Variation of a Lightning NOx Indicator for National Climate Assessment

W. J. Koshak[1*], B. Vant-Hull[2], E. W. McCaul[3], and H. S. Peterson[3]

[1]Earth Science Office, NASA Marshall Space Flight Center, Huntsville, AL, U.S.A.
[2]City College of New York, New York, NY, U.S.A.
[3]Universities Space Research Association, Huntsville, AL, U.S.A.

ABSTRACT: In support of the National Climate Assessment (NCA) program, satellite Lightning Imaging Sensor (LIS) data is used to estimate lightning nitrogen oxides (LNOx) production over the southern portion of the conterminous US. The total energy of each flash is estimated by analyzing the LIS optical event data associated with each flash (i.e., event radiance, event footprint area, and derivable event range). The LIS detects an extremely small fraction of the total flash energy; this fraction is assumed to be constant apart from the variability associated with the flash optical energy detected across the narrow (0.909 *nm*) LIS band. The estimate of total energy from each flash is converted to moles of LNOx production by assuming a chemical yield of 10^{17} *molecules Joule*$^{-1}$. The LIS-inferred variable LNOx production from each flash is summed to obtain total LNOx production, and then appropriately enhanced to account for LIS detection efficiency and LIS view time. Annual geographical plots and time series of LNOx production are provided for a 16 year period (1998-2013).

INTRODUCTION

The intense heating of air by a lightning discharge, followed by rapid cooling, results in the production of nitrogen oxides (NO_x = NO + NO_2) as discussed in *Chameides* [1979]. The LNOx indirectly influences our climate since these molecules are important in controlling the concentration of ozone (O_3) and hydroxyl radicals (OH) in the atmosphere [*Huntrieser et al.*, 1998]. Since climate is most sensitive to O_3 in the upper troposphere, and since lightning NO_x is the most important source of NO_x in the upper troposphere at tropical and subtropical latitudes, lightning is a particularly useful parameter to monitor for climate assessments [*Schumann and Huntrieser*, 2007].

In support of the Global Change Research Act (GCRA) of 1990, the National Climate Assessment (NCA) program analyzes the effects of global change on the natural environment, human health and welfare, human social systems, agriculture, energy production and use, land and water resources, transportation, and biological diversity. Participants of the NCA program analyze natural and human-induced trends in global change, and project major trends 25 to 100 years out.

During the past few years, a software tool was developed at the NASA Marshall Space Flight Center (MSFC) to conduct NCA-related analyses [*Koshak et al.*, 2014]. The tool monitors and examines long-term changes in lightning characteristics over the conterminous US (CONUS).

In this study, we have expanded the capability of the tool so that it can provide a unique estimate of LNOx production, thereby further supporting the climate assessment process. The estimate is computed using data from the Tropical Rainfall Measuring Mission Lightning Imaging Sensor (TRMM/LIS; *Christian et al.* [1999]; *Cecil et al.* [2014]). Despite the 16+ years operational life of LIS thus far, the information content of the LIS data has not been fully exploited to gain valuable insight on LNOx production. Hence, inferring LNOx production on a flash-by-flash basis using LIS observations, as performed in this study, represents key progress. Since the trend in lightning NO_x production is sought over a long (i.e., 16 year)

*Corresponding author, email: william.koshak@nasa.gov, Earth Science Office, NASA Marshall Space Flight Center, Huntsville, AL USA.

period, it is suggested that the estimate here has some benefit over the commonly used *flash extrapolation method* described in *Lawrence et al.* [1995]. The methodology applied to compute the LIS-inferred LNOx estimate is described, and results (i.e., geographical distributions, time series) are provided, along with a summary.

