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Thunderstorms and their Influence on Meteorology and Atmospheric Composition over Southern Peninsular India

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Abstract

The study examines the long-term (2011-2023) analysis of thunderstorm and lightning activities and their impacts on local meteorology and air pollutants over Bengaluru. The diurnal thunderstorm events occur mainly in the late evening hours (1900–2100 IST) and on monthly maximum in May while minimum in January. Annually, Bengaluru experiences an average of 41 thunderstorms and 157 lightning strikes, both of which have shown a statistically significant upward trend at a 95% confidence level. The rate of increase is 3.41% per year for thunderstorms and 3.3% per year for lightning events. Local temperatures coupled with abundant moisture supply from the southwest/northeast monsoon creates a favourable condition for the initiation of thunderstorms over the region. This study also focused on the trend analysis of meteorological parameters and atmospheric compositions, a rising trend were found in rainfall (1.44 mm $year^{-1}$), RH (0.74% $year^{-1}$) & pressure (0.03 hPa $year^{-1}$) whereas a slight declining trends in temperature (0.06 0C $year^{-1}$) & wind speed (-0.02 ms^{-1} $year^{-1}$). As the availability of heat and humidity are two main prerequisites for the occurrence of thunderstorm and hence the probability of severe thunderstorms may increase in future. The AOD, NO_2 & O_3 showed a significant increasing trend while no trend for SO_2. The Pearson correlations showed the AOD, NO_2 & SO_2 concentrations are significant negatively correlated with wind speed but positively correlated with atmospheric pressure. A further study indicated a significant impact of thunderstorm on the air pollutants has also been quantified and it was observed that $PM_{2.5}$ concentration gradually decreases after the

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commencement of thunderstorm while quick increase response (less than 1 hour) was observed in O_3 and delay response (after 2:30 hours) in NO_2 which may linked to lightning activities. The results reveal that thunderstorms can affect both the local meteorology as well as atmospheric pollutants and vice-versa from regional to global.

Introduction

A thunderstorm is a dynamic meteorological event marked by thunder and lightning, typically accompanied by rain, turbulence, strong winds, and sometimes severe squalls. These storms can lead to flash floods, trigger landslides, ignite wildfires from lightning strikes, and produce tornadoes, hail, and other dangerous conditions that pose significant risks to life and property on a regional scale.[1-2] In addition, the strong wind raises dust and light particles above the ground that alter the atmospheric composition and poor visibility.[3,4] It develops rapidly and the effects of these hazards are sudden and highly localized.[5] Consequently, the monitoring of thunderstorms is important in many sectors including aviation, insurance, health, energy, water, and wildfire management. In recent years, researchers have been paying much attention to the study of thunderstorms and lightning activities and trends due to an increase in the frequency of natural hazards in a global warming/changing climate.[6,7]

Thunderstorms mostly occur in the temperate and tropical regions of the world. However, their frequency of occurrence is predominant in the tropical region due to its low Coriolis force and weak pressure gradient. Several earlier studies have investigated the spatiotemporal patterns of thunderstorms across various regions globally, focusing on aspects such as their frequency, intensity, and timing of occurrence.[12-15] However, the occurrence of thunderstorms varying from region to region depends on the combination of factors like strong thermal convection, atmospheric instability, presence of high-water vapor, synoptic-scale disturbances, and ENSO (El-Nino Southern Oscillation).[8-9] Thus, the global distribution of thunderstorms exhibits a complex frequency pattern. India is also a vast tropical country with a unique geographical setup, where there is no month without the occurrence of thunderstorms[10] and the latitudinal distribution of thunderstorms over India is different from the rest of the regions in the tropics. North-East India experiences the highest number of thunderstorms (more than 100/year) followed by the southern peninsula (60-80/year), and central parts of India (30-50/year) whereas the lowest (15/year) over western and northwestern parts of India. Thus, the variability is due to the regional topographical and meteorological features.[11] Several studies have provided long-term information about thunderstorms on a regional basis.[12,13] The knowledge of the thunder-storms at the city scale is also required for weather prediction and thunderstorm disaster climatology in highly populated urban regions. Several researchers have studied thunderstorm variability at city scales,[25-27] but these studies were limited to specific seasons or short time frames. Therefore, it is also important to assess thunderstorm and lightning activities, along with their trends, in the context of a changing climate.

Researchers are making use of lightning data to understand climate change.[14] The lightning activity is closely related to thunderstorms, precipitation, and other meteorological parameters.[15] Thunderstorms are responsible for 40–50% of overall precipitation and 70–80% of extreme precipitation in continental areas.[16] Researcher[17] found a positive correlation between lightning activity and surface temperatures, indicating that a 1°C rise in temperature could lead to a 20–40% increase in lightning activity across the Indian region. Additionally, the concentration of saturation water vapor increases by 7% for every 1°C increase in surface temperature,[15] which significantly contributes to the intensification of thunderstorms. Further, studies also showed that lightning and thunderstorm activities are highly correlated with air pollution.[18] The study[19] was observed that an increase in aerosol loading over the region leads to a rise in both lightning flashes and storm heights. Another study found that under conditions of high aerosol concentration, both precipitation and lightning activity increased by approximately 16% and 50%, respectively.[20] On the contrary, delaying heavy precipitation and lightning activities during polluted conditions than clean air conditions.[21]

However, all these observations suggest that the occurrence of thunderstorms and lightning activities is highly interdependent with meteorology and air pollution. Therefore, our knowledge about thunderstorm and lightning activity, their dynamics and effects on the air pollution is still insufficient at urban scale.

Present study, an attempt is made to analyse thunderstorms and lightning activities to examine their variations and impacts on local meteorology and atmospheric pollutants. Based on comprehensive long-term datasets of thunderstorms, meteorological parameters, and atmospheric pollutants over Bengaluru, the following aspects are addressed: (1) the intra-annual, inter-annual and long-term trends of thunderstorms and lightning activity; (2) the quantitative linkage between these meteorological parameters and atmospheric composition and trends; and (3) studying the possible changes of the air pollutants, i.e., $PM_{2.5}$, NO_2 and O_3 in the time of thunderstorms.

