

We thank the reviewers for their constructive feedback. In the following responses, the reviewers comments are shown in black, our replies in blue, and any text added to the revised manuscript in red.

REVIEWER 1

The paper describes a study to characterise NO_x production from lightning in a specific region and time frame using various ground- and space-based instrumentation which is supported by various modelling and calculation techniques. The paper is incredibly detailed and clearly outlines all aspects of the study, although some further illustrations/schematics would be helpful as certain parts (particularly the method) can become confusing without something to refer too.

The inclusion of uncertainties is important, particularly as the research is essentially trying to cross-reference various measurements, and it relies on some basic assumptions which may not necessarily be true (although this is mitigated to some extent). Lightning phenomena varies widely across the world, and this one specific study in this location may not be representative of other types of storm systems / lightning cells elsewhere –

We thank the reviewer for these encouraging comments. As the reviewer noted, this study is focused on a particular region. We cannot be sure if the obtained relationships between the LNO_x PE and flash metrics are similar in other regions. However, we have included different types of thunderstorms by covering almost one year of data.

It may be worth discussing how this could relate to other similar systems or regions? It is, however, a very good step forwards and a very interesting and comprehensive study.

We thank the reviewer for this interesting suggestion. However, we think that using the obtained results to make assumptions of how thunderstorms in other regions would produce LNO_x is out of the scope of this paper. That would be a original study by itself and would need acquiring new lightning and atmospheric composition data.

A few minor specific comments:

Ln 14-15: The way the references are included here are a little confusing; one from 1947 (a book I cannot fully access) and another from 2007, with the sentence suggesting that NO_x from lightning has, over a period of 60 years, stayed relatively stable at about 10%. But this is not true as, currently, human-made NO_x sources are at around 70-80% but would not have been this high in the 1940s (the absolute amount of NO_x from lightning may not have changed, but the percentage will have). Maybe some recognition that the 10% is just what the LNO_x split is now but that, years ago, it likely had a much bigger split.

We made an effort to include all the most relevant references, starting from the first reference for the Zeldovich mechanism. The reference of 2007 is a highly cited review that includes a detailed description of how lightning produces NO_x. More modern references appear later in the introduction.

We do not claim that LNO_x has stayed relatively stable at about 10% for 60 years. We have rewritten these lines in order to make them clearer:

“Lightning produces nitrogen oxides (NO_x = NO + NO₂) by following the Zeldovich mechanism (Zeldovich et al., 1947). Lightning accounts for about 10% of total emissions of NO_x (Schumann and Huntrieser, 2007) in the atmosphere, producing between 2 and 8 Tg N in NO_x per year, or between 100 and 400 mol NO_x per flash.”

Ln 96: There is a large amount of text describing the methodology in great detail, but it may be helpful to include a schematic illustrating the ground-based networks and satellites used as a ‘quick reference’ – particularly as so many are mentioned and it is quite hard to understand exactly what data is associated with each specific instrument. This extends to including maps with the specific latitude and longitude ranges used both for the case study and from the modelling perspective.

We have added a new figure (Figure 1 in the revised manuscript) to be used as a quick reference for the methodology. We did not add any new map because it is already shown in previous Figure 1.

Ln 257: I can understand where the 311 moles of NO per flash has come from, but does the study not distinguish / can it not distinguish between CG and IC flashes? There is also an over-simplification in the reference quoted here (Price, 1997) – 1112 for CG is just ten times 111.2 for IC; it is quite an old reference which has been observed to be incorrect (and there are some recent publications on this). I appreciate that this is just utilising a number for a model, and that if it is incorrect, it is an incorrectness which is carried through and so relative comparisons can be made.

We have added this text in order to explain this:

“Previous studies have reported substantially different estimates of the amount of NO produced per lightning flash (Schumann and Huntrieser, 2007). In the present study, the specific choice of the absolute LNO_x production per flash is not expected to significantly affect our main conclusions, as our analysis focuses primarily on the relative variability of LNO_x PE among individual thunderstorms, rather than on its absolute magnitude. Therefore, while the assumed emission factor influences the absolute LNO_x concentrations simulated by WRF-Chem, it should have a limited impact on the relative differences in LNO_x PE between the selected storm cases.”

