Analysis of Thunderstorm Activities in Moscow and Bengaluru

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ABSTRACT

Thunderstorm events in Moscow (Russia) and Bengaluru (India) are commonly occurred atmospheric phenomena resulting disasters in the cities. There is a need of understanding the climatology of such events so that the results can be used as important tools for forecasting and improving the predictability of such disaster events. In this work, the climatology of thunderstorms in both the cities are presented using long term data. Climatology of thunderstorms in Moscow city is analyzed using the data from Moscow State University (MSU) Meteorological Observatory for the period 1954-2017 whereas over Bengaluru city, long term data (1969-2017) observed at the Meteorological Centre of India Meteorological Department have been analysed. The total amount of days with thunderstorms as well as their duration during a year in Moscow nearly remains the same; changes in time of these parameters during the last 64 years are non-significant. Same results are also observed at the city of Bengaluru in India during 49 years of analysis. The annual course of thunderstorms is noted by a clear maximum from May to August in Moscow due to frequent unstable stratification, strong convection, and high humidity. Over Bengaluru also, the maximal frequency has been observed in May followed by in the monsoon season i.e. June-September. The diurnal variation analysis demonstrates maximal occurrence probability of this phenomenon in the evening in both the cities. Bengaluru has also witnessed thunderstorms in the night time, but during the morning time there is rarely any event recorded. The impact of thunderstorm on the air composition has also been quantified and it is observed that neither Ozone (O3) nor Nitrogen Dioxide (NO2) demonstrates significant changes in their surface concentrations during the strong thunderstorms over Moscow.

Keywords: *Thunderstorms, Climatology, Annual Course, Long-term Changes, Air Composition, Ozone and Chemical Reactions.*

1. Introduction

The reason for this work is based on the fact that our knowledge about thunderstorms, their dynamics and influence on the air quality in big cities is still insufficient. Thunderstorm is a dangerous weather phenomenon which is detected by the ground meteorological networks all over the World and is often connected with shower, wind strengthening and, sometimes, even strong squall. Among others, thunderstorms may significantly influence on the air composition as a result of both the chemical reactions inside lightning, and strong vertical mixing in Cb clouds. The evolution of thunderstorms is associated with processes like splitting or merging and it generally leads to convection intensification resulting extreme rainfall (Ćurić et al., 2009; Spiridonov et al., 2010). As one knows, necessary conditions for this phenomenon include not only strong thermal convection but also a high water vapor pressure in the atmosphere. As a result, the spatial distribution of the thunderstorms' probability all over the World is complex and characterized by the main maximum in wet Tropics close to Equator (Central Africa, North of South America, Indonesia, Eastern India, etc.), clear minimum in dry Tropics (e.g., over Sahara desert) and secondary maximum in mid-latitudes (e.g., Mediterranean and Eastern Europe, including Moscow region). It is known that about 1800 thunderstorms are detected in the World simultaneously (Climate of Russia, 2001). Also, there is a need to understand the diurnal variability of the frequency of such events which will help in the now-casting and short-term forecasting. These events are generally accompanied by heavy rain falls, large hails, wind, flash floods resulting huge disasters like loss of life and properties in the society (Brooks, 2013; Papagiannaki et al., 2017). The knowledge of the thunderstorm climatology will be helpful in the weather prediction and the disaster assessment at a city scale. There is also a need of quantifying these events by studying their trends resulting due to climate change.

There are no automatic sensors for the reliable detection of thunderstorms yet. Thus, methodology of their determination remains traditional: it is done manually by specialist-observer (Changnon and Changnon, 2001; Bielec-Bąkowska, 2003). Moscow, the capital city of Russia sometimes witnessed severe thunderstorms resulting loss of life and property in the city. Main climatologic features of the thunderstorm phenomenon in Moscow was known from several works (Arkhipova, 1957; Climate, Weather, and Ecology of Moscow, 1995; Climate of Russia, 2001). However, these researchers in the past used old data so now there is a need to update the earlier results under the climate change situations.

In India, the pattern of thunderstorm variability is studied by several researchers for different periods at city scales (Gupta and Chorghade, 1961; Krishnamurthy, 1965; Kumar, 1992; Moid, 1996, Kar and Bandopadhyay, 1998; Santosh et al., 2001). The long term spatial trend at country scale is also carried out recently which indicates there are mainly 3 thunderstorm maximum regions over northwest Indian Himalayan region, east India and the southern peninsular India and there is a diffused trend in the thunderstorm maxima over the north and south peninsular India (Sen Roy and Roy, 2021). Some studies indicate that the hot and humid extensive land region of the ITCZ over the Indian subcontinent is suitable for frequent thunderstorm. There is also east west contrast of the thunderstorm activities (Monhar and Kesharkar, 2003) prevailing over the north Indian region. Tyagi (2007) represented the climatology of thunderstorms over the whole of India and his analysis with observations from the India Meteorological Department (IMD) shows highest annual frequency of Thunderstorms (around 120) observed over Assam, Jammu and west Bengal while lowest frequency is observed in Ladakh (<5). In southern India Kerala recorded highest thunderstorm followed by Karnataka (50-60 days) and Andhra Pradesh (50-55 days). In the west part of country i.e. Saurashtra and Kutch record lowest number (less than 15 days) of thunderstorm in the country. Some studies also focused on the field experiments on the observation and modeling of thunderstorm activities in the south Asian region including India (Das et al., 2014).

Bengaluru, the capital city of the state of Karnataka situated in the south peninsular India (12°.40'N,13°.15'N, 77.20°E, 77.50°E) covering an area of 741 Km2 is witnessing the growth in migrating population with a population density of about 4000/ km2 and growing in industry also results in more anthropogenic forcing to the environment. It is very much needed to know the thunderstorm disaster climatology in the city as it witnessed frequent thunderstorms in recent times and also these events have direct implication on multiple sectors like aviation, agriculture, water resource, and health and disaster management. Earlier studies on the thunderstorm describe the climatology for shorter period (Mohapatra et al. 2004; Agnihotri, 2013) and it is shown that the convective activity is very consistent with the seasonal variability.