METHODOLOGY

Trending LNOx

The *flash extrapolation method* [*Lawrence et al.*, 1995] is commonly employed to estimate LNOx production. In such an approach, the LNOx production rate takes the form $G = \gamma \bar{P} F$ [*Liaw et al.*, 1990]. Here, F is a (typically global) flash rate, $\bar{P}$ is the average NO_x production per flash (e.g., a constant 250 moles/flash), and γ is a constant coefficient that converts the units of G into Teragrams of nitrogen per year (*Tg(N)* yr^{-1}). A closely related expression that integrates the production rate over time is

$$P = \sum_{k=1}^{N} P_k = N\bar{P} \quad . \tag{1}$$

Here, P is the total LNOx production (in *moles*), and P_k is the LNOx production from the k^{th} flash of the set of N flashes that occur in a specified period of time. By definition, $\bar{P}$ is the mean LNOx production per flash. Suppose the period of interest is a year, and one wanted to trend P from year to year. Whereas N would vary from year to year in general, $\bar{P}$ is restricted to one's assumption about the mean LNOx production per flash (i.e., $\bar{P}$ would be fixed at the commonly employed value of 250 *moles/flash*). In reality however, the value of $\bar{P}$ also likely changes from year-to-year. Therefore, the *flash extrapolation method* is not an optimal approach for trending LNOx production.

LIS-Inferred Flash NO_x Production

LIS data not only provide total lightning flash count (a variable obviously important to LNOx production), but also information about the optical brightness and spatial extent of individual lightning flashes. This additional information is key for better understanding flash energetics, which in turn is fundamental to flash LNOx production.

To overcome the over-restrictive nature associated with assuming a fixed mean LNOx production per flash, LIS lightning optical event energies from each flash are examined to estimate the total flash energy, E_k, of each k^{th} flash observed.

$$P = \sum_{k=1}^{N} P_k = \sum_{k=1}^{N} \left(\frac{Y}{N_A}\right) E_k = \left(\frac{Y}{N_A}\right) \sum_{k=1}^{N} \frac{Q_k}{\beta_k} \quad . \tag{2}$$

Here, Y is the NO_x *yield* and is assigned a value of 10^{17} *molecules* J^{-1} (see for example *Borucki and Chameides* [1984]). The factor $N_A = 6.022 \times 10^{23}$ *molecules mole*$^{-1}$ is Avogadro's number. The quantity Q_k is the amount of optical energy emitted by the k^{th} flash that is detected by LIS, and $\beta_k = Q_k/E_k$ is the fraction of the total flash energy detected by LIS.

With a flash exciting n pixels in the LIS charge coupled device (CCD) array across m LIS frames (each frame is 2 *ms* in duration), the value of Q_k can be expressed as (see *Koshak* [2010])

$$Q_k = CA\Delta\lambda \sum_{i=1}^{m}\sum_{j=1}^{n} \Delta\omega_{jk}\bar{\xi}_{\lambda ijk} = CA\Delta\lambda \sum_{i=1}^{m}\sum_{j=1}^{n} \left[\frac{a_{jk}\cos\alpha_{jk}}{r_{jk}^2}\right]\bar{\xi}_{\lambda ijk} \quad . \tag{3}$$

Here, $A = 2.9225 \times 10^{-3} m^2$ is the area of the LIS entrance aperture, and $\Delta\lambda = 0.909 \times 10^{-3} \mu m$ is the LIS spectral bandwidth. The quantity $\bar{\xi}_{\lambda ijk}$ is the LIS event "radiance" product which is actually in units of $\mu J/m^2/sr/\mu m$, and $C = 10^{-6}$ for converting μJ to Joules. The solid angle $\Delta\omega_{jk}$ subtended by the event footprint at the LIS detector can be obtained in a straight-forward manner and is given in the square brackets in the last equation of (3). The LIS event footprint area product (in units of km^2) is given by a_{jk}. The quantity α_{jk} is the *foreshortening angle*; i.e., the angle between the normal vector of the event footprint area and the unit vector pointing from LIS to the event footprint, so that $a_{jk} \cos\alpha_{jk}$ is the projected area. The *range* r_{jk} is the distance from LIS to the event footprint. These two quantities are given by

$$\alpha_{jk} = \sin^{-1}\left[\left(\frac{R+z}{R+H}\right)\sin\theta_{jk}\right] \quad , \quad r_{jk} = (R+H)\frac{\sin(\alpha_{jk}-\theta_{jk})}{\sin\theta_{jk}} \quad . \tag{4}$$

