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Association of thunderstorm frequency with rainfall occurrences over an Indian urban metropolis

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ABSTRACT

Thunderstorm, associated with strong convective activity in the tropics, is one of the most prominent weather phenomena in the atmosphere. A critical analysis is done on the nature of variation of the thunderstorm frequencies over an urban metropolitan location Kolkata (22°32′N, 88°20′E), India with the pre-monsoon and monsoon rainfall amounts during the period 1997–2008. The occurrences of severe thunderstorms are decreasing during the last decade, although the number of ordinary thunderstorms occurring in this period has an increasing trend. A decrease in Convective Available Potential Energy (CAPE), Vertical Wind Shear (VWSH), Deep Layer Shear (0–6 km AGL) and an increase in Lifted Index (LI) may be an indicator for the suppression of the severity of thunderstorms over the urban location. There is also a decreasing trend for the pre-monsoon rainfall and an increasing trend in the monsoon rainfall amounts over the region. A further study indicated a significant positive correlation for all the types of thunderstorm (severe, ordinary and total) events with the pre-monsoon rainfall amount which are mainly associated with the vigorous convective phenomenon. On the other hand, a significant anti-correlation is observed between the severe thunderstorm frequencies with the monsoon rainfall amount for the same period. The decrease in the severity of the thunderstorm events is accompanied by an increase of pre-monsoon cloud Liquid Water Content (LWC) with Integrated Water Vapor (IWV). Hence, there is an expected strong association of the thunderstorm frequency with the pre-monsoon and monsoon rainfall amounts at this tropical location. Possible explanations are presented.

1. Introduction

Thunderstorms are one of the most vigorous convective activities that Indo-Gangetic plain including Kolkata (22°32′N, 88°20′E) and Northeast India (20°N–24°N latitude, 85°E–93°E longitude) encounter every year during the pre-monsoon season (March–May). It is a mesoscale weather phenomenon with space scale varying from a few kilometers to a couple of 100 km and time scale varying from less than an hour to several hours. The wind in these severe thunderstorms comes generally from some north-westerly direction and hence is commonly known as "Nor'westers" or "Kal-baishakhi" (Midya et al, 2011b). The phenomenon is important to meteorologists and a serious hazard to aviation (Awadesh, 1992; Litta et al., 2012a). Severe thunderstorms as a function of large-scale environmental conditions have also a strong impact on climate change (Brooks, 2013). The prediction of this weather event has continued to be a serious challenge to meteorologists within the framework of mesoscale meteorology (Chaudhuri, 2008a). The mesoscale convective systems can develop under the large-scale envelope of the seasonal and low-level trough over the West Bengal–Bihar–Jharkhand belt with a possible embedded low pressure area. The common feature of the weather phenomenon is the outburst of severe local convective storms,

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which may reach tornadic violence associated with thunder, squall lines, lightning, torrential rain and hail, causing considerable loss in agriculture, damage to property and sometimes even loss of life. The casualties reported due to lightning associated with thunderstorms in this region are among the highest in the world. Depending on the conditions present in the atmosphere, the three stages of thunderstorm formation — the cumulus stage, the mature stage and the dissipation stage, can take anywhere from 20 min to several hours to occur. The thunderstorm occurrences are generally divided into two categories — severe (horizontal wind speed > 64 km/h) and ordinary (horizontal wind speed ≤ 64 km/h). Determination of these two types of thunderstorms comes primarily from the wind profile in conjunction with the instability condition of the atmosphere.

The phenomenon of monsoon is global in character, affecting a large portion of Asia, parts of Africa (Sahel) and northern Australia, which cover more than 50% of the world population. Asian Monsoon is a spectacular phenomenon due to the huge landmass of Asia collocated with the huge water mass of the Indian Ocean (Mooley and Shukla, 1987). Indian summer monsoon rainfall is the rainfall carried by the southwest monsoon during June to September every year in India and accounts for approximately 80% of the annual Indian rainfall. Monsoon occurs mainly due to the differential heating of land and ocean and deflection of wind due to rotation of earth. India being a tropical country, the south-west monsoon winds have great importance in Indian agriculture. The regions which receive the largest rainfall are along the west coast of India and the states of Assam and West Bengal in northeast India. In these regions orographic features play an important role, because the moisture laden monsoon winds strike against physical barriers by way of mountains. Apart from orographic features, atmospheric convection plays an important role during the monsoon and the period just preceding it. In the pre-monsoon months, parts of northeast India, especially West Bengal, Bihar and Assam experience severe pre-monsoon thunderstorms or Nor'westers. The rainfall associated with these thunderstorms is of a transient nature. The intensity of precipitation is high but the rainfall is of short duration. Monsoon rain is of a different genre. It has continuous spread over days, and the intensity of precipitation is not as high as that of convective rain. Ganda and Midya (2012) reported that rainfall trend of most of the urban areas is gradually increasing with respect to non-urban regions of Indian landmass. It is concluded that AVOC (Anthropogenic Volatile Organic Compounds) which is related to tropospheric ozone may play an important role to form CCN (Cloud Condensation Nuclei) of proper dimension of raindrop formation.