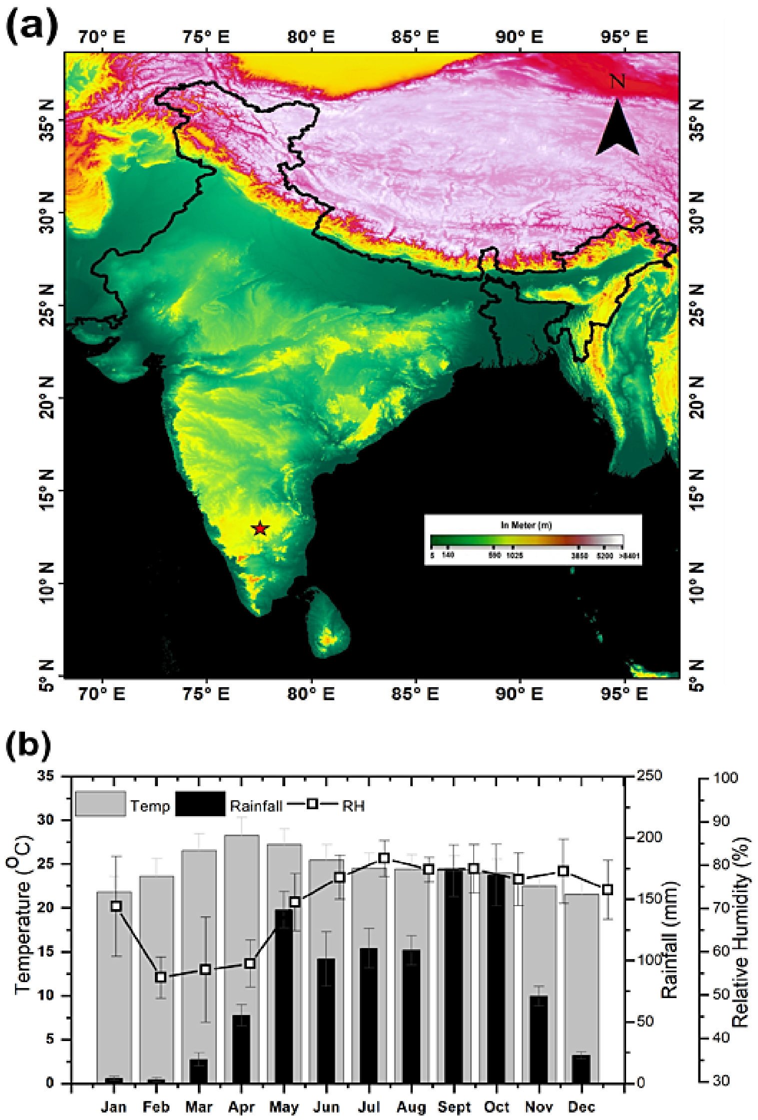


Fig. 1: (a) Map showing the topography and geographical location of Bengaluru city, (b) Monthly average variations in temperature, rainfall, and RH at the observation site from 2011 to 2023.

Materials and Methods

Study Area

Kempegowda International Airport (KIA), also known as Bengaluru International Airport, is located at coordinates 12.97°N and 77.56°E in the Bengaluru district of Karnataka, India. The airport is positioned in the core of the Mysore Plateau, a part of the larger Precambrian Deccan Plateau, at an altitude of 920 meters above mean sea level (AMSL) (Fig. 1a & b). Bengaluru is a fast-growing industrialized metropolitan city, moreover, it is the hub of information technology, economic, cultural, and education in southern India, thus facing a tremendous burden of overpopulation, traffic congestion, and logistic problems.[22] Topographically, the southern part has a complex terrain; the northern part is almost a plateau lined with a prominent ridge along the NE-SW direction. Thus, the meteorological conditions and pollution levels at this location display distinct characteristics when compared to other areas in India.[23] Bengaluru experiences a tropical climate with distinct wet seasons (June to September) and dry seasons (December to February) and also experiences a unique meteorological phenomenon like thunderstorm events during pre-monsoon. Fig. 1(c) presents the meteorological parameters recorded at the India Meteorological Department (IMD) observatory KIA, Bengaluru. The dominant feature of the sampling site is the strong northeast monsoon (September to November) followed by south-west monsoon (June to August). During the northeast monsoon, the site experiences a monthly average rainfall ranging from 71 mm to 173 mm with the highest rainfall usually occurring in September and October whereas during monsoon season, the rainfall range from 101 mm to 112 mm. Bengaluru receives an average annual rainfall of approximately 980 mm. The city experiences mild summers, with average temperatures around 28.26°C in April and May, and mild winters, with temperatures averaging 21.5°C during December and January. Throughout the year, the mean relative humidity stays above 50%, reaching about 80% during the monsoon season.

Meteorological Data

The Thunderstorm activity and meteorological data over a period of 13 years from 2011 to 2013 have been obtained from the Aerodrome Meteorological Office (AMO), IMD, Bengaluru. A thunderstorm day is noted when thunder is heard by an observer at the observatory location from a distance of 25-30 kilometres away, according to the methodology reported by previous researcher.[24] Currently, there are no automated sensors available for accurately detecting thunderstorms. As a result, the determination process relies on traditional methods, conducted manually by skilled observers. It's important to note that these observers typically identify the onset of thunderstorms with a high degree of accuracy. More details are found elsewhere.[25] Half-hourly averaged meteorological data at Bengaluru airport was obtained from the Meteorological Aerodrome Report (METAR) web portal. The data are already quality controlled, and widely used for aviation operations and assist in weather forecasting. Daily accumulated rainfall data collected from the airport meteorological observatory, IMD-Bengaluru. IMD maintains the standardization of meteorological observations, archives, and preserves data after thorough scrutiny which ensures that data quality controls. Further the monthly mean planetary boundary layer (PBL) for the period 2011–2023 was obtained from the MERRA-2 Model (M2TMNXFLX) with a spatial resolution of 0.5° × 0.625°, accessed through the NASA Giovanni portal.