REVIEWER 2

The authors examine the moles of NO_x produced per flash using flash information from a satellite-based network (MTG-LI) and a ground-based LMA and meteorological/trace gas information from TROPOMI. By pairing the analysis with model simulations (WRF) they reduce uncertainties in the tropospheric background and in the profile of lightning-NO_x that plague satellite-based estimates of LNO_x PE. The authors provide detailed information on the method they used to estimate the PE. The discussion is good although can be focused more.

Using the 98th PCTL vertical density score as a constraint on the region-of-interest seems like a great idea. The method of determining the NO_x column due to lightning appears sound.

Main Comments:

The authors should add a paragraph discussing why they believe their PE values are lower than most other estimates.

Added in the conclusions:

“However, it is important to note that this study primarily focuses on determining the storm-to-storm variability of LNO_x. It does not aim to retrieve an absolute value for NO_x produced per flash. This is because the background NO_x was calculated from WRF-Chem simulations, which already incorporate an assumed LNO_x PE as an input parameter.”

The authors need to shorten the discussion of Figure 6. Possible methods for doing that are shown below.

Figure 6 and discussion:

1. This array contains too much information to be grasped easily. It would help to only show the lower-left plus the diagonal.
2. You could also remove LMA-av.length or LMA-volume variables as their correlation is 0.99.
3. Unfortunately, I feel the remaining array would still too large. I would then remove any variables that are not discussed or only briefly mentioned in the text. Hopefully, this will get you to a 10x10 array or less.
4. You might also consider moving some of the discussion to the legend as it is tough to move back and forth between the text and the plot. At the very least, add some numbers to the main body.
5. Also, is it necessary to show both the LMA and MTG variables here.
6. You might also break this into 2 plots and the discussion of Figure 6 drags on and on.
7. Finally, I would use bullets or numbers to emphasize the points given in the text. Otherwise, you will lose some readers here.

We thank the reviewer for this detailed and constructive suggestion to streamline Figure 6. We fully appreciate the goal of improving readability given the amount of information in the matrix. To make the figure more accessible without losing critical context, we have modified the plot to present only the lower-left triangle along with the diagonal, effectively cutting the displayed matrix elements in half and removing redundant information. However, after careful consideration, we have decided to retain all the current variables and keep them integrated within a single plot. Removing specific variables or splitting the array into separate figures would make it difficult for the reader to compare all parameters simultaneously, which is essential for extracting the full relationships presented in this study. We believe this compromise significantly improves the clarity of Figure 6 while preserving the full scope of the multi-variable analysis.

Minor Comments:

L37: Did Rahman et al. (2007) include an estimate of the uncertainty or is that given by the small difference between 2 and 2.4?

Rahman et al. (2007) did not provide an estimate of the uncertainty because their study was focused on analyzing the production of NO_x in different phases of the discharge. The difference between 2×10^{22} and 2.4×10^{22} NO_x molecules per meter is based on the three analyzed flashes (Rahman et al., 2007, Table 1).

We have rewritten the phare in line 37:

“Estimations of LNO_x PE from triggered lightning reported by Rahman et al. (2007) found a production of LNO_x per flash channel length in three measured flashes, with values ranging between 2×10^{22} and 2.4×10^{22} NO_x molecules m⁻¹.”

L46-48: Please re-write this awkward sentence; its meaning is unclear.

We have rewritten this sentence:

“Recent results have already shown that global Extremely Low Frequency (ELF) magnetic field signals, which are strongly influenced by the presence of continuing current in lightning, can serve as a proxy for estimating inter-annual variations in LNO_x (Wang et al., 2025)”

L77-78: Please re-write this awkward sentence. Perhaps “In this study, to reduce uncertainties in estimates of LNO_x PE, we investigate relationships between ... Ebro Valley.

Done.

L125: Are data collected between July 8th and October 31st valid for scientific purposes? Aren't data available beginning July 4th?

There is a typo in the date of data availability. The correct date is July 4th. We have corrected this date.

