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Investigating the Relationship between Upper Tropospheric NOx Dynamics and Lightning Events using WRF-Elec Chemistry

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Abstract

This study explores the relationship between upper-tropospheric nitrogen oxides (NOx) concentrations and lightning intensity through WRF-Elec Chemistry modeling methodologies. By scrutinizing this connection, the research endeavors to elucidate the nuanced interplay between NOx levels and lightning events, offering substantive insights into atmospheric processes. The model simulations are carried out with a spatial resolution of 15 km to refine the understanding of NOx emissions from lightning events. Adjusted for background levels, the derived NOx concentrations exhibit a robust correlation with lightning flashes detected by the LDSN, contributing invaluable insights into atmospheric processes. Significantly, correlation coefficients of r=0.5593 across the entire Indian region and r=0.8472 within selected domains at 9 kilometers altitude underscore the study's findings. These results deepen our understanding of lightning's impact on atmospheric chemistry,

Keywords: WRF-Elec chemistry; Lightning Nox; CG Flash; LDSN

Introduction

In the troposphere, nitrogen oxides ($NOx = NO + NO_2$) constitute a crucial component of atmospheric chemistry, originating from diverse natural and anthropogenic sources. Among these sources, lightning discharges emerge as a significant contributor, contributing approximately 10-15% to the total NOx budget alongside other natural phenomena. The dissociation of abundant atmospheric components such as N_2 and O_2 during lightning discharges at high altitudes leads to the formation of nitrogen oxides [1].

Recent studies have underscored the importance of lightning-induced NOx emissions, particularly in the upper troposphere, where most Lightning NOx (LNOx) is concentrated, notably above 7km altitude (Murray et al. 2012). This altitude range is pivotal due to the longer lifetime of NOx molecules, which influences climate dynamics by impacting ozone (O_3) production and other chemical processes [2].

However, the production of LNOx remains subject to uncertainties influenced by various factors, including the strength of convective activity and lightning characteristics [1]. While uncertainties exist in other NOx sources, the potential positive feedback loop between lightning activity and surface temperatures underscores the urgency of refining our understanding of LNOx production.

Accurate comprehension of the global LNOx budget is essential for precise modeling of NOx and O_3 variations and trends, as well as for analyzing the influence of different NOx sources on atmospheric dynamics. Therefore, this paper aims to investigate the relationship between lightning discharges and NOx emissions, shedding light on the mechanisms and implications of lightning-induced atmospheric chemistry.

Methodology

The study employed the Weather Research and Forecasting (WRF) Model with Chemistry Version 3.9.1.1 to investigate the correlation between nitrogen oxide (NOx) emissions from lightning and atmospheric dynamics (e.g., Cummings et al. [3]; Pierre et al. [4]). The model simulation spanned from June 18th to 20th, 2022, utilizing a horizontal resolution of 15km within a single domain and featuring 29 vertical levels. To enhance the representation of lightning events, the study integrated the NSSL two-moment microphysical scheme alongside the Grell-Devenyi ensemble scheme for cumulus physics. These namelist options were chosen to improve the simulation of convective processes and cloud microphysics critical for accurately capturing lightning-induced NOx emissions.

Meteorological initial and boundary conditions were sourced from the Global Forecast System (GFS), provided every 6 hours at a horizontal grid resolution of 0.25° x 0.25°. Boundary conditions for gas-phase species and aerosols were obtained from MOZBC at a resolution of 1° x 1° and spatially interpolated to match the study's domain every 6 hours. The study area is shown in the Figure 1. Additional chemical models employed in the study to simulate atmospheric chemistry include, wesley, exocolden, megan, finn and anthro. By incorporating these chemical models into the atmospheric simulation framework, the study aims to capture the complex interactions and feedbacks between natural and human-induced emissions, atmospheric chemistry, and meteorological processes. This integrated approach enables a more holistic understanding of atmospheric dynamics and pollutant distributions, contributing to improved air quality management and climate change mitigation strategies.