Here, the mean Earth radius $R = 6371$ *km*, the cloud top height $H = 11$ *km*, and the LIS orbital altitude is $z = 350$ *km* (prior to the August 2001 orbital boost) and $z = 402.5$ *km* (following the August 2001 orbital boost). The lens boresight angle θ_{jk} associated with the optical event is obtained by using the event CCD address LIS data product (x_{pixel}, y_{pixel}) in conjunction with the LIS lens transfer function obtained from the LIS calibration [*Koshak et al.*, 2000].

In general, β_k varies with changes in: cloud scattering properties, lightning properties, and LIS instrument properties. For example, the location of the flash within the thundercloud and the optical scattering characteristics of the thundercloud represent complicating factors. A lightning flash that is embedded deeply within an optically thick thundercloud would not produce as bright of an optical cloud-top illumination as if the same flash occurred closer to cloud-top. In addition, a horizontally propagating flash at a given altitude would illuminate a larger area of cloud-top than had the flash instead propagated downward, all else being equal. But, given the large sampling of flashes and the myriad of different thundercloud morphologies encountered with the 16 years of LIS data employed here, we expect that many of these complications average out. In addition, the LIS instrument has been found to be remarkably stable [*Buechler et al.*, 2014]. Therefore, we fix the value of $\beta_k = \beta = 1.8451 \times 10^{-19}$. This is the value required such that the mean production in the 73,292 flashes observed by LIS over CONUS in the year 1998 (an arbitrarily selected reference year) is 250 *moles/flash*. With this simplification, and substituting (3) into (2), the LNOx production inferred by LIS becomes

$$P = \frac{CYA\Delta\lambda}{\beta N_A}\sum_{k=1}^{N}\sum_{i=1}^{m}\sum_{j=1}^{n}\left[\frac{a_{jk}\cos\alpha_{jk}}{r_{jk}^2}\right]\bar{\xi}_{\lambda ijk} \quad , \tag{5}$$

where the foreshortening angle and range are as given in (4).

Because LIS detection efficiency is under 100% and because LIS does not continually view a geographical region, the LIS flash counts are appropriately corrected (i.e., increased); see for example *Cecil et al.* [2014]. Therefore, for any given 0.5 $\times$ 0.5 degree latitude/longitude bin over CONUS, there will be N_o LIS counts (i.e., observed flashes), and an associated much larger projected total count N_t due to these corrections. Hence, the total number of flashes assumed, but unobserved, is $N_u = N_t - N_o$. Even though there is no LIS event data for the unobserved flashes, the large number of observed flashes N_o obtained throughout a year (and across all seasons and the diurnal cycle) provide a reasonable estimate of the mean LNOx production per flash for the year. Hence, a reasonable way to correct (5) for LIS detection efficiency and view time is to express the total production P_t for a given region as

$$P_t = \sum_{k=1}^{N_o} P_k + N_u\left(\frac{1}{N_o}\sum_{k=1}^{N_o} P_k\right) \quad , \quad P_k = \frac{CYA\Delta\lambda}{\beta N_A}\sum_{i=1}^{m}\sum_{j=1}^{n}\left[\frac{a_{jk}\cos\alpha_{jk}}{r_{jk}^2}\right]\bar{\xi}_{\lambda ijk} \quad . \tag{6}$$

Table 1: Summary of flash counts, associated LNOx production, and LNOx production per flash.