In this work, the updated analysis of quantification of the climatology of thunderstorm events over Moscow in Russia and Bengaluru in India is carried out using the long term observed data from the Moscow State University (MSU) Meteorological Observatory and the observatory of Meteorological Centre at Bengaluru city. The temporal distribution of the thunderstorm activity at annual, monthly and diurnal scale is also presented. Both the observatory data sources are more accurate and provide best estimation of the thunderstorm activities in the cities.

Besides climatology as mentioned earlier, the possible changes in the ground air composition also have been studied in the time of extremely strong thunderstorms by the data of joint ecological station of Obukhov Institute of Atmospheric Physics (IAP) and MSU, Moscow. The surface concentrations of two minor air gases: ozone and nitrogen dioxide are considered in this study as these gases have direct impact on the human health. The main chemical effect is the generation of NO in the lightning channel due to extremely high air temperature and, then, its oxidation to NO2. Ozone may be also generated there as a result of dissociation of oxygen molecules. An important task needed is studying the possible changes of the air composition in the time of thunderstorms. Similar analysis on a base of ground, aircraft and satellite measurements was presented in earlier works (Davis, 1973; Huntriser et al., 2009; Winterrath et al., 1999; Jadhav et al., 1996). A lot of similar measurements regarding nitrogen oxides was collected in the review work by Schumann and Huntrieser, 2007. Usually, an increase in both of O3, and NO2 as a result of thunderstorms were found in the air columns, at some heights and, sometimes, even in the ground air layer (Davis, 1973). Thus, one of the objectives of this study is to test whether indeed the surface concentrations of these two gases demonstrate significant changes in the time of thunderstorms or not both in Moscow and Bengaluru.

2. Data and Methodology

General climatology of thunderstorms in Moscow city (Russia) has been investigated for the period from 1954 to 2017 by using the data of MSU Meteorological observatory including their total probability, duration, annual and diurnal courses. Similarly, for the same analysis over Bengaluru city in India the thunderstorm data were collected from the daily weather report and three hourly synoptic observations using the data from the meteorological observatory at the Meteorological Centre of IMD in the city centre for the period from 1969 to 2017. The number of days with thunderstorm and the duration of the thunderstorm are computed. The inter annual variability and long term monthly climatology as well as the diurnal variations are also computed.

In this study also the possible changes in the ground air composition due to thunderstorm activities are investigated and quantified during the extremely strong thunderstorm events by using the surface concentrations of two minor air gases i.e. ozone and nitrogen dioxide observed at the Joint ecological station of Obukhov Institute of Atmospheric Physics (IAP) and MSU, Moscow. Special joint ecological station of Obukhov Institute of Atmospheric Physics and Lomonosov Moscow State University operated at the Meteorological Observatory of the University since 2002 till 2014. Surface concentrations of a lot of minor air gases (ozone, nitrogen oxides, carbon oxide, sulfur dioxide, methane, etc.) were measured there with high accuracy and with 1 min temporal resolution. The instruments operating at the station were of the same types as those used in the GAW WMO network. They were regularly calibrated according to the international standards and standard admixtures provided by the Climate Monitoring and Diagnostics Laboratory (United States) and the Max Planck Institute for Chemistry (Germany). The secondary European standard ENV 0341M No.1298 has been at the IAP since 2003 and was used to regularly calibrations (Elansky et al., 2015). Among others, ozone was measured at this station by Dasibi 1008-RS and 1008-AN gas analyzers from the ozone-caused attenuation of 253 ηm ultraviolet radiation; the measurement error is ±1 ppb. Nitrogen oxides (NO and NO2) was measured by TE42C-TL gas analyzer; the chemiluminescence method according to the intensity of infrared radiation resulting from the chemical reaction is used. The measurement error of NO2 is about ±1 ppb.

3. Results and Discussion

In this segment, the climatology of thunderstorms in Moscow and Bengaluru are presented in Section 3.1 and 3.2 respectively. The results of change of surface concentration of O3 and NO2 during high thunderstorm events are discussed in Section 3.3.

3.1. Climatology of Thunderstorms in Moscow

The long-term dynamics of thunderstorms in Moscow city is presented for the period of 64 years (1954-2017) in Figure 1. Two parameters i.e. number of days when thunderstorms, one or several, took place and, besides, durability of all thunderstorms during each year were analyzed. As it is seen that the long-term changes for both the parameters are non-significant. Both number of days with thunderstorms and their durability demonstrate negative linear trends so this number on an average slowly reduces with a rate of 0.08 per year whereas the durability becomes less on 0.22 of the hour (i.e. 13 min) per year. However, with the account of great dispersion, a statistical significance of both trends is low (significance parameter R2 is only 0.05 and 0.12 for the number of days and durability, respectively). Thus, current climate warming does not lead yet to clear changes in the probability of thunderstorms at least, in Moscow region. As a result of the analysis during the period 1954–2017 it is observed that there are 26 thunderstorms days on an average during a year; record high value was 45 in 1984. It also should be noted that nearly the same average value was detected in the past: ~25 days in Moscow region for the period 1891-1948 reported in earlier study (Apkhipova, 1957); from 22 to 28 days at separate weather stations in Moscow for the period 1935-1980 according to another study (Climate, Weather, and Ecology of Moscow, 1995); 26 days in Central region of European Russia, including Moscow, for the period 1936-1980 as reported in a study (Climate of Russia, 2001). Previous record high value of days with thunderstorm in Moscow was almost the same: 44 (Climate, Weather, and Ecology of Moscow, 1995).

Regarding durability, the average value for the same period is 31 hours 06 min of thunderstorms during a year. This value is less than total durability estimation for the φ=55º latitude and the λ=30…50º longitude: 50 hours during a year (Climate of Russia, 2001). According to a study average thunderstorm durability in Moscow varied in 1935-1980 from 17 to 34 at different weather stations (Climate, Weather, and Ecology of Moscow, 1995). Maximal durability (68 hours 56 min) was observed at MSU during 64 years in 1959.