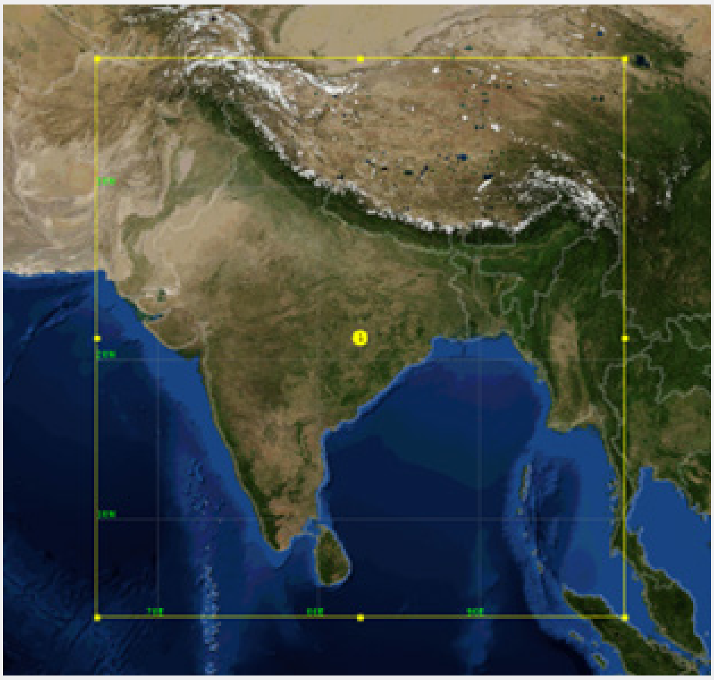

Figure 1: Domain selected for WRF model run, covering complete India.

Figure 2 illustrates the NRSC's Lightning Detection System Network (LDSN), comprising 46 omnidirectional antennas with a 300-kilometer detection range each, strategically positioned to monitor lightning activity nationwide. More details on LDSN are elaborated elsewhere [5,6].

Results and Discussion

The model outputs were compared with ground-based lightning data on June 18, 2022, at 10:00 UTC across India. Figure 3 shows a difference image obtained by subtracting it from the previous time image of the model outputs. The correlation coefficient between the difference image and LDSN data (shown in Figure 4) is 0.5593, suggesting a positive correlation between model predictions with observed lightning activity. However, notable overestimations around the Western Ghats and the lower Northeast region are also noteworthy which is consistent with previous findings that model show large deviations from the observations (e.g., Venkatesh et al. [7]). Moreover, within selected 5° x 5° domains at 9 kilometers (shown in Figure 5) altitude for all chosen times, the correlation coefficient is r=0.8472 (Figure 6).

It is evident that the regression analysis between NOx variations and the average number of CG flashes reveal a noteworthy correlation with slope of 0.13581. This slope indicates that, on average, for each additional unit increase in the average number of CG flashes, there is a corresponding increase of 0.13581 units in delta NOx concentration. Moreover, Pearson's r coefficient of 0.8472 signifies a strong positive correlation between delta NOx and the average number of CG flashes. This coefficient suggests that there is a robust linear relationship between these variables, further supported by the high R-squared value (COD) of 0.71775. The R-squared value indicates that approximately 71.775% of the variability in delta NOx can be explained by variations in the

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average number of CG flashes. These statistical findings provide compelling evidence of the influence of lightning activity on NOx concentrations in the upper atmosphere, underscoring the importance of considering lightning dynamics in atmospheric modeling and environmental studies.

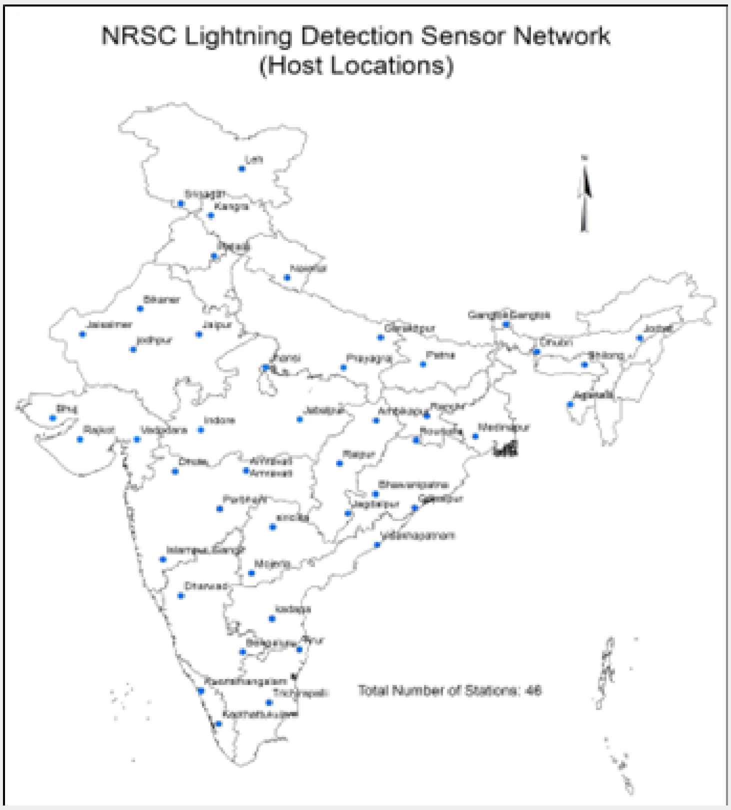

Figure 2: LDSN Host locations covering mainland India.