Year	N_o	P_o $(megamoles)$	Λ_o $(moles)$	N_t $(\times 10^6)$	P_t $(gigamoles)$	Λ_t $(moles)$
1998	73,293	18.32	250.0	49.25	12.08	245.2
1999	71,806	19.79	275.6	45.88	12.41	270.5
2000	61,701	16.69	270.4	40.03	10.50	262.2
2001	71,226	16.80	235.9	43.11	9.96	231.0
2002	79,530	17.64	221.8	42.67	9.28	217.5
2003	100,090	21.42	214.1	50.44	10.72	212.5
2004	100,695	21.89	217.4	51.83	11.15	215.2
2005	96,522	20.11	208.4	47.84	9.91	205.0
2006	78,787	17.33	220.0	40.51	8.71	215.0
2007	87,181	18.25	209.4	44.37	9.12	205.5
2008	90,307	19.30	213.8	44.77	9.44	210.8
2009	95,793	18.70	195.3	48.72	9.28	190.6
2010	93,751	17.65	188.3	49.25	8.94	181.5
2011	96,680	17.05	176.3	48.99	8.43	172.1
2012	86,766	17.71	204.1	44.14	8.92	202.0
2013	80,431	15.59	193.8	40.96	7.80	190.4

RESULTS

In this section, we apply (6) to obtain geographical variations of LNOx production over CONUS (upto 38^{o}N latitude, the northern limit of LIS viewing) from year-to-year, and the associated total LNOx production time-series.

Fig. 1 provides the year-to-year geographical variability of the total LNOx production, P_t, for the 8 year period 1998-2005. Fig. 2 continues the geographical series for the follow-on 8 year period 2006-2013. The values of P_t are in units of *megamoles*. In addition, Table 1 summarizes the values of the variables (N_o, P_o, N_t, P_t), along with the average LNOx production per flash ($\Lambda = P/N$) using the observed and projected total values. Again, note that the value $\Lambda_o \equiv 250$ *moles* in the year 1998 since this is the reference value employed in the calibration of β_k. Finally, Fig. 3 summarizes the variability in (N_o, P_o, N_t, P_t) as time-series plots.

The average (given to a precision of one decimal place) of the flash count N_t in the first 8 yr period (1998-2005) is 46.4 million flashes, and the average in the following 8 yr period (2006-2013) is 45.2 million, a drop of only 2.5%. However, the average LNOx production P_t in the first 8 yr period is 10.7 *gigamoles*, and 8.8 *gigamoles* in the following 8 yr period, a more substantial drop of 17.8%. On a per flash basis, the average LNOx per flash for the respective periods is 232.4 and 196.0 *moles*, a drop of 15.7%.

SUMMARY

A method was introduced for estimating the LNOx production on a flash-by-flash basis using LIS data products, and the LIS lens transfer function obtained from the laboratory calibration of the LIS. By summing up the optical energy from the set of LIS-observed optical events in a flash, appropriately scaling the sum to total flash energy, and employing an acceptable NO_x chemical yield per Joule of flash energy, an estimate of the production of LNOx from the LIS-observed flash is obtained. Thus, this study has emphasized that LIS does not just simply count and locate lightning flashes, but also provides important additional information that can be related to flash energetics, and hence LNOx production.

The method was applied to analyze the 16 year period (1998-2013) over the region of CONUS viewed by LIS, and geographical and time-series plots of the variation of total LNOx production have been provided. Because LNOx is an important component of climate variation, this study supports the National Climate Assessment (NCA). Although there is a modest (2.5%) drop in total lightning count (obtained by comparing the mean count in the first 8 yr period with the mean count in the subsequent 8 yr period), there is a more substantial (17.8%) drop in the total LNOx production between these same two periods. Hence, lightning energetics should not be ignored when estimating long-term trends in LNOx production. In other words, trending lightning count alone is inadequate for monitoring the impact of lightning chemistry on climate.

Finally, the method introduced here can be applied to analyze future Geostationary Lightning Mapper (GLM; *Goodman et al.* [2013]) data. Because GLM will continuously view a region (whereas LIS view time is limited), application of the method to GLM will provide even better LNOx estimates. The method can also be applied to analyze future International Space Station Lightning Imaging Sensor (ISS/LIS) data; the higher inclination orbit of the ISS will allow for global LNOx estimation.