The monthly climatology value of the number of days with thunderstorms in Moscow is presented in Figure 2. As one can see it demonstrates a strong maximum in warm season from May to August. At this time, a probability of thunderstorms is comparatively high i.e. more than 4 days with thunderstorms during each of these four months. The highest probability of days with thunderstorms (7.6 out from 31 during whole year) in July is a result of the highest air temperature and the highest air humidity. This result confirms previous data about annual course of thunderstorms which was also detected maximum in July (from 6 to 8 days with this phenomenon) at all weather stations in the city (Climate, Weather, and Ecology of Moscow, 1995). In April and in September probability is much lower: 1.0 and 1.3, respectively. In October, this parameter almost goes to nothing and remains close to zero up to March. Nevertheless, even in winter thunderstorms are possible in Moscow although their probability is extremely low: only 0.06 in December, 0.03 in January and 0.06 in February. It means that during the whole period of 64 years, thunderstorms were detected in Moscow only four times in December and February and only two times in January. Nothing to say, that winter thunderstorms are weak. Evidently, the annual course of thunderstorms is quite different for mid-latitudes.

One more aspect of the analysis is studying the diurnal variability or the daily course of thunderstorms. As is seen from Figure 3, over the Moscow city, the highest probability of thunderstorms is on evening time from 5 to 7 p.m. Average number of separate thunderstorms which started on 7 and 5 p.m. on average of 52 years is equal to 197 and 180, respectively. After 7 p.m. this parameter begins to fall quickly. After midnight this reduction becomes slower, and the least value is observed at around 11 a.m. i.e. only 14. After 11 a.m. the number of thunderstorms begins to grow quickly. Thus, maximum and minimum in the daily course of the thunderstorm amount are replaced forward in time in the comparison with maximum and minimum of the air temperature daily course. Indeed, the strongest thermal convection in mid-latitudes is connected with a time of the warmest ground temperature in the afternoon (from 2 to 5 p.m.). This replacement is explained by the inertia of development of Cb clouds which leads to the later beginning of thunderstorm on the evening when the surface starts cooling.

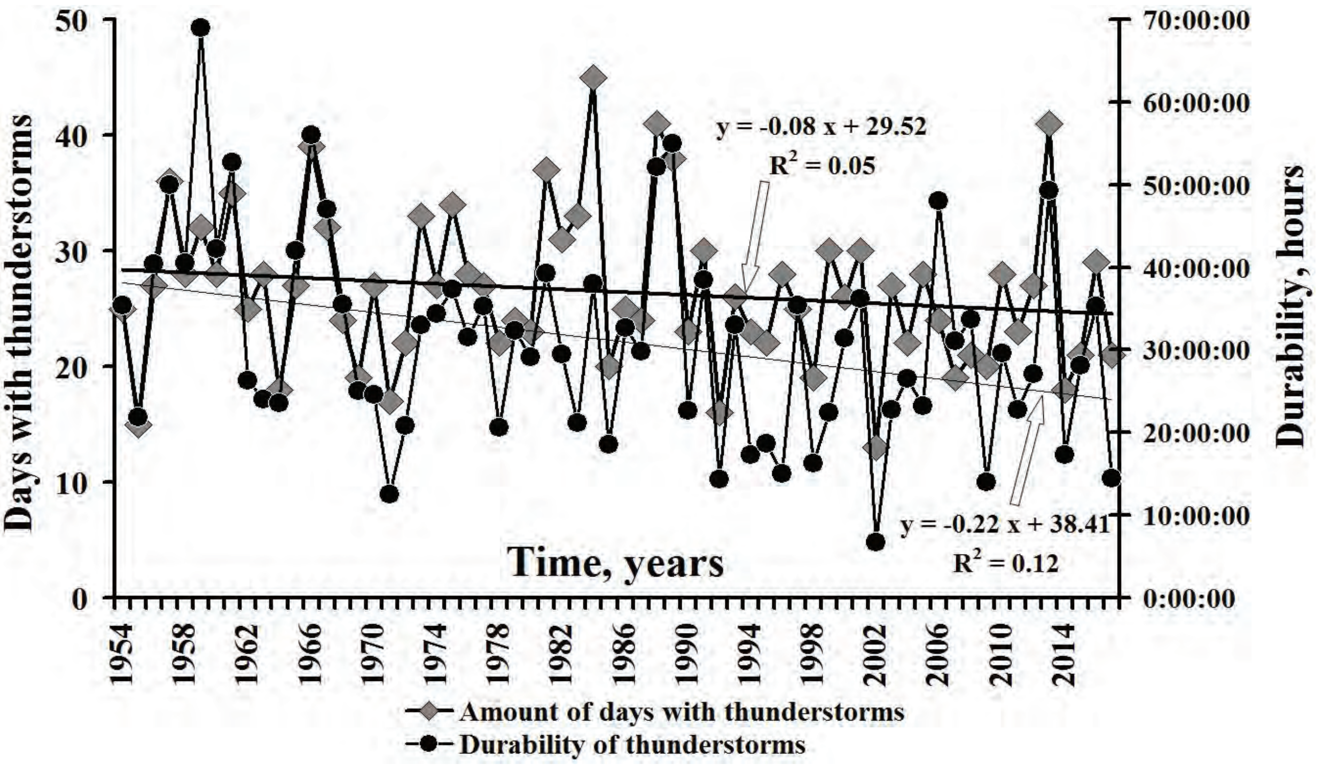

Figure 1: Long-term changes of thunderstorms in Moscow analyzed by using the data of Moscow University Meteorological observatory during 1954–2017. White arrows indicate linear trends for which the equation and significance parameter are presented.

