related to the energy? Would inclusion of water vapor in the theoretical and laboratory measurements result in significant enhancements of NO production [*Peyrous and Lapeyre*, 1982]? Is the corona sheath around the lightning discharge a significant source of NO in thunderstorms? What about in-cloud corona from ice particles? We used a value of 10×10^{16} molecules NO/J in all our calculations. Our range of uncertainty for this value is ±50%, or $10 \pm 5 \times 10^{16}$ molecules NO/J. If a better estimate is obtained in the future, it will be easy to rescale our results. Using a value of 5×10^{16} molecules NO/J and the lowest annual production rate (1986) would imply an annual mean production rate of 5.2 Tg N/yr, while a value of 15×10^{16} molecules NO/J and the maximum annual production rate (1984) would give an annual production rate of 22 Tg N/yr. This would imply an upper limit of 25 and a lower limit of 5 Tg N/yr.

Only part of the charging current of the global atmospheric electric circuit is transmitted through energetic CG strokes. The obvious limitations on this fraction provide one of the more robust limits on lightning-produced NO_x. Using the year-to-year statistics of the fair weather currents or ionospheric potential with this method may allow us to derive interannual variations in the natural sources of NO_x with likely links to corresponding interannual variations in tropospheric ozone.

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