Bližňák and Sokol (2026) demonstrated that MTG-LI data during October 2024 are valid for scientific purposes after comparing with ENTLN.

L137-139: Be explicit as to how you determine the number of time-contiguous groups per flash and the ratio of “long-duration” to total flashes, i.e., what standard MTG-LI L2 products were used to create the new products, and how the standard products were used to create the new products.

Added:

“The total number of time-contiguous groups per flash and the ratio of flashes containing at least 5 ms of time-contiguous optical signal to the total number of flashes are determined by using MTG-LI L2 group data. A time-contiguous group is defined as a set of groups within the same flash where at least one group occurs with a time difference of less than 1.1~ms.”

L225: Did you use the WRF processing system to go from 34 meteorological levels to 37 model levels? Also, why did you choose a different number?

Yes, that is correct. The decision to interpolate the meteorological input data from 34 to 37 vertical levels in the simulation using the WRF preprocessing system is driven by the need for enhanced vertical resolution in the model. The flexibility of WRF in vertical discretization allows for a more accurate representation of atmospheric processes, particularly in the boundary layer and upper atmosphere, where finer resolution can capture critical dynamics and thermodynamic structures. By increasing the number of model levels, we ensure better alignment with the physical parameterizations and improved simulation of phenomena such as convection, turbulence, and vertical transport, which are sensitive to vertical grid spacing. This adjustment enhances the ability of the model to resolve key atmospheric features, ultimately leading to more reliable and physically consistent results. Added:

“To improve the vertical resolution of the simulation in both domains, the WRF preprocessing system was used to interpolate the meteorological input data from 34 to 37 vertical levels. This adjustment enhances the ability of the model to resolve atmospheric processes, particularly in the boundary layer and upper atmosphere, leading to more accurate and physically consistent simulations”

L256: It appears that you used lightning-nudging to ensure that deep (“high”) convection occurred at the location of observed flashes and to place lightning-NO_x emissions? Be sure this is clear in the text.

Yes, that is correct. We added:

“to ensure that deep convection occurred at the location of observed flashes and to place lightning- NO_x emissions.”

L259-262: I don't understand how sensitivity simulations with a different PE can be used to determine the background- NO_x ?

The background- NO_x is determined by comparing simulations with lightning and simulations without lightning. However, there are two dataset of lightning: MTG-LI and XCALMA. This is why we performed two simulations to estimate the background- NO_x : one based on the total number of flashes reported by MTG-LI and another based on the total number of flashes reported by XCALMA. However, since the detection efficiency of XCALMA is not spatially homogeneous across the simulation domain, we opted for a simplified approach. Instead of running two simulations with the same PE but different total flash counts, we conducted two simulations with the same total number of flashes but different PE values, which achieves the same analytical outcome. We added:

“Given that the DE of XCALMA varies across the simulation domain, we adopted a simplified approach: rather than performing separate simulations with identical PE but differing total flash counts, we maintained a consistent total number of flashes in both simulations and adjusted the PE values accordingly”

L303-305: Is the summertime ratio also elevated because summertime storms produce more lightning than spring/autumnal storms or did you control for that?

No prior assumptions were made regarding the ratio before conducting the simulations. Instead, the simulations were explicitly used to derive the ratio for each analyzed thunderstorm, which was then applied in the LNO_x PE estimation algorithm.

Figure 4b: I don't understand what one obtains when you subtract $\text{VCD}_{\text{strat}}$ from the total SCD and then divide by $\text{AMF}_{\text{strat}}$. I'm more used to seeing $\text{VCD}_{\text{strat}}$ multiplied by $\text{AMF}_{\text{strat}}$ and then subtracted from the SCD, which is of course the operational tropVCD.

The reviewer is right. In fact, we were showing $\text{VCD}_{\text{strat}}$ multiplied by $\text{AMF}_{\text{strat}}$, then subtracted from the SCD, and then divided by $\text{AMF}_{\text{strat}}$. We have now changed the figures to show the $\text{VCD}_{\text{strat}}$ multiplied by $\text{AMF}_{\text{strat}}$ and then subtracted from the SCD.