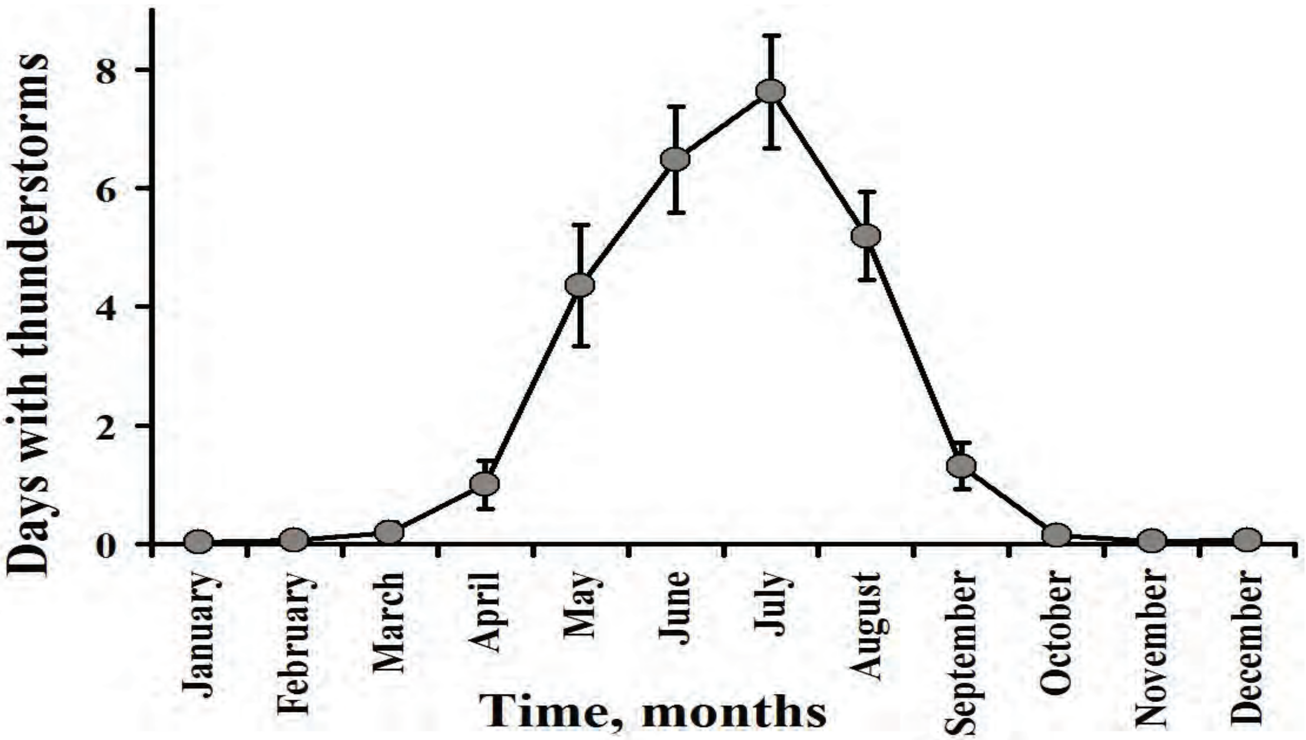

Figure 2: Annual course of thunderstorms in Moscow observed by the Moscow University Meteorological observatory in 1954–2017. The confidence intervals are calculated with 0.99 confidence probability.