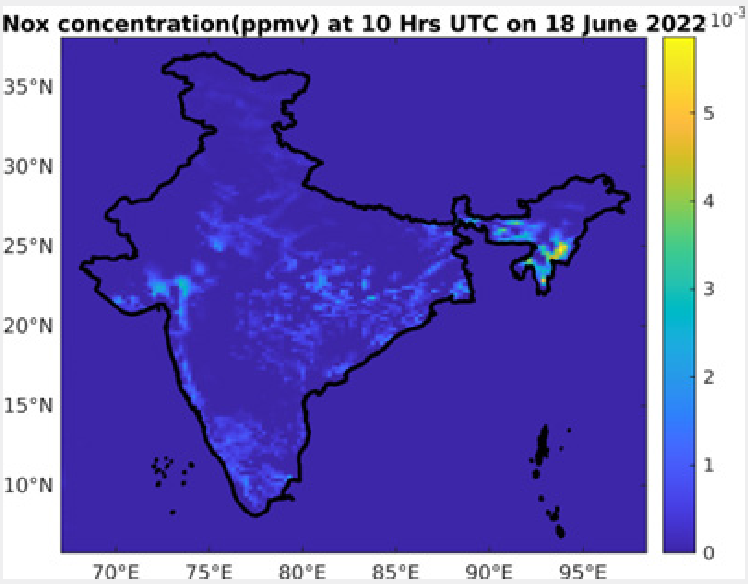

Figure 3: NOx concentration on 18 June 2022 at 10Hrs UTC.

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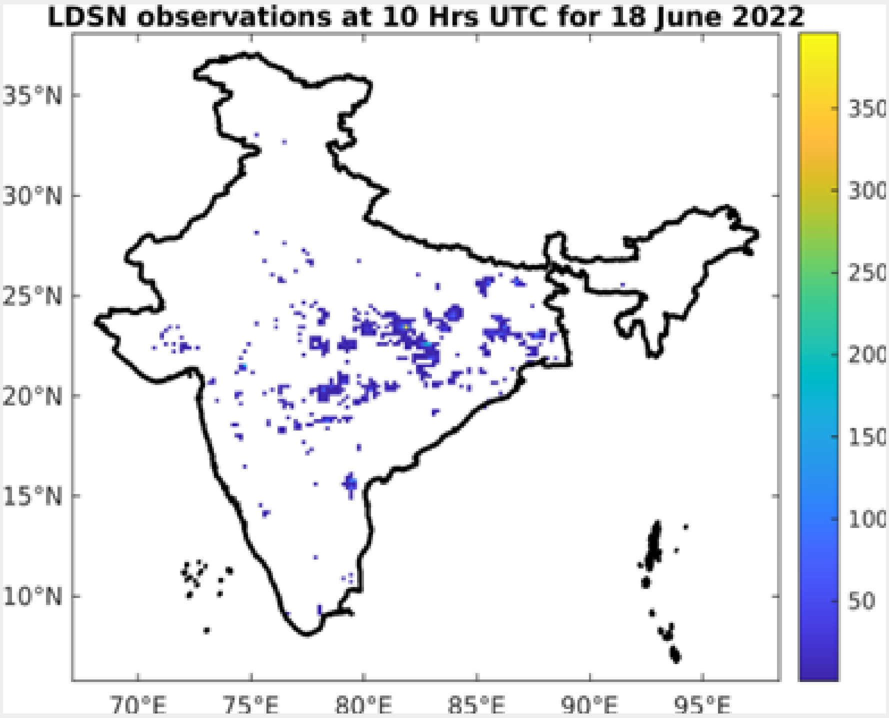

Figure 4: LDSN Ground data on 18 June 2022 at 10Hrs UTC.