Satellite Data

Space-based Earth observation instruments provide valuable data on environmental parameters across extensive areas, supporting assessments at regional to global scales. In this study, daily lightning flash data were obtained from two sources: (i) the Lightning Imaging Sensor (LIS) aboard the Tropical Rainfall Measuring Mission (TRMM) satellite, covering the period from January 2011 to March 2015, and (ii) the LIS on the International Space Station (ISS), from March 2017 to December 2023. It is important to note that no lightning data was available from April 2015 to February 2017. The LIS sensor is designed to measure the distribution, location, and timing of total lightning events, with a flash detection efficiency ranging from 73±11% to 93±4%.[26] It operates across the entire tropical region, spanning latitudes from 35°N to 35°S. More details about LIS measurement concepts and regional variability can be found elsewhere.[26-27]

Aerosol optical depth at 550 nm (AOD550) data were derived from the MYD08_D3 V6.1 sensor of the Moderate Resolution Imaging Spectroradiometer (MODIS), available at a level 3 grid resolution of 1° × 1°. The MODIS on the NASA-Aqua satellite is essential for monitoring the Earth's surface, providing observations every 1-2 days and collecting data across 36 different spectral bands. It provides valuable insights into atmospheric aerosols and their characteristics on a global scale, and its data has been widely used and validated in various environments across India.[28,29] The Ozone Monitoring Instrument (OMI) aboard NASA's Aura satellite is used to measure the levels of various gases in the atmosphere like NO_2, SO_2, and O_3. It provides data at a spatial resolution of 0.25° by 0.25°, capturing backscattered solar radiation from the Earth's atmosphere. OMI offers daily global coverage and operates within a spectral range of 0.27 to 0.5 μm, which spans ultraviolet to visible light. The air quality products provided by OMI are widely used to evaluate regional and global air quality distributions, achieving an accuracy of 86%. However, satellite data is limited by factors such as local cloud cover, as well as relatively low temporal and spatial resolution. For this study, daily area-averaged data spanning from 2011 to 2023 were retrieved from the NASA Giovanni web portal.

CPCB Air Pollution Data

To assess the influence of thunderstorms on local air pollutants, half-hourly data on $PM_{2.5}$, NO_2, and O3 were obtained from the Central Pollution Control Board in India. The measurements were recorded at the Hebbal site, located about 20 km from the observation point. The CPCB utilizes certified reference standards to calibrate its instruments and adheres to strict protocols for data sampling, analysis, and calibration to ensure the consistency and accuracy of the data. The measurement accuracy is maintained within 2 μg m^{-3}.[30] Present study, pollution data were specifically collected during thunderstorm days.

Methodology

Trend analysis of a time series includes assessing both the strength of the trend and its statistical significance. Various researchers have employed different methodologies to identify trends.[31] Previous researchers have used non-parametric statistical methods employed to analyse the linearity and time-based trends of hydrologic and climatic variables.[48-50] In the study, time series data of meteorological and atmospheric composition parameters (AOD, NO_2, SO_2, and O_3) were analyzed to identify monotonic trends using the nonparametric seasonal Mann-Kendall (MK) test, along with Sen’s method for estimating the slope.

Results and Discussion

Temporal Variation of Thunderstorm and Lightning Activities

Diurnal variation of thunderstorm and lightning activities observed over Bengaluru International Airport from 2011 to 2023 as shown in Fig. 2(a). Both thunderstorms/lightning flashes (i.e., counts/km^2) showed a similar diurnal unimodal increasing pattern after 15:00 hour IST, reaching a maximum around 19:00-20:00 IST (annual mean thunderstorm activities ~350 and flashes ~91). Thereafter reduced until the morning hours up to 10:00 IST. The majority of thunderstorms tend to occur during the afternoon and late evening, suggesting that land surface heating plays a key role in triggering convection. This intense surface heating leads to the initiation of storms. Additionally, the observed variations in thunderstorm and lightning activity align well with numerous prior ground-based and satellite observations in the Indian region.[32,33,10] Researchers[13] studied the diurnal variation of thunderstorms for some selected states and locations in the north-east and adjoining east India region. They found that the maximum thunderstorms occurred during late evening/night in April and afternoon/early evening in May over Jharkhand and Bihar, in the afternoon/early evening over Gangetic West Bengal and Orissa, in early hours/early morning over southern Assam, Manipur, Mizoram & Tripura in both the months but late evening hours observed study found maximum thunderstorms occurred at afternoon/late evening Bengaluru region. Study[34] also noted that in southern peninsular India, the majority of thunderstorms occurred in the afternoon and evening, while in north-western India, thunderstorms were most common in the afternoon. Both regions experienced minimal activity during the morning and forenoon hours. Further, the favourable time of occurrence of thunderstorms is during the night over Puri, afternoon over Keonjhargarh, and evening over Barakpore.[13]