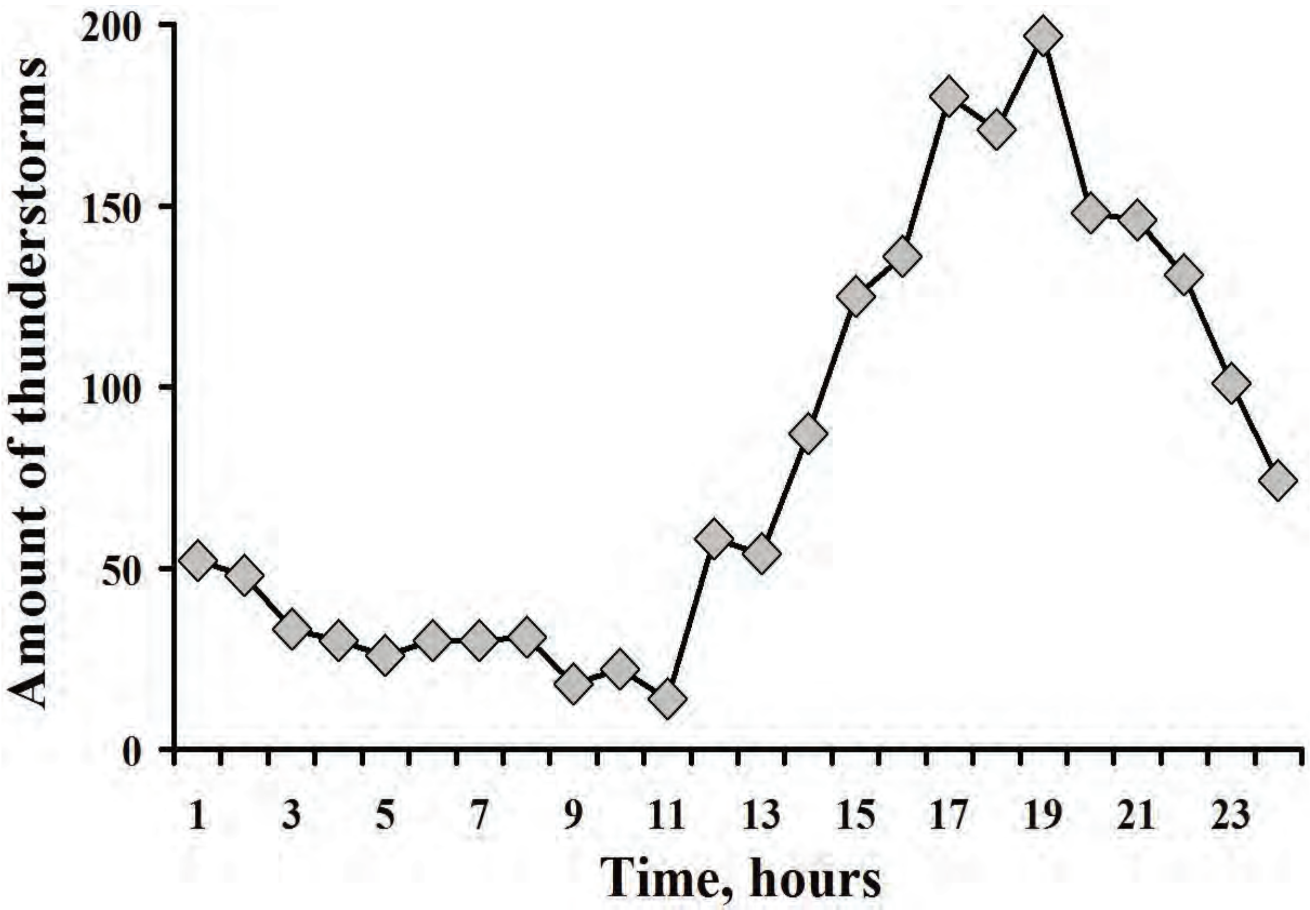

Figure 3: Diurnal variability of the course of thunderstorm as observed by the Moscow University Meteorological observatory at UTC +3.00. The results represent the averaged data analysis over the years 1966 to 2017.

3.2 Climatology of Thunderstorms in Bengaluru

The inter annual variability in the total number of days with thunderstorm over the city of Bengaluru along with the total duration of the events in each year starting 1969 up to 2017 are presented in Figure 4 which clearly indicates a positive but not significant trend in the thunderstorm days in the city. The trend of thunderstorm days is about 0.09 days/year and that of the durability is very low i.e. 0.37 hrs/year or 22.2 min/year. During the 49 years of analysis of the thunderstorms, it is observed that on an average in a year the city witnesses 44 days of thunderstorm with an average durability of 86hr 15 min. The standard deviation in the number of thunderstorm day found to be 9.45 days and the deviation in the total annual durability of thunderstorm is about 28hours. While analyzing the trend for first 25 years (1969-1993) the thunderstorm day trend is very strong (+0.42 days/year) and in the recent 24 years (1994-2017) it's about zero (-0.1 days/year) and the trend of durability is 1.89 hours/year during the period 1969-1993 and only 0.3 hours/year in the recent 24 years i.e. 1994-2017 as presented in Figure 4. The maximum number of thunderstorm days (62) observed in 3 years i.e. 1977, 1991 and 2017 whereas the minimum (22) was observed in 1990. Similarly, in terms of total annual thunderstorm duration the maximum is recorded in 1991 (161 hours) and the minimum is recorded in 1990 (40 hour) and the average thunderstorm time during a year is about 27.9 hours.

The monthly climatology of the number of days with thunderstorms over Bengaluru is presented in Figure 5. It clearly indicates that 40% events occurred during the south west monsoon (June-September) 43% during pre-monsoon (March-May) and 17% during post monsoon (Oct-Nov) season respectively which is consistent

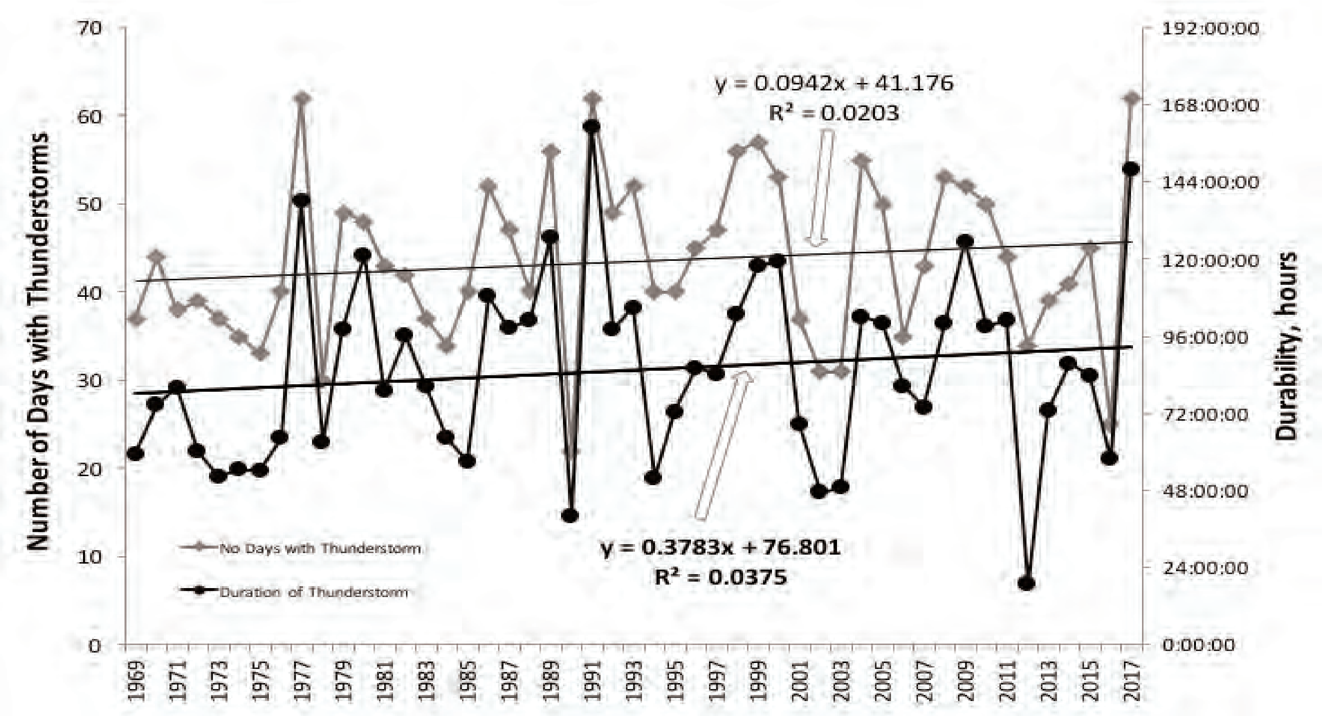

Figure 4: Long-term changes of thunderstorms in Bengaluru as observed by the observatory at the Meteorological Centre, IMD in Bengaluru for the period 1969 to 2017. White arrows indicate linear trends for which the equation and significance parameter are presented.

