Role of lightning in NOx production: direct atmospheric pathways and indirect contributions via forest fires in Nepal

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Abstract: Nepal experiences rampant forest fires during the dry season (March-June) coinciding with the lightning peak season. Forest fires emit a large amount of gaseous pollutants that adversely impact the environment and hence our climate. Although unexplored, lightning strikes can be a potential cause of forest fires that in turn deleteriously impact on our environment. This study investigates the possible role of lightning strikes in generating nitrogen oxides (NOx) referred to as LNOx considering the forest fires across Nepal. We examined forest fires and lightning activities that occurred between 2015 and 2023. We utilized lightning data obtained from VAISALA's GLD-360 and fire data obtained from NASA's MODIS. An examination of time lag between the peak lightning activities and the fire events unveiled that fire events lag 5 to 20 days with an average of 11.78 days. An exploration into the remote national parks revealed that lightning strikes with higher magnitude over 40 kA are more likely to ignite fire. The tropospheric NOx has significantly increased by an order of magnitude during the pre-monsoon season coinciding with the lightning and forest fire season as compared to that in the preceding winter season signifying that lightning produces enormous NOx in our atmosphere. This study lays a strong foundation for a robust study on the quantitative contribution of lightning in producing NOx.

Keywords: Climate change; Forest fire; Lightning; LNOx.

Introduction

Lightning is a complex atmospheric electrical discharge that occurs due to an electrical imbalance in the atmosphere. A lightning discharge is accompanied by a huge amount of electrical current ranging from a few thousand amperes to a few hundred thousand amperes. The large current flowing through the atmosphere produces extremely hot channel (~30,000 K) of ionized gases changing the chemistry of the atmosphere. The study of lightning and related phenomena involves the synthesis of many branches of physics, from atmospheric physics to plasma physics to quantum electrodynamics, and provides a plethora of challenging unsolved problems[1]. Lightning converts the atmospheric nitrogen molecule into its oxides namely nitrogen dioxide (NO_2) and nitric oxide (NO) as the extreme temperatures within lightning channels break apart molecular nitrogen (N_2) and oxygen (O_2)[2]. Nitrogen oxides produced by lightning (termed as LNO_x) play an important role in determining mid- and upper-tropospheric concentrations of the hydroxyl radical (OH), methane (CH_4), and ozone (O_3) [2, 3]. Lightning can influence the climate via the production of nitrogen oxides ($NO + NO_2 = NOx$) followed by the production of ozone, another efficient greenhouse gas. Bond et al[4], observed that production of NO_x by tropical lightning is significant throughout the year. Lightning accounts for almost all the NO_x emitted over the oceans and 50–90% of NO_x emitted over some continental areas on a seasonal basis[4,18]. Lightning-induced NOx (LNOx) is one of the major ordinary sources of NOx in the

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upper atmosphere, particularly in the tropical region, but it is still highly uncertain as to the exact quantity[5]. Using the NOx data obtained from Ozone Monitoring Instrument (OMI) Allen et al[2] found that lightning flash counts from Worldwide Lightning Location Network (WWLLN) were distinctly correlated with LNOx estimates[1]. They reported that a mean midlatitude production efficiency (PE) of the lightning flash as 180 ± 100 moles of NOx per flash. Whereas, in the tropics, they found a mean lightning flash as 180 ± 100 moles of NOx per flash. Whereas, in the tropics, they found a mean LNO_x production of 170 ± 100 mol per flash with the mean PE at tropical marine locations with low flash rates approximately twice as large as at tropical continental locations with high flash rates[3] commonly experienced atmospheric phenomenon and carrying huge amount of electric current, light and the loudest sound commonly occurring on earth. A study of LNO_x in the mainland of China estimated a range of 0.157–0.321 × 10^9 kg per year [Tg(N) yr^{-1}][6].

In addition to the direct generation of NOx by lightning discharges from the atmospheric nitrogen, NOx is generated from the forest fire /biofuel burning that may get ignited from the lightning strokes. Analyses of the pollutants emitted by forest fires disclosed that their main components are particulate matter (PM), CO_2 (90–95%), CO, nitrogen oxides (NO_x), sulfides (XS), hydrocarbons (THC), and volatile organic compounds (VOCs)[7,18].