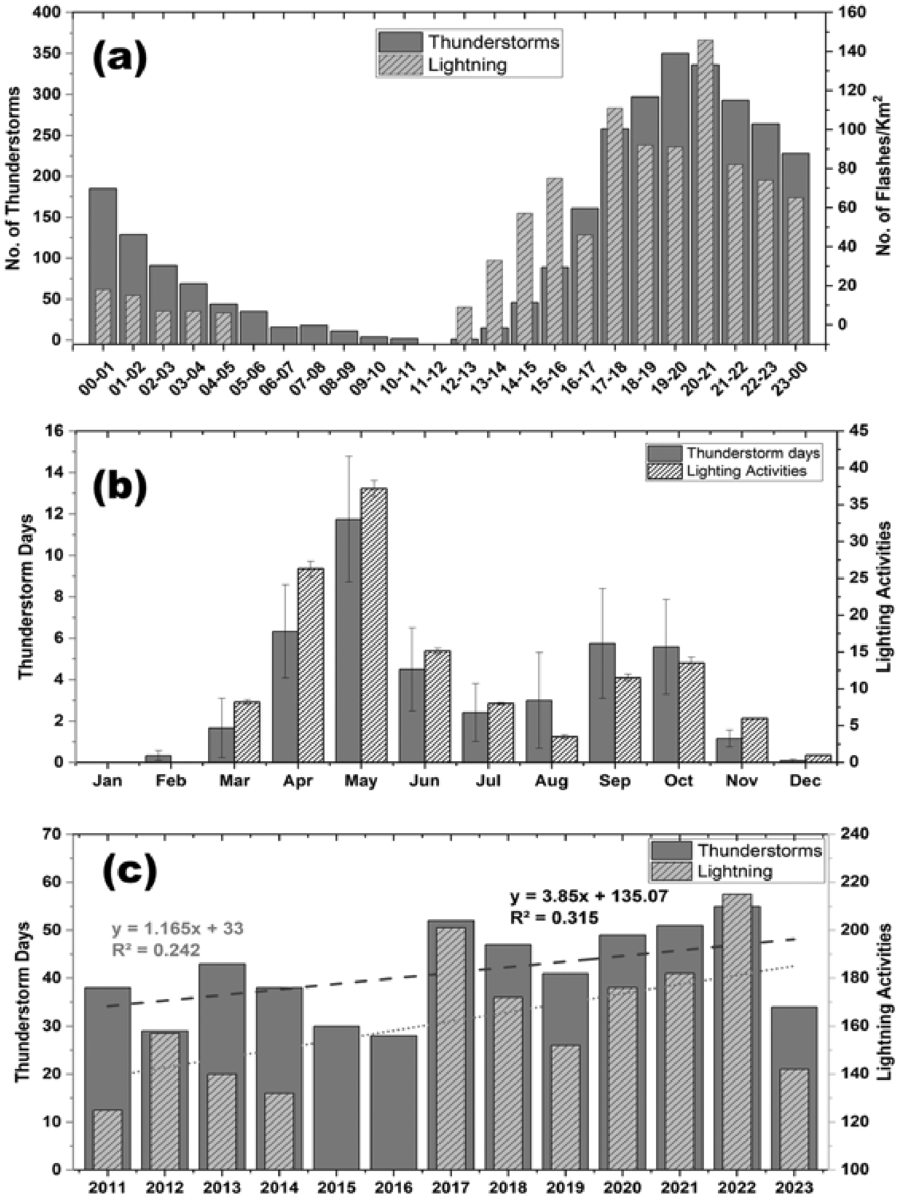


Fig. 2: (a) Diurnal variations in thunderstorm and lightning occurrences, (b) Monthly patterns of thunderstorm days and lightning events, (c) Yearly fluctuations and trends in thunderstorm days and lightning activity recorded at KIA, Bengaluru from 2011 to 2023

The monthly mean of thunderstorm days and lightning activities observed over Bengaluru during 2011- 2023 is shown in Fig. 2(b). The Figure depicts the variations of thunderstorms with lightning flashes pronounced two peaks every year, i.e., The first peak occurs during the pre-monsoon period (March-April), followed by a second peak in the post-monsoon season (September-October). The thunderstorm/lightning flashes increased from March onwards and reached a peak value in May (average ~ 12 thunderstorm days and 37 lightning activities) and then it decreased sharply after the onset of monsoon in June (~5 thunderstorms and 15 lightnings). The thunderstorms again increased during September (~6 thunderstorms and 12 lightnings) and October (~6 thunderstorms and 14 lightnings). After October, the thunderstorm activity showed a decreasing trend from November to December. This is the characteristic feature of thunderstorms and lightning activity over Bengaluru as well as the southern Indian region. The maximum thunderstorm/lightning flashes were observed in May due to high surface temperature and availability of abundant moisture supply supported by other synoptic conditions over the region.[25,10] On a seasonal basis, the pre-monsoon season thunderstorms are occupied by 46.4% of total annual thunderstorm events while in monsoon and post-monsoon thunderstorms are 36.8% and 15.8% respectively. During the pre-monsoon, the highest frequency of thunderstorms is typically linked to the influence of various synoptic (convective) features, including: (i) depressions and cyclonic storms originating in the Indian Ocean, (ii) an east-west concerned with shear line in the upper-troposphere (300-200 hPa) across the Indian subcontinent, and (iii) a discontinuity or trough in the lower tropospheric winds over central and peninsular India. In monsoon, the thunderstorm occurrences are relatively low as the rainfall occurs mostly from stratified clouds formed by westerly and south-westerly winds.[25] Moreover, winds are very strong which does not allow to develop vertical clouds. During September and October, a somewhat weak pressure gradient is observed as the monsoon trough moves southward which leads to the formation of a low-pressure region over the southern region and adjacent to the south-west Bay of Bengal.[35] Similar results are found in different parts of India using the long-term IMD data sets[33] over India and Bangladesh region[36] whereas contrasting results are found in China[16] and Russia.[37]

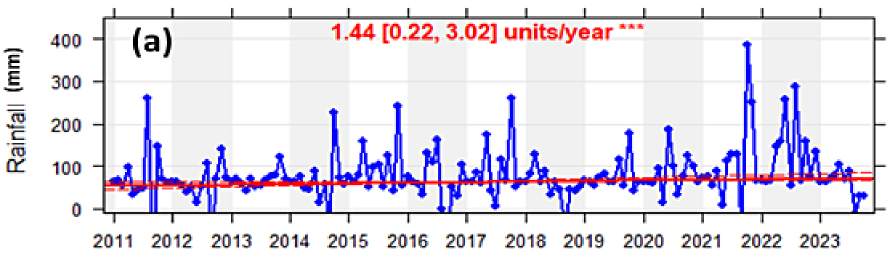
The time series of thunderstorm days and lightning events at KIA, Bengaluru, spanning annually, reveals notable fluctuations. The data shows the highest occurrence in 2022, with 55 thunderstorm days and 215 lightning flashes, while 2012 recorded the lowest values, with 26 thunderstorm days and 82 flashes, over the 13-year period. On average, approximately 41 thunderstorm days and 157 lightning events were recorded annually in the Bengaluru region. To analyze long-term trends, the non-parametric MK-test was applied to the data for thunderstorms and lightning strikes. The results indicate a significant upward trend (at 95% confidence level), with an annual increase of 3.41% for thunderstorm days and 3.3% for lightning flashes. The interannual variation in thunderstorms/lightning activities may be influenced by several factors like El Nino, La Nino, and ENSO oscillations which resulted in regional drought/flood conditions.[9,38] During the study period (2011-2023), it can be seen that in the El Nino years, the thunderstorm days are relatively less while lightning flashes are slightly high. These results supported earlier studies.[39,5] Study[39] used the 15 years (1998-2013) of IMD thunderstorm data and TRMM LIS lightning data over the entire Indian region and found during the El Nino years, the number of thunderstorm days decreased while lightning flashes and flash rates increased. Similar results are observed, with a decreasing trend in moderate thunderstorms during El Niño episodes.[40] Further, a decline in the frequency of severe thunderstorms has been observed, while the number of ordinary thunderstorms have increased over the Kolkata region in the past decade (1997–2008).[5] Similarly, a reduction in pre-monsoon thunderstorm occurrences at three eastern Indian locations—Bhubaneswar, Kolkata, and Ranchi—between 1987 and 2006.[41] While severe thunderstorms have been decreasing over the past decade (1997–2008), there has been an increase in the frequency of ordinary thunderstorms during this period. However, rising global temperatures could significantly contribute to more intense thunderstorms and an increase in lightning strikes.[42] Further, El Niño occurs in the Pacific Ocean during which the south and southeast Asian region experiences warmer and drier and produce lesser no. of thunderstorms, but their severity is higher, and severe thunderstorms produce more no. of lightning flashes.[43,39] Finally, the local meteorology effect is more for thunderstorm initiation instead of the large-scale atmospheric circulation over the Bengaluru region.