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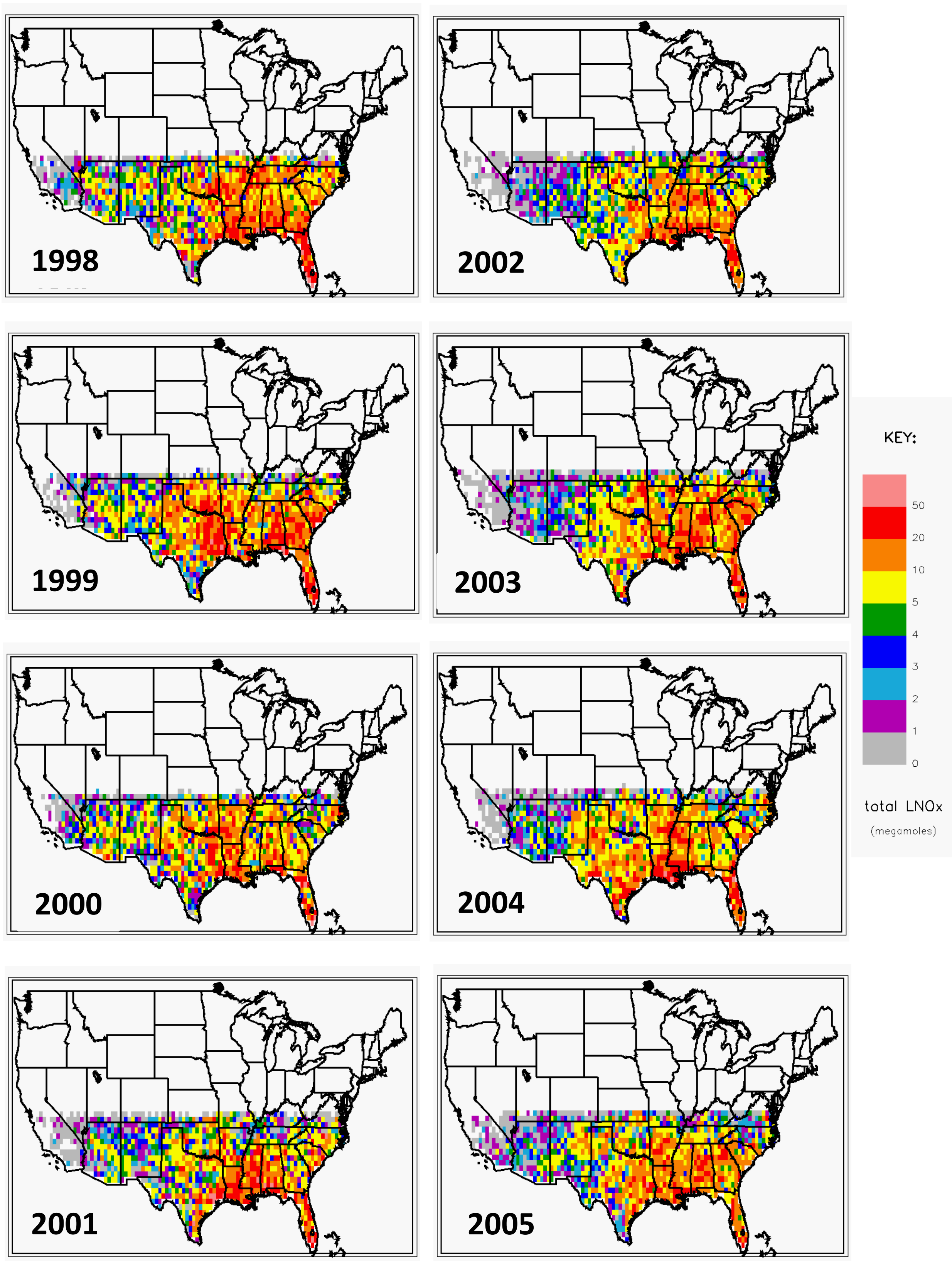

Figure 1: LIS-inferred LNOx production (megamoles) for the period 1998-2005.