Forest fire is an essential emission source for greenhouse gases (GHGs) and air pollution[8]. The frequency, burn area, and intensity of forest fires are expected to increase with global warming[9]. Several smoke pollutants released by combustion have serious impacts on the atmosphere and forest ecosystems in the vicinity of the burned area[10, 11]. While majority of forest fires are believed to have been initiated by the anthropogenic activities, there is a serious knowledge gap about other possible natural elements that could play a big role in this growing issue. Lightning strikes are one such element that can serve as a powerful cause of forest fire ignition[12].

Approximately two-thirds of the wildfires that occur in the U.S.A. are caused by lightning strikes[13]. In Australia, lightning strikes caused 30% and 90% of wildfires and burned areas, respectively[14]. Specifically, in Victoria, Australia, from 1973 to 2014, lightning strikes accounted for 70% of burned land, contributing to 11% of wildfire ignition[15].

While lightning appears to be a key ignition source of forest fire globally and is expected to become more frequent with climate change that might significantly increase burn area, its impact on Nepal's forest fires remains largely unexplored[17].

This study explores the contribution of lightning in producing LNOx indirectly by igniting forest fire during the pre-monsoon season across Nepal. To the best of our knowledge, this is the first investigation of its kind being conducted in Nepal.

Methodology

a) Data acquisition and computation

- **Fire incident data**: We obtained forest fire records for Nepal from the Government of Nepal's MODIS dataset for years 2015 to 2023. These records comprise of the fire location, its date and time.

  • **Lightning strike data**: High-resolution lightning data were obtained from Vaisala's GLD – 360 for the selected years from 2015 to 2023. These records comprise of the location of the occurrence, date and time along with the amplitude of the Lighting and its polarity.
- **NOx data**: NOx data have been acquired by NASA's Ozone Monitoring Instrument (OMI) from 2019 to 2021.These specific years were selected as they provided a more consistent dataset of NOx readings and with the best resolution with lesser data gaps in comparison to other years allowing us a more reliable seasonal comparison. But we did use the complete 2015 - 2023 dataset of NOx for a trend analysis.

b) Data pre-processing and computation

- **Data filtering**

  The datasets pertinent to the lightning strikes and fire incidents were cleaned using pandas' data frame in python to recover the missing values and to remove the duplicate values.

- **Spatial join**: We used the GeoPandas library and performed spatial joins for fire incidence points and lightning strikes deploying the geodesic parameters to identify events within a 10 km radius.

c) Technical implementation

- **Coding environment**: We performed analysis majorly using Python, and the main libraries that we used were NumPy, scikit-learn, GeoPandas, pandas, matplotlib, and seaborn.
- **Time lag calculation:** Custom Python functions were developed to calculate the time difference (in days) between each fire event and the nearest preceding lightning strike. These functions incorporated spatial distance filtering and temporal sorting**.**
- **Visualization**: We used libraries matplotlib and seaborn to produce the time series plots, bar plots and pie charts for various visualizations such as polarity distribution and Time lag scatterplots.

Analysis, Results and Discussion

In this study we utilized three years data (2019-2021) as a preliminary study on the contribution of lightning in producing NOx by igniting forest fires. We selected data for pre-monsoon season from 2019 to 2021 as this period experiences maximum lightning and forest fire incidents. Depicted in figure 1 is a map of fire incidents recorded MODIS for the pre-monsoon period of 2020.

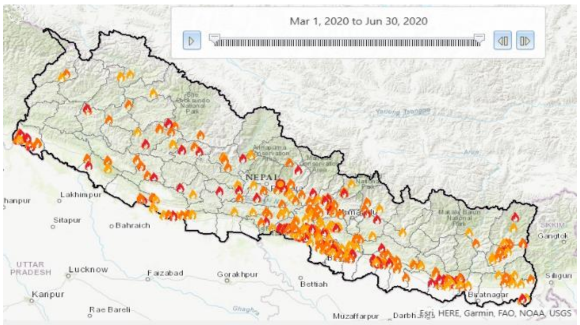

Figure 1: Forest fire incidents across Nepal during March to June 2020 recorded by MODIS.

Figure 2 depicts the lightning flash density across Nepal for the pre-monsoon period of 2020 incorporating fire points in the remote national parks where the anthropogenic activities are scarce. This indicates that forest fires might have initiated due to lightning in such locations.

Investigating the possibility of lightning igniting the forest fire, we plotted a graph depicting the variation of lightning incidents and forest fires. Figure 3 depicts the variation of lightning incidents and forest fires for the year 2020.