Meteorological Parameters and Atmospheric Composition Trends

To assess the impact of thunderstorms on the Bengaluru region, we analyzed long-term trends (linear trends) in various meteorological factors, such as rainfall, surface temperature, RH, surface pressure, wind-speed, and atmospheric boundary layer conditions, from 2011 to 2023. A statistical overview of these parameters is provided in Table 1, and the annual seasonalized linear trends for all parameters are displayed in Fig. 3. During the study period, the average annual accumulated rainfall was approximately 918 mm (± 277 mm), with 51% of the total rainfall occurring between June and September. It is also important to highlight the significant year-to-year variability observed. During the last 13 years period, rainfall showed a significant increasing trend ~1.44 mm $year^{-1}$, with a 99.9% confidence level ($p < 0.001$) over Bengaluru. The annual average temperature is observed to be 24.30 ± 4.51 ºC with large seasonal variations, minimum in winter (21.89 ± 1.66 ºC) and maximum in pre-monsoon (27.22 ± 1.66 ºC). The significant (95% confidence) decline trend in temperature was observed (-0.06 ºC $year^{-1}$) during the study period. From Fig.3, it is also noticed that the inter-annual temperature changes are very small except from September 2014 to May 2016, which may influence the extreme drought period recorded in southern India.[44] The annual mean of relative humidity and surface pressure are found to be 70.9% and 1014.38 hPa. The RH and surface pressure showed significantly increasing trend (0.74% $year^{-1}$ and 0.03 hPa $year^{-1}$) while the surface wind showed a very small decreasing trend (-0.02 ms^{-1} $year^{-1}$). Our findings indicate an upward trend in rainfall, relative humidity, and pressure, along with a downward trend in temperature and wind speed. This suggests a strong correlation among local meteorological variables, which contrasts with the global climate pattern where temperatures are generally on the rise.[45]

Table 1: Statistical summary of meteorological parameters and atmospheric Composition.

Parameter	Mean	Standard Deviation	Intercept	Theil-Sens Slope	%Change	Significant	Result
Rainfall (mm)	918.65	277.2	4.08	1.44	35.3	***	Up-trend
Temperature (ºC)	24.30	4.51	26.56	-0.06	0.22	*	Down-Trend
RH (%)	70.90	5.4	34.37	0.74	2.17	***	Up-Trend
Surface Pressure (hPa)	1014.38	3.03	1012.82	0.03	0.002	+	Up-Trend
Wind Speed (m/s)	3.66	2.04	4.328	-0.015	0.34		Down-Trend
AOD	0.217	0.194	0.103	0.006	5.82	***	Up-Trend
$NO^2 \times 10^{15}$ (molec./cm^2)	3.572	0.903	3.032	0.01	0.33		Up-Trend
SO_2 (DU)	0.181	0.156	0.113	0.0	0		No-Trend
Ozone (DU)	261.87	16.13	246.56	0.33	0.134	***	Up-Trend



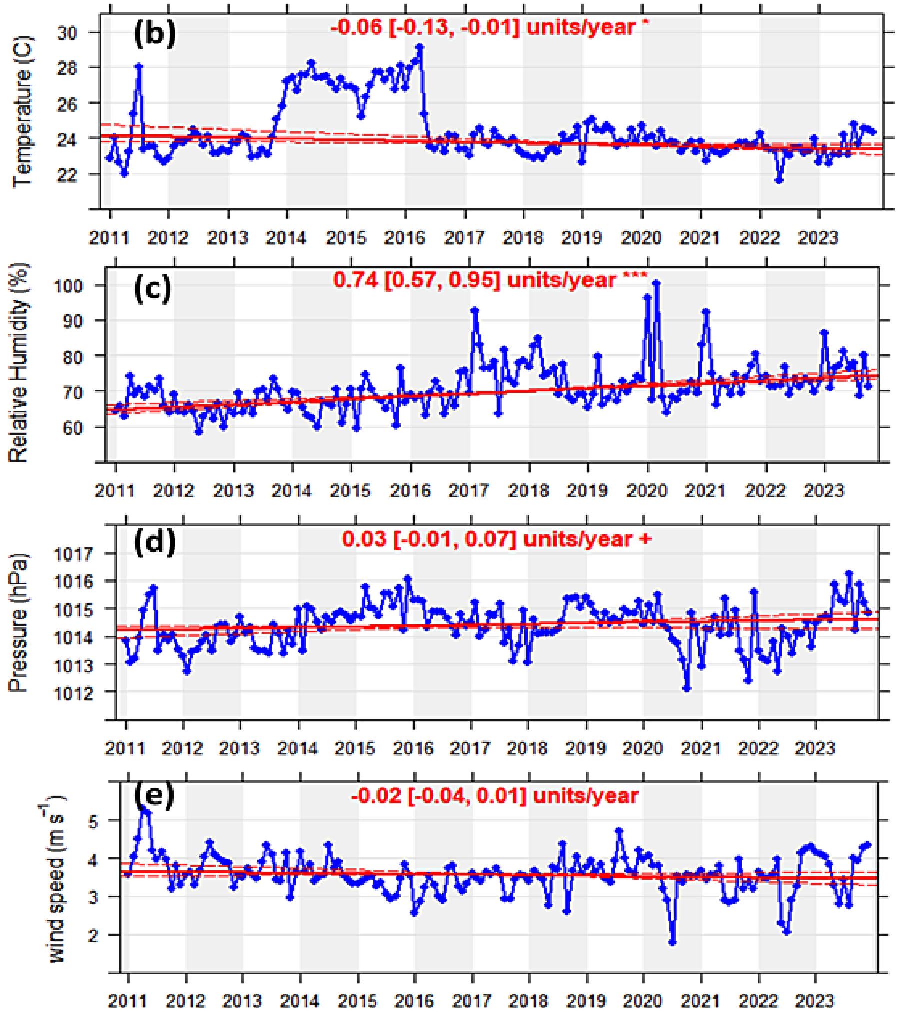


Fig. 3: Inter-annual Theil-Sen linear trend for meteorological parameters observed at KIA, Bengaluru from 2011 to 2023. Panels (a) to (e) represent Rainfall, Temperature, RH, Atmospheric Pressure, and Wind Speed, respectively. The blue circles depict the monthly average values, while the red line shows the estimated Theil-Sen trend. The dashed red line represents the 95% confidence intervals based on resampling data.