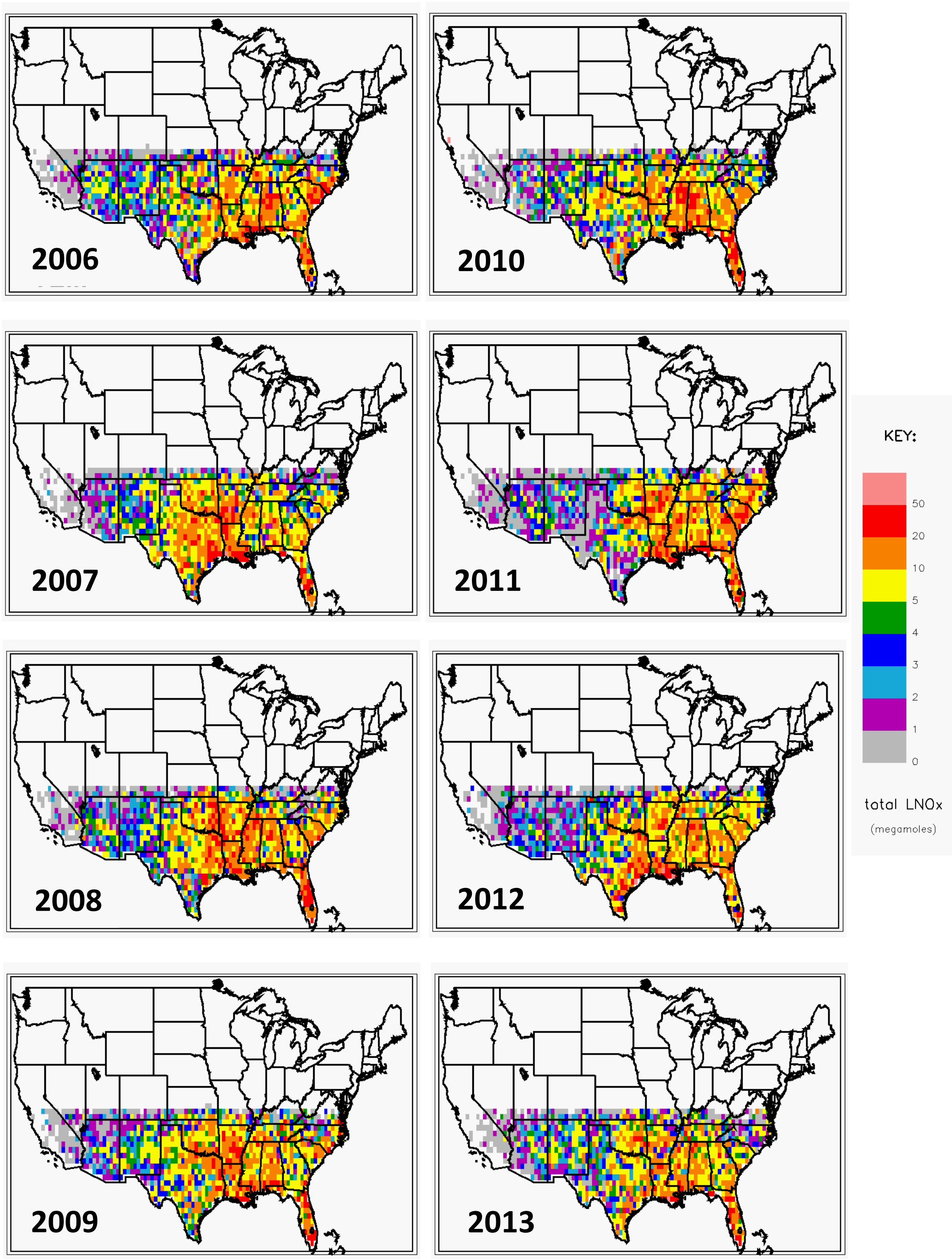

Figure 2: LIS-inferred LNOx production (megamoles) for the period 2006-2013.