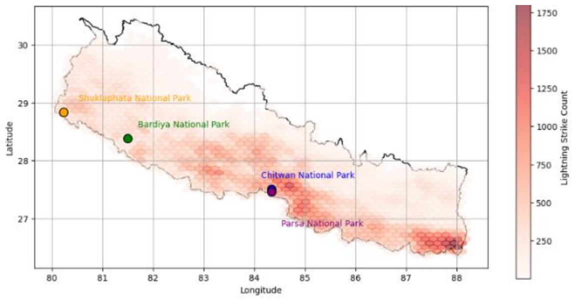

Figure 2: Lightning flash density for the pre-monsoon period of the year 2020. The solid circles in the map indicate the national parks where fire incidents were recorded during the season.

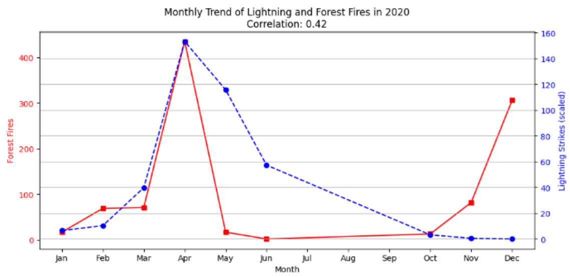

Figure 3: Monthly variation of forest fire incidents and lightning stroke incidents for the year 2020.

Thunderstorms and lightning play a vital role in maintaining Global Electrical Circuit (GEC). Thunderstorms charge the ionosphere to a potential of several hundred kilovolts with respect to the Earth's surface. This potential difference drives a vertical electric current downward from the ionosphere to the ground in all non-thunderous or fair-weather regions, thus closing the global current system in GEC[16]. Lightning not only maintains the GEC but also plays a vital role in changing the atmospheric chemistry. Lightning is hot enough to convert the non-reactive nitrogen (N_2) and oxygen (O_2) into highly reactive nitrogen oxides (NOx). While lightning directly converts atmospheric nitrogen and oxygen into NOx, it changes atmospheric chemistry indirectly by igniting forest fires. This study shows the severity of the contribution of lightning in producing NOx indirectly through forest fires. We plotted the NOx for two seasons, one for pre-monsoon season and the other for winter season of 2019-2021. Figure 4 depicts the NOx column over Nepal during the pre-monsoon period of 2019-2021, whereas figure 5 depicts the NOx column during winter season for the same years. A significant increase is seen in NOx column during pre-monsoon season as compared to that during the winter season. Two distinct hot spots can readily be noticed from figure 5, one over Kathmandu and the other over Lumbini during the winter season. This indicates that anthropogenic activities over these regions produce significant amount of NOx, whereas it is not observed in other regions across Nepal. Moreover, the NOx column during the pre-monsoon season significantly increases all over the southern part of Nepal coinciding with the forest fire incidents. Since lightning can be attributed to igniting forest fire in the remote locations, it contributes to the production of NOx through fire events.

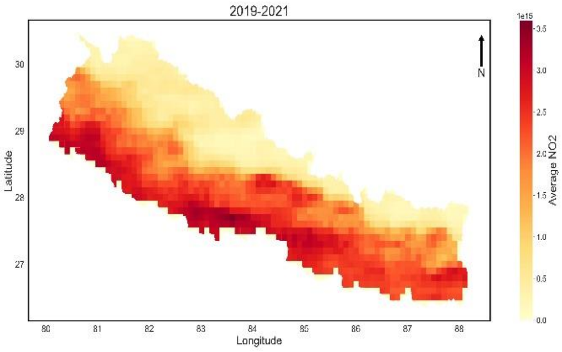

Figure 4: Density of NOx over Nepal for the pre-monsoon period for three years (2019-2021).

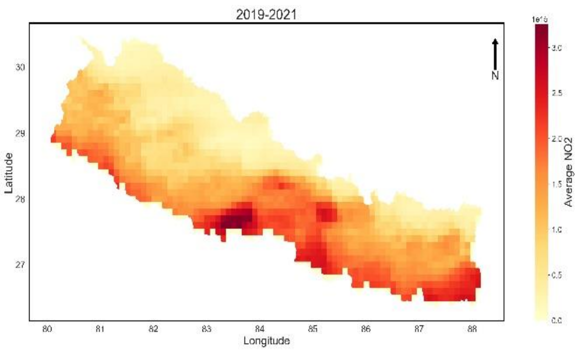

Figure 5: Density of NOx over Nepal for the winter season for three years (2019-2021).