Numerous studies have investigated the trends in meteorological parameters, particularly rainfall and temperature, across different regions of India. The results have mixed, with certain areas showing upward trends, while others display downward trends or no noticeable change. Climatic conditions are unique over Bengaluru region as compared to other locations in south-peninsula India since unique topographical future. For instance the rainfall patterns across India have no overall significant trend in monsoon rainfall, however specific regions like Jharkhand, Kerala, and Chhattisgarh have experienced notable declines in rainfall.[46] On the other hand, areas like Jammu & Kashmir, Uttar Pradesh, West Bengal, Maharashtra, Andhra Pradesh, and Karnataka showed marked increasing trends. Similar study[47] reported that 10% of India demonstrated a significant increase in total annual rainfall, while 8% experienced a significant decrease. In terms of temperature patterns, data from 125 weather stations across India revealed that most of the stations, particularly 53 located in the southern, central, and western regions, experienced an increase in temperatures over both seasonal and annual averages. In contrast, 17 stations in the northern and northeastern parts reported a decline in annual mean temperatures between 1941 and 1999.[48] A recent study revealed a downward trend in rainfall in Karnataka, Gujarat, and Rajasthan, while Maharashtra experienced an increase in rainfall. Temperature patterns across these states, with the exception of Maharashtra, generally indicated a rise.[49] A similar study[30] also highlighted a significant increase in rainfall, relative humidity, and surface pressure in the Delhi region between 2007 and 2021, while temperatures and wind speeds slightly declined during the same period.

The trends observed in meteorological parameters for Bengaluru show a rise in surface pressure, accompanied by a decrease in both wind speed and PBL height (refer to Fig. S1). This suggests that atmospheric concentration in the region is likely on the rise. Thus, we investigated the trends in atmosphere components like Aerosol optical depth (AOD; columnar aerosol concentration), Nitrogen Dioxide (NO_2), and Ozone (O_3) concentrations which are highly variable in regional atmospheric phenomena. The long-term (2011–2023) inter-annual trends in AOD (a), NO_2 (b), and O_3 (c) observed over Bengaluru as shown in Fig. 4. The figure reveals a clear inter-annual pattern across all datasets. For example, both AOD and O_3 exhibit upward trends, increasing at rates of 0.01 per year and 0.33 per year, respectively, with a high level of statistically significant ($p < 0.001$) whereas the NO_2 showed a very slight uptrend (0.01 × 1015 molec.cm^{-1} year–1) but it does not show any significant trend. The long-term average values of satellite-based AOD, NO_2, and O_3 are found to be (AOD_{550} ~ 0.21 ± 0.19), (NO_2 ~3.57 ± 0.9 × 1015 molecules/cm^2) and (O_3 ~ 261.87± 16.13 DU) were found highest during pre-monsoon and post-monsoon seasons owing to wind-blown dust and biomass burning activities & local carbonaceous emissions respectively. These results align with the trends observed from 2005 to 2018 in Delhi, where the AOD increased by +2.5% year^{-1} and NO_2 rose by +2.0% year–1. 50 In contrast, over Kanpur, AOD showed a higher increase of +3.1% year^{-1}, while NO_2 increased by +0.9% year–1. A recent study observed a decline in trends across most Indian cities between 2015 and 2020.[51] In Delhi, the concentrations of PM_{10}, $PM_{2.5}$, and NO_2 have decreased by[17] µg/m³ per year (r^2 = 0.69), 5.0 µg/m³ per year (r^2 = 0.58), and 3.3 µg/m³ per year (r^2 = 0.91), respectively. In Kolkata, the rates of decrease for PM_{10}, $PM_{2.5}$, and NO_2 are 5.1 µg/m³ per year (r^2 = 0.15), 12 µg/m³ per year (r^2 = 0.87), and 3.9 µg/m³ per year (r^2 = 0.44). The variations in the trends between these two cities may be attributed to differences in the absolute magnitude of the data, which could result from factors such as variations in instrument sampling methods, time periods, and sample locations.

Table. 2: Summary of Pearson's correlation coefficient (r) values between meteorological parameters and atmospheric components.

	AOD	NO_2 (10^{15}* molec./cm^2)	SO_2 (DU)	O_3 (DU)
Rainfall (mm)	0.300	-0.303	-0.388	0.496
Temperature (ºC)	0.190	-0.073	-0.335	0.581
Relative Humidity (%)	0.077	-0.532	-0.399	0.392
Pressure (hPa)	0.007	0.525	0.536	-0.689
Wind Speed (m/s)	-0.145	-0.441	-0.464	0.619

To explore the relationship between meteorological conditions and air pollutant concentration (AOD, NO_2, SO_2, and O_3) in Bengaluru, Pearson's correlation analysis with a 5% significant level was performed on the monthly average data. Table 2 presents the correlation coefficient values, while Fig. S2 illustrates the graphical representation of the relationship between meteorological parameters and air pollutants. Most of the air pollutants were positively correlated with atmospheric pressure while negatively correlated with wind speed.