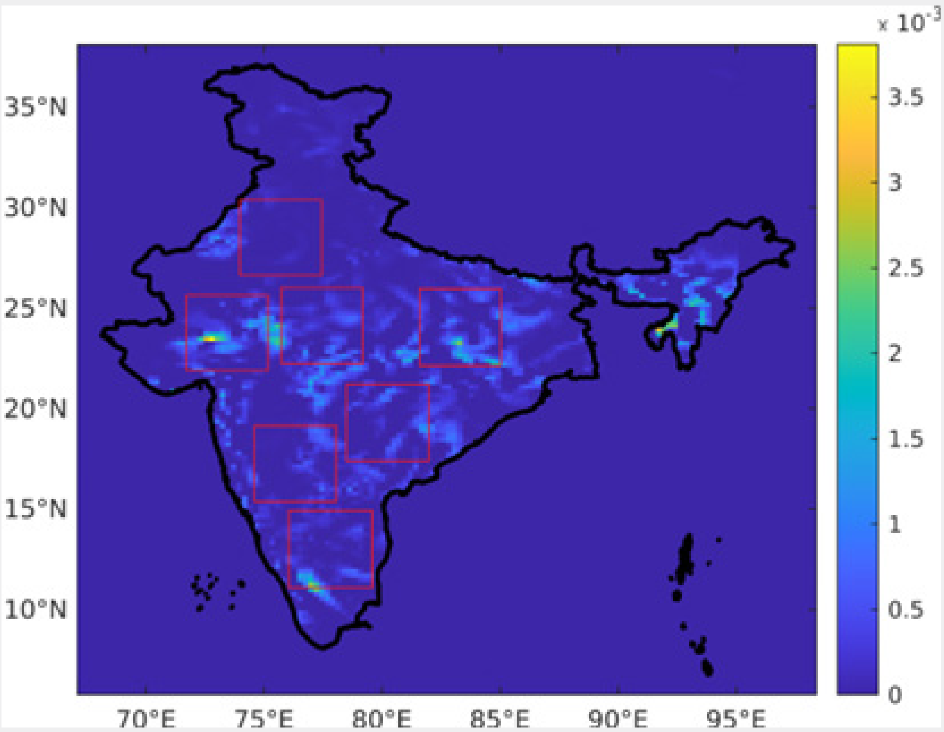

Figure 5: NOx concentration on 19 June 2022 at 20Hrs UTC with 5° x 5° grids selected (highlighted in red) for carrying out the comparison.

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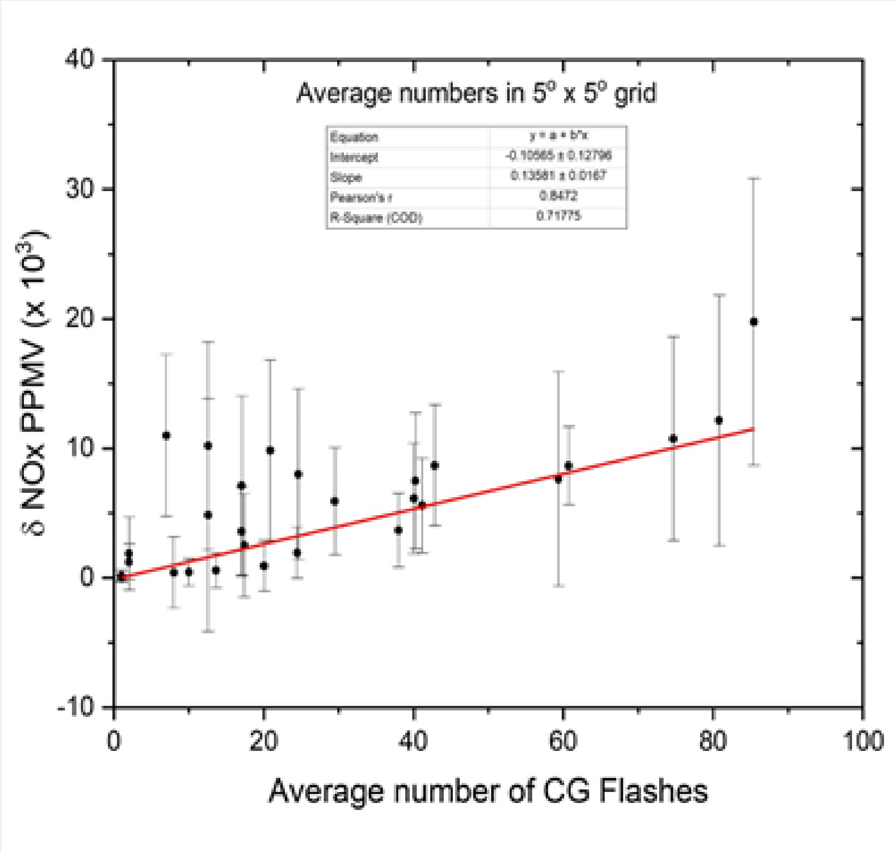

Figure 6: Plot showing comparison between NOx concentration and CG Flashes over 5° x 5° selected grids.

Acknowledgement

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