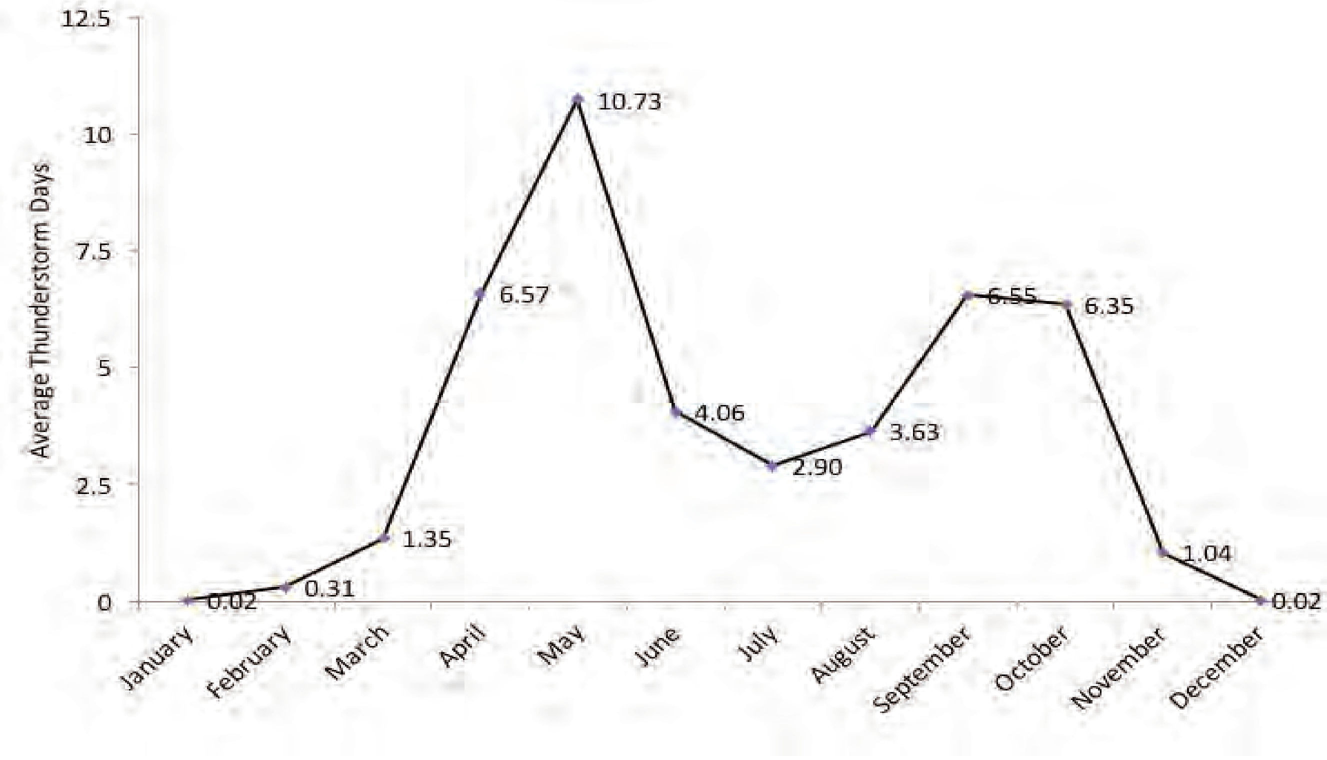

Figure 5: Monthly climatological frequency curve of the thunderstorm days over Bengaluru city. The analysis represents the average analysis of thunderstorm data for the period 1969-2017.

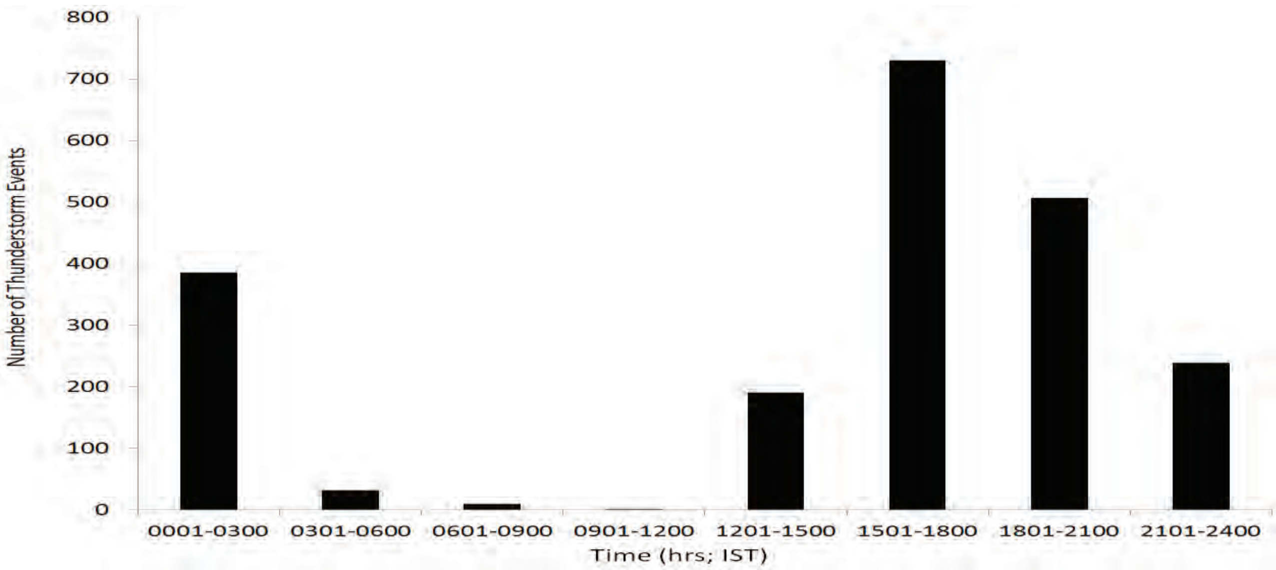

Figure 6: Diurnal variability of the course of thunderstorm as observed in Bengaluru city. The results represent the averaged data analysis over the years 1969 to 2017.