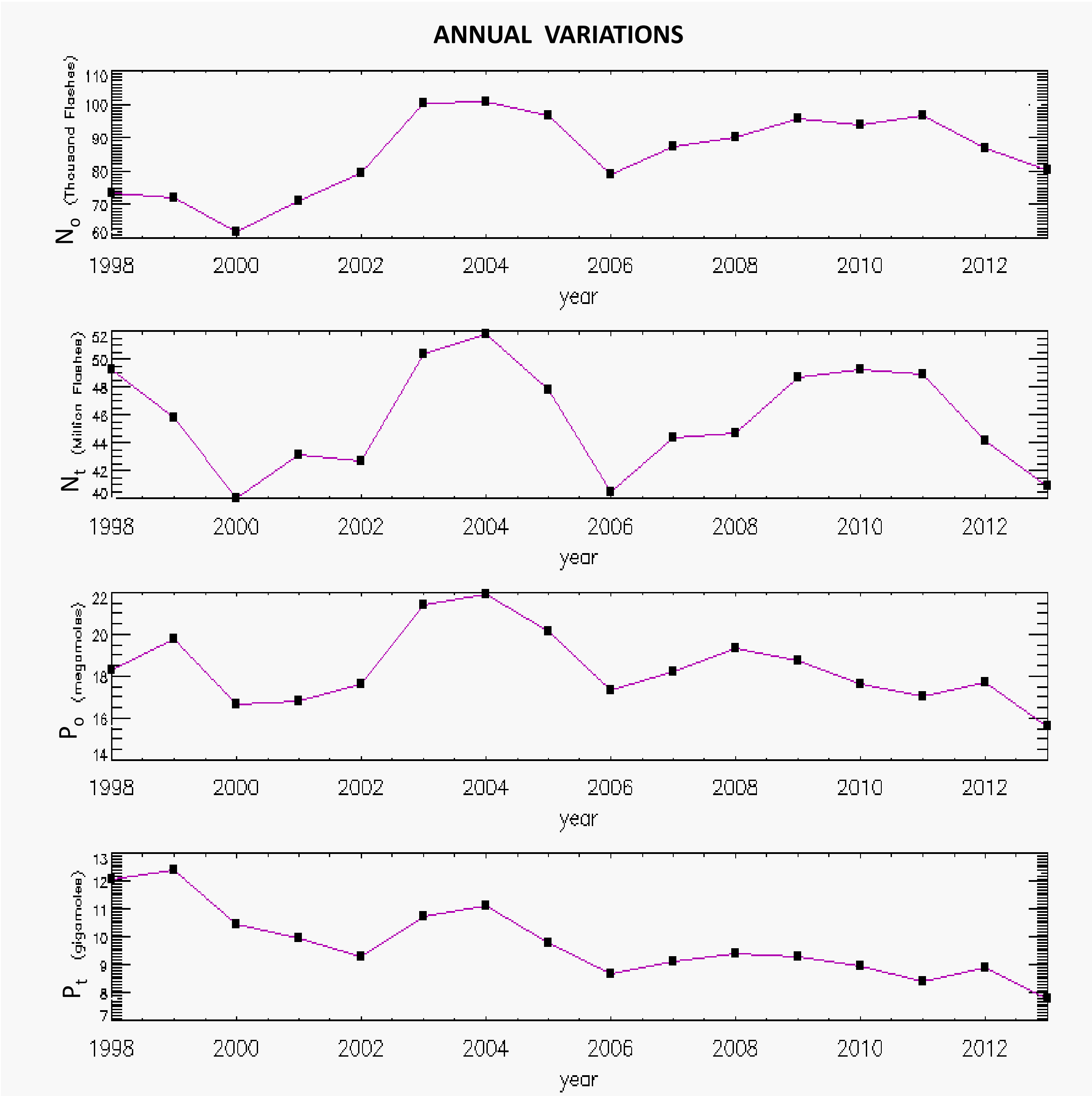

Figure 3: Time-series plots of flash counts and associated LNOx production.