L375-394: You pack a lot of interesting information into this paragraph. Yes, it probably makes sense to use groups rather than flashes when determining which grid boxes are lightning-influenced.

Thank you.

Table 2: I'd suggest adding a summary row containing the mean and standard deviation for each of the parameters.

Done.

L429-430: You state that the PE is significantly influenced by the PE choice used in WRF-Chem. How much did it change by when you adjusted the PE using the ratio of LMA to MTG flashes? Can you quantify the significance?

This is already shown in Table 2. Added:

“as shown in rows 10 and 11 of Table 2”

L453: I don't understand this --- Are thunderstorms more active near sunrise?

This is an error. Corrected:

“which is consistent with previous findings of **shorter** flashes in more active thunderstorms”

L455-456: Wouldn't a higher DE during the early morning mean that MTG-LI would capture more weak flashes during the morning that would be missed when the DE is lower?

These are two competing effect: a higher DE could mean reporting shorter flashes, but also reporting a larger portion of larger flashes. In the analyzed cases, the second effect is more important. Added:

“Conversely, a higher DE during the early morning could allow MTG-LI to capture more weak flashes that would otherwise be missed when the DE is lower. However, the effect of observing a larger portion of bigger flashes when the DE is higher ultimately dominates.”

L479: Isn't the flash energy also proportional to the pressure?

Yes. However, we do not include pressure in our analysis.

L505-506: I'd be careful here. I believe GLM and presumably MTG-LI detects CG flashes more efficiently than IC flashes. What do you mean by activity?

We do not mean that GLM or MTG-LI detects more efficiently CG or IC flashes. With activity we mean to the source of the light signal. For example, during a CG stroke, GLM and MTG-LI would probably detect more light coming from the portion of the channel that is in-cloud than from the portion of the channel that attached to the ground. This is described by Wemhoner et al. (2025).

L507-509: Interesting hypothesis: Emphasize how large the difference in correlation is between LNOx PE and duration/multiplicity. Is the difference significant?

Added:

“The lower correlation of the LNO_x PE with the total number of contiguous groups per flash than with the total duration reported by the LMA (**0.36 vs 0.68**)”

There is a factor of about 2 in the correlations, while both of them are significant (asterisk in Figure 6).

Technical Comments:

L16: accounting up --- accounting for up

Corrected.

L24: are essential --- is essential

Corrected.

L29: or the EULINOX --- and the EULINOX

Corrected.

L34: unit discharge energy --- unit discharge of energy

Corrected.

L84: metric --- metrics

Corrected.

L84: cloud covers --- cloud cover

Corrected.

L108: research products used in this study provide --- research products provide

Corrected.

L126: Earth's full (what?)

Corrected: Earth's full disk

L129: define sub-satellite point

Added: "0° latitude, 0° longitude"

L152: ELMA or eLMA?

Corrected: eLMA.

L167: from breaking them up into multiple--- from being broken into multiple

Corrected.

L168: no longer being detected --- no longer detectable

Corrected.

L183: calculate the total number of CG --- calculate the ratio of CG

Corrected.

L184: composed by --- composed of

Corrected.

L192: flashesy. --- flashes.

Corrected.

L223-225: No need to also write out "degrees" when you are using the degrees symbol.

Corrected.

L280: clearly seen in when comparing Figure 2(c) --- clearly see by comparison of Figure 2(c)

Corrected.

L346: is not exactly the same than the --- is not exactly the same as the

Corrected.

L446: av. Lenfth --- av. Length

Corrected.

L446-449: Please delete information within quotes to improve readability.

Information within quotes is necessary to define the variables in Figure 6.

L451: flashes then to have --- flashes tend to have

Corrected.

L487-489: lower altitudes accordingly to the LMA --- lower altitudes

Corrected.

L519: which is agreement with – are compare to (I'm not sure they agree as 0.56 is less than the lower range (0.8).

Replaced: "which falls in the lower range"

L553: that variations --- that variation

Corrected.

L600: will provide --- providesL487-489: lower altitudes accordingly to the LMA --- lower altitudes

Corrected.