with the earlier reported works for the period 1980-2010 (Agnihotri, 2013). The winter season (Dec-Feb) has insignificant thunderstorm events over the city. The monthly climatology also shows an increase in the average thunderstorm days in a month from February (0.3 days) to April (6.6 days) and maximum in May when it attains 10.7 thunderstorm days in a month and then decreased during monsoon (June-August) season as this time the rainfall is mostly due to stratified clouds formed down slope because of westerly and south westerly winds (Agnihotri, 2013) and again the frequency increase to 6.6 and 6.4 days during September, October and become low in November (1.0) and close to zero in December over Bengaluru. Only 1 event of thunderstorm witnessed in December 1987, January 2004 whereas in February total 15 days of thunderstorm is recorded in this long-term analysis over the city of Bengaluru. The maximum thunderstorm events observed in the month of May due to high temperature and humidity and other supporting synoptic conditions (Agnihotri, 2013; Mohapatra et al., 2004; Rao and Ramamurty, 1972; Basu and Mondal, 2002).

In order to study the diurnal variability in the time of commencement of the thunderstorm, we have used the 3-hourly synoptic report by Meteorological Centre, Bengaluru observation and here a day is divided into 8 three hourly periods like 0001-0300, 0301-0600 and so on. The time selected is considered as Indian Standard Time. It is observed from the analysis (Figure 6) that mostly 35% of thunderstorms occurs during the time 1501-1800 hrs IST followed by 24% during next time segment of 3 hrs i.e. 1801-2100 hrs IST in the evening. About 18% and 11% of the events occurred during midnight i.e. 0001-0300hrs and late evening i.e. 2101-2400 hrs IST respectively. During afternoon in the time 12 noon to 15 hrs also Bengaluru experienced about 10% of the total thunderstorms during the analysis period from 1969 to 2017.

The season wise computation indicates during all the seasons i.e. pre-monsoon, monsoon and post monsoon mostly the thunderstorm occurs in the afternoon and late evening time over the city of Bengaluru. This is mainly due to the strong thermal convection in the city during afternoon and early evening.

3.3 Influence of thunderstorms on the air composition.

As it is known, thunderstorms may influence the air composition (concentrations of minor air gases, especially ozone and nitrogen oxides) and the possible reasons for O_3 changes due to thunderstorms are:

(a) Chemical reactions inside lightning leader.

(b) Strengthening of vertical mixing in Cb clouds and intensification of the ozone downward transport to the ground from upper troposphere.

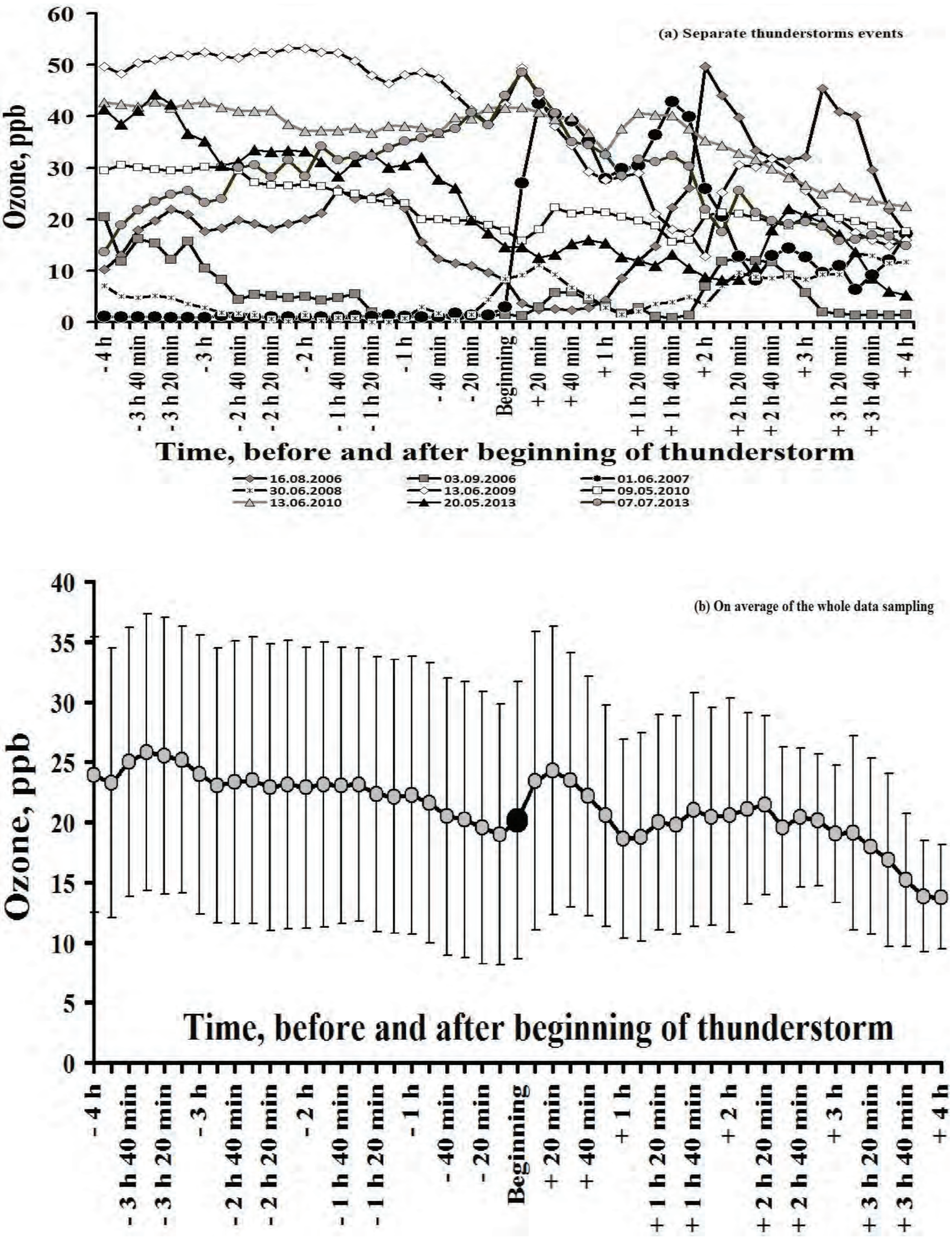

Figure 7 (a & b): Surface concentrations of ozone during the time of severe thunderstorms in Moscow. The confidence intervals are calculated with a significance level of 5%.