Also, depicted in figure 6 and figure 7 are the NOx columns for pre-monsoon season and winter season of 2020. Similar patterns can be witnessed from the plots for 2020 as those obtained for a three-year period from 2019 to 2021.

A further investigation of NOx over the remote locations where human activities are very uncommon in association with the forest fire incidents shows that there is a significant

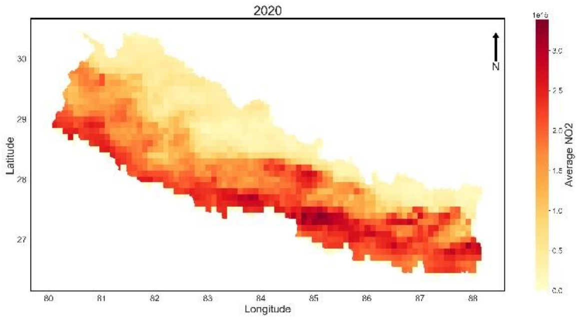

Figure 6: Density of NOx over Nepal for the pre-monsoon season of 2020.

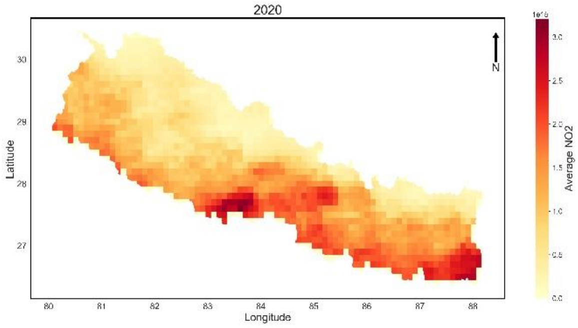

Figure 7: Density of NOx over Nepal for the winter season of 2020.

increase in NOx during the pre-monsoon season as compared to that of the other seasons as depicted in figure 8. We conducted ANOVA test to determine the p-values over four remote locations (i.e. national parks) namely Chitwan, Bardiya, Parsa and Shuklaphanta national parks. Extremely low p-values (around 10^{-207}, 10^{-178}, 10^{-201} and 10^{-28} respectively) have been obtained for the ANOVA test. The differences in NO_2 levels between Winter, Pre-monsoon, and post-monsoon are not due to random chance. Seasonal changes are a major factor affecting NO_2 levels in these parks. These findings highlight that seasonal factor namely Winter, Pre-monsoon, and post-monsoon play a crucial role in driving variability in NO_2 levels across the study parks. The spike of Lightning Induced Forest fires tend to align with the spike in NO_2 values i.e. the pre-monsoon seasons every year, indicating that Lightning induced forest fires tend to soar the NO_2 values.

Conclusion

The results show that lightning plays a crucial role in producing atmospheric NOx. The results provide strong evidence that NOx levels in the pre-monsoon season are significantly higher than in other seasons and this trend is observed across four remote locations where human access

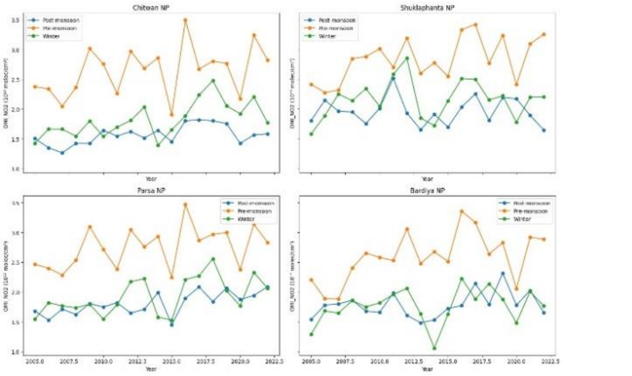

Figure 8: Variation of NOx column over the Density of NOx over four national parks where fire incidents were observed during the study period.

is very limited and the probability of human-caused forest fire is rare. The extremely low p-values indicate near zero probability that these differences are due to random chance reinforcing that seasonal factor, such as lightning and forest fires, are driving the increase in NOx.

This study lays a strong foundation for an elaborate and meticulous study on the cause of NOx production.

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