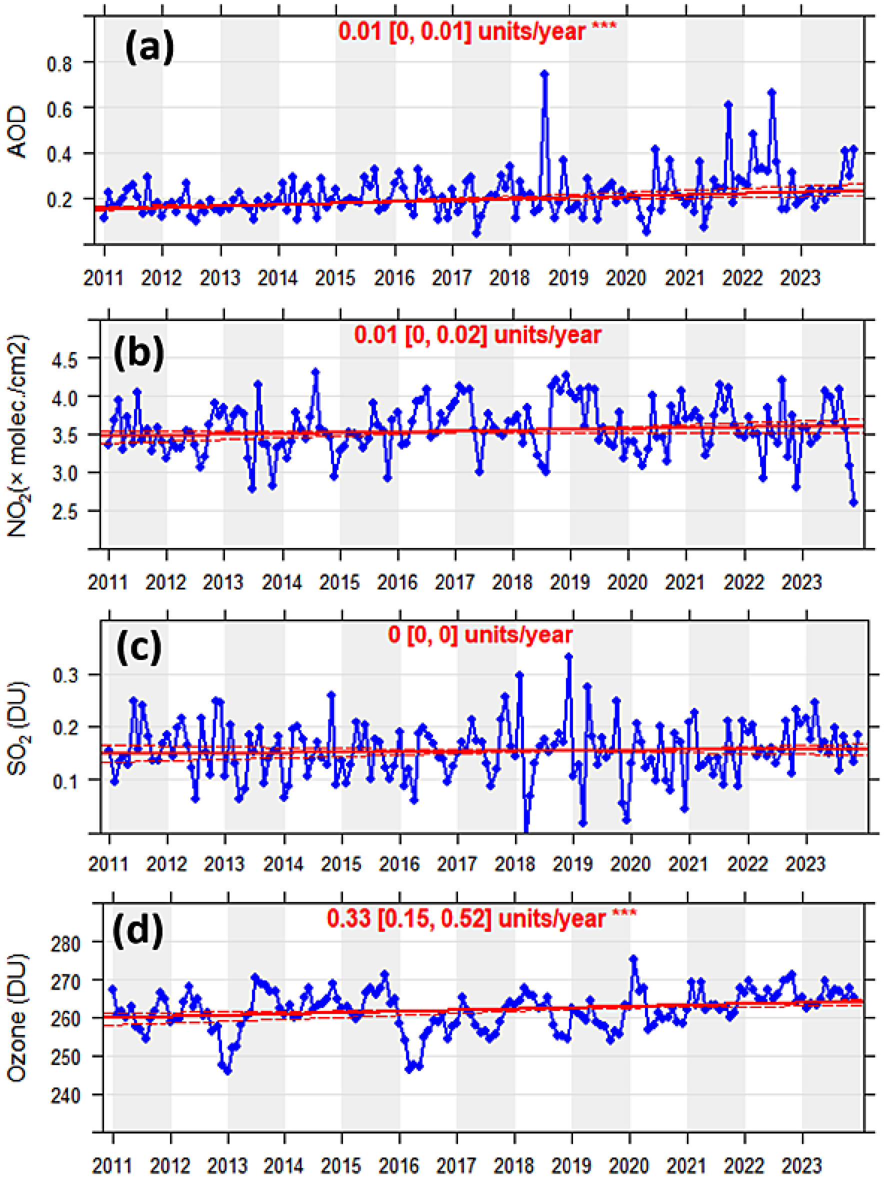


Fig. 4: Inter-annual Theil-Sen linear trend analysis of atmospheric composition parameters from 2011 to 2023 for KIA, Bengaluru: (a) MODIS AOD, (b) NO_2, (c) SO_2, and (d) Ozone. The blue circles represent the monthly average concentrations, while the red line shows the Theil-Sen trend estimates.

An increase in atmospheric pressure suggested that the increase in atmospheric concentration whereas higher wind speeds can lead to dispersion and dilution of pollutants.[52] For the whole data, AOD has a positive correlation with rainfall, air temperature & RH while a negative correlation with wind speed. Typically, an inverse relationship is observed between AOD and rainfall, as AOD primarily consists of soil or road dust, which is rapidly deposited on the ground by rainfall. However, in this study, the positive correlation may arise because the MODIS AOD algorithm tends to interpret cloud condensation as aerosols, especially during the monsoon season.[53] Comparable observations are found in previous studies.[54,55] The concentrations of NO_2 and SO_2 show significant negative correlations with rainfall, temperature, RH and wind speed, while a positive correlation is observed with atmospheric pressure. In contrast, O_3 concentration is significantly positively correlated with all meteorological parameters except for atmospheric pressure. These results are consistent with previous studies,[56,52] and they found that an increase in wind speed leads to improved air quality conditions. Further, it is also observed that gaseous pollutants (SO_2 and NO_2) negative correlation with temperature. This is inconsistent with previous studies,[57,56] they found a positive correlation between all pollutants and temperature.

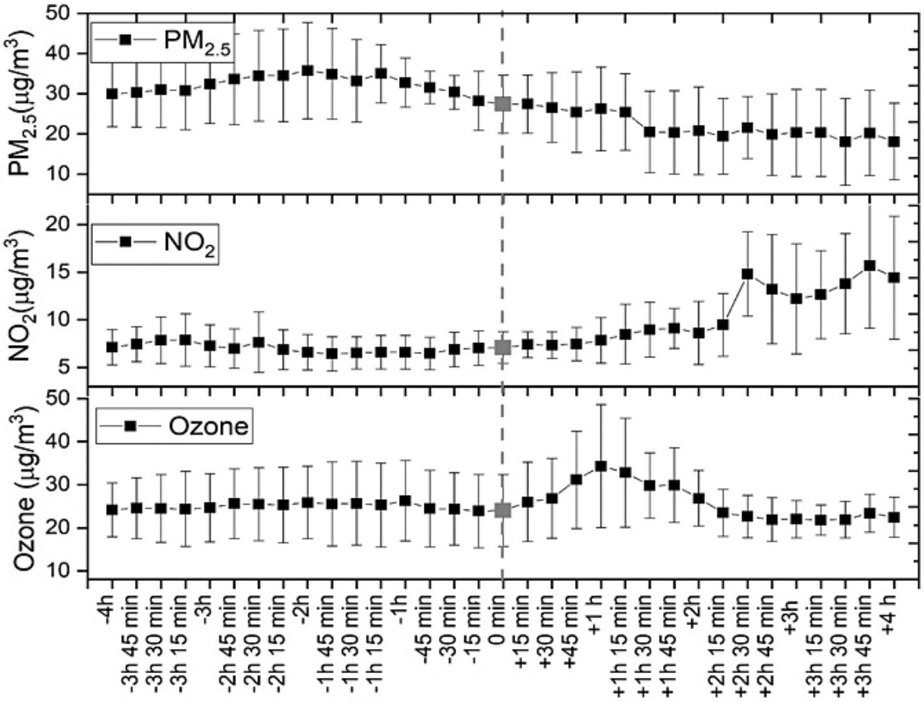


Fig. 5: Variation of average $PM_{2.5}$, NO_2 and ozone concentrations during the time of thunderstorm events over Bengaluru. The dashed line represents the beginning of the thunderstorm.