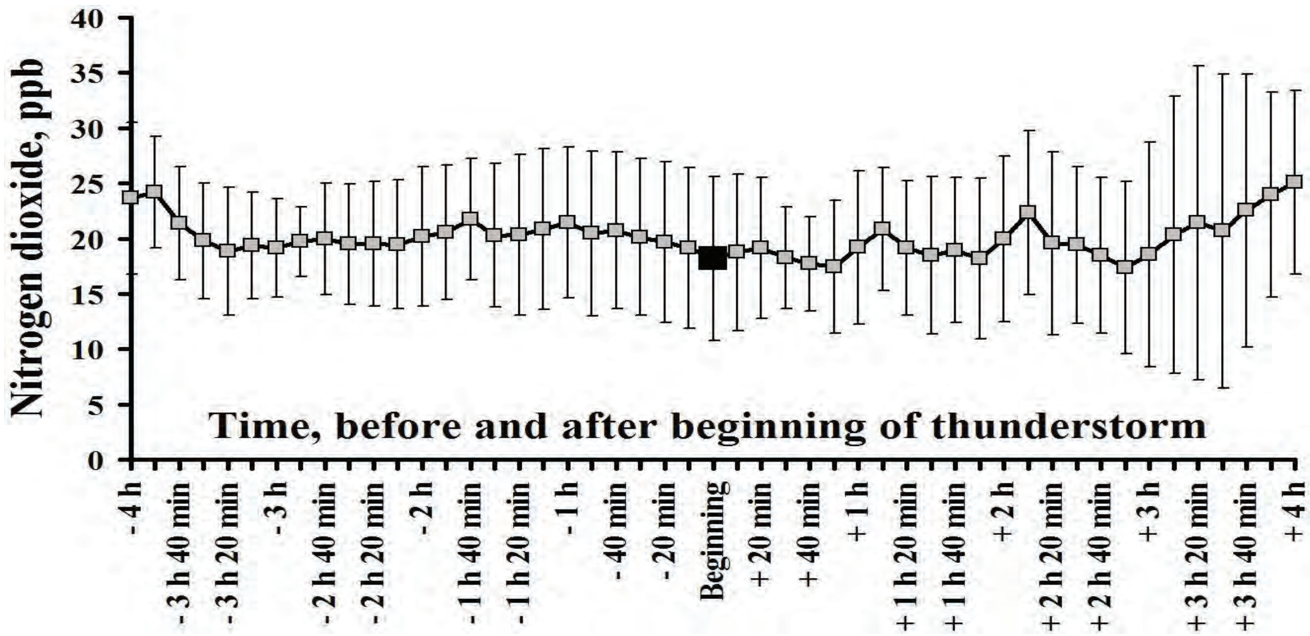

Figure 8: Surface concentrations of nitrogen oxide during the time of severe thunderstorms in Moscow. The confidence intervals are calculated with a significance level of 5%.

(c) Change of background ozone levels at different air masses (in cases of frontal thunderstorms).

The main chemical reactions as a result of a thunderstorm are:

- $N_2 + O_2 \rightarrow 2\ NO$
- $2\ NO + O_2 \rightarrow 2\ NO_2$
- $NO_2 + OH^- \rightarrow HNO_3$
- $3O_2 \rightarrow 2\ O_3$

For the analysis of possible changes of the ground air composition in the time of thunderstorms nine cases of extremely strong thunderstorms by stationary data for the period 2002–2014 in Moscow were chosen. It should be noted that the time of thunderstorm beginning is detected by an observer as a rule with high accuracy. Dynamics of two gases, ozone, and nitrogen dioxide, was studied precisely during eight hours (four hours before starting of the thunderstorm and four hours later). In Figure 7a a conventional time axis is used where zero indicates a moment of thunderstorm starting (really its time is different depending on a case). As a result, (Figure 7a) dynamics was found as quite different at separate thunderstorm events. Sometimes the ozone surface concentration sharply increases just after the beginning of thunderstorm (e.g., on June 1st, 2007). However, in other cases that is in conditions of a strong thunderstorm it is, vice versa, becomes less (May 20th, 2013) or remains nearly the same (for example, on May 9th, 2010). Calculation on average of this data sampling (Figure 7b) demonstrates a weak maximum of the O_3 level during 30 min just after thunderstorm beginning. However, as one can see, this effect is non-significant with the account of confidence intervals (which are calculated with the 0.95 confidence probability). So, no statistically reliable changes in the surface ozone dynamics due to thunderstorms are found. Similar conclusion (Figure 8) is made about the dynamics of the NO_2 surface concentrations.

4. Conclusions

The important results of this study are summarized below:

(i) No statistically significant long-term changes in the probability of thunderstorm occurrence during the last 64 years in Moscow and 49 years in Bengaluru are found. However, the thunderstorm occurrence in Bengaluru has generally been more than that over Moscow.

(ii) Annual course of thunderstorms in Moscow demonstrates clear maximum from May to August;

winter thunderstorms are extremely rare events there. Same analysis over Bengaluru indicates the maximum events in May followed by the monsoon period (June-August), secondary maximum in September-October and almost no events during intense winter i.e. December and January.

(iii) In a day, the time of beginning of thunderstorm in Moscow is noted maximum on the evening from 5 to 7p.m. The analysis over Bengaluru indicates the beginning is high during the afternoon (3 to 6p.m) followed by the evening (6 to 9 p.m.). Also, good number of events started during 9p.m to next morning 3a.m. Whereas very rare events initiated during morning 3a.m. to 12 noon throughout the year in both the cities.

(iv) No significant changes have been found in the ground air composition during the severe thunderstorms in Moscow.

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