Impact of Thunderstorm/Lightning Activities on Surface Air Pollution

Thunderstorms, through lightning activity, can impact the regional climate by removing aerosols via rainfall washout and generating nitrogen oxides (NOx), which subsequently affect ozone levels. To assess the possible thunderstorm influences on the ground atmospheric composition, we have chosen more than 15 cases of extremely strong thunderstorm events for the period 2011–2023. Here, considering the account for all these events is moderate rainfall, thus the washout effect on the trace gases is negligible. Dynamics of pollutant concentrations ($PM_{2.5}$, NO_2, and O_3) were studied precisely during eight-hour period in each event i.e., 4 hours before the starting of the thunderstorm and 4 hours later. The variation of the concentrations is shown in Fig. 5. In Fig. 5, the time axis (x-axis) is used where zero minutes indicates a moment of thunderstorm starting (real-time is different for different cases, few individual cases are shown in Fig. S3, S4, S5, S6 & S7). Fig. 5 depicts the $PM_{2.5}$ concentration gradually decreasing after the beginning of a thunderstorm. This may be due to the washout of PM particles by the thunderstorm rain. It is also noticed that in some cases the PM concentration increases before the beginning of the thunderstorm (see Fig. S4.) which may be due to the convective activity associated with wind-blown dust. The ozone concentration sharply increases just after the beginning of the thunderstorm and reaches maximum after 1 hour and goes on decreasing while the late increasing response (after 2 hours) was observed in NO_2 concentration (Fig. 5b). Comparing the concentrations observed before the beginning of the thunderstorm (-4 hours) and after the thunderstorm, the $PM_{2.5}$ concentration is reduced by 37% whereas the concentrations of NO_2 and Ozone are increased by 41% and 6% respectively. The combined effect of lightning activities and wind reversal within the thunderstorm are responsible for increased concentrations of surface NO_2 and Ozone.[58] The results closely match the observed values in Moscow[37] and Kolkata.[59] Recent research has highlighted alterations in surface pollutant concentrations that occur right after local thunderstorms.[60-61] Surface particulate matter concentration was always reduced and the NO x ($NO+NO_2$) was always enhanced, but the ozone response depended on the local regimes. Study[62] reported that in Pune, India, the production of NOx from lightning during thunderstorms can significantly impact surface ozone concentrations. The fresh NOx emissions do not immediately contribute to photochemical ozone production, which results in decrease in ozone concentration. Further, the positive correlations observed between lightning flashes and surface concentrations of NOx and ozone in Taipei, Taiwan (with mixing ratios of ΔO3/ΔNOx = +1.3)[63] and Kolkata, India (mixing ratios of ΔO3/ΔNOx = +0.6)[59] indicate that ozone production was consistently sustained in these megacities.

Conclusion

The present study examines the temporal variations of thunderstorm and lightning activities and its impacts on local meteorological parameters and atmospheric composition using the ground and multi-satellite observations over KIA, Bengaluru during 2011 - 2023. The study was also made to analyse the response of the thunderstorm activity on local air pollutant concentrations ($PM_{2.5}$, NO_2, and O_3). This provides valuable insight into the variability of thunderstorm activity associated with atmospheric concentration and climate variability in the past 13 years. The major findings are summarized as follows

Thunderstorms were most commonly observed between 7 and 9 PM (IST), with a significant number of events continuing until 3 AM. Rare occurrences were noted from 3 AM to noon, typically linked to triggering mechanisms such as cyclonic activity in the Bengaluru region. Additionally, variations in the timing of thunderstorms were noted based on the specific region and season.

The variation of thunderstorm activity over the Bengaluru region follows a biannual pattern. It attains the first maxima in the month of May followed by April. It remains a slightly steady state till the end of August (monsoon season) and attains a second peak in September followed by October months. The temperature and abundant moisture supply from the southwest/northeast monsoon create a favourable condition for the occurrence of thunderstorms over the region.

Thunderstorm activity shows considerable year-to-year variability. An annual average of 41 thunderstorm days and 157 lightning events were observed over Bengaluru; it's also shown in a significant (95% confidence level) increasing trend with a rate of 3.41% and 3.3% per year respectively.

Throughout the study period, there was a notable fluctuation in meteorological parameters and air pollutant concentrations. Over the past 13 years, there have been notable upward trends in rainfall, relative humidity, and atmospheric pressure, with increases of 1.44 mm $year^{-1}$, 0.74% per year, and 0.03 hPa per year, respectively. In contrast, temperature and wind speed have experienced slight declines, decreasing at rates of -0.06 °C per year and -0.0_2 m/s per year. Satellite observations reveal a general rise in atmospheric concentrations, with AOD, NO_2, and O_3 increasing at rates of +0.01 per year, 0.01 µg/m³ per year, and 0.33 µg/m³ per year, respectively. However, SO_2 levels showed no significant change.

The influence of meteorological parameters on air pollutant concentration is different for different pollutants. Except for O_3, the concentration of other air pollutants (AOD, NO_2 & SO_2) was significantly negatively correlated with wind speed but positively correlated with atmospheric pressure. A strong correlation was observed between AOD and O_3 with temperature, possibly because higher temperatures lead to increased convective activity and turbulence. As a result, atmospheric aerosols may be transported from the surface to higher altitudes which leads to higher AOD and for O_3 under high-temperatures accelerating photochemical reaction rates leads to higher O_3 production.

Thunderstorms have a considerable influence on surface pollutant levels, though the extent of this effect changes depending on the type of pollutant and thunderstorm severity. $PM_{2.5}$ concentration gradually decreases after the beginning of the thunderstorm whereas quick response (below 1 hour) is observed in O_3 concentration while delayed response (after 2:30 hours) in NO_2 concentration. Variations attributed to the mature phase of the thunderstorm activity and linked with the wind reversal characteristics.

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- **Chanabasanagouda Sanganagouda Patil:** Conceptualization, Methodology, Data analysis, Visualization, Writing- Original manuscript preparation.
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