In recent years, atmospheric scientists have shown much concern about the pronounced differences in the precipitation yield and dynamical and electrical properties of the tropical mesoscale cumulonimbus regimes embedded in the monsoonal convection during the monsoon season and the more vigorous but sparsely distributed thunderstorms of the pre-monsoon season (Rutledge et al., 1992; Williams et al., 1992; Jayaratne, 1993). Considerable amount of literature is available on thunderstorm studies over the Indian region as well as in the other region (Sohoni, 1931; Rao and Raman, 1961; Raman and Raghavan, 1961; Williams, 1961; Chaudhury, 1961; Balogun, 1981; Sivaramkrishnan, 1990; Awadesh, 1992; Moid, 1995; Chaudhuri, 2008b; Midya et al., 2010, 2011b) during several decades to reveal the related climatology, frequency, diurnal variation, month wise and season wise distribution of thunderstorms. Saha et al. (2011) mentioned that the pre-monsoon thunderstorm frequency over Kolkata attains its maximum during solar peak phase of the 23rd solar cycle and it is due to the increase of solar activity. The pre-monsoon thunderstorm frequencies increase after the solar maximum due to the depletion of O_3 concentration and increase of greenhouse gases over Kolkata. The rate of depletion of total column ozone (TCO) is also related to wind speed of tropical cyclone and surface temperature (Midya et al., 2011a; Midya et al., 2012; Midya and Goswami, 2013). Again, humidity and rainfall are reported to be correlated to ozone concentration (Midya and Saha, 2011a,b; Midya et al, 2011c). Williams et al. (1992) have pointed out that although the above mentioned differences usually common in the tropical monsoonal storms, there is a need for an assessment of similar information from the Indian region where land and warm waters are juxtaposed for monsoon development. Since the convective phenomena play an important role in the generation of thunderstorm activities in the tropical region, and at the present location, as both pre-monsoon and monsoon rainfalls are associated with convection, it is intended to study the association of rainfall with thunderstorm activities (Manohar et al., 1999) which affect the lives of people, particularly at urban locations. The purpose of this paper is to present the study of thunderstorm frequency over Kolkata (22°32′N, 88°20′E) and summer monsoon rainfall over the same in Gangetic West Bengal.

2. Data and methodology

The data for the thunderstorm over Kolkata (22°32′N, 88°20′E) during pre-monsoon and monsoon seasons for the period 1997–2008, used in the present study, are collected from Regional Meteorological Centre, Kolkata. We have used the ISMR (Indian Summer Monsoon Rainfall) dataset of the Indian Institute of Tropical Meteorology (IITM), Pune (ftp://www.tropmet.res.in). The sub-divisional rainfall data from Gangetic West Bengal, which includes the location of Kolkata (Fig. 1), are utilized for the present study. The dataset covers pre-monsoon (March to May) and monsoon (June to September) months.

The thunderstorm occurrences are divided into three categories in our study — severe (horizontal wind speed > 64 km/h), ordinary (horizontal wind speed ≤ 64 km/h) and total (severe and ordinary) thunderstorm. The yearly variations of the severe, ordinary and total thunderstorm frequencies over Kolkata against pre-monsoon and monsoonal rainfall amounts over Gangetic West Bengal (Kolkata) are also plotted.

Radiosonde measurements obtained by the University of Wyoming from the website http://www.uwyo.edu at Kolkata, India (22°32′N, 88°20′E), a tropical location, during the period 1997–2008 for the months March to May (pre-monsoon) and June–September (monsoon), have been used in the present study. Usually, radiosonde observations are made twice a day, at around 00 and 12 GMT (0530 and 1730 IST). The stability indices, namely, Convective Available Potential Energy (CAPE) and Lifted Index (LI) data were also extracted from the Radiosonde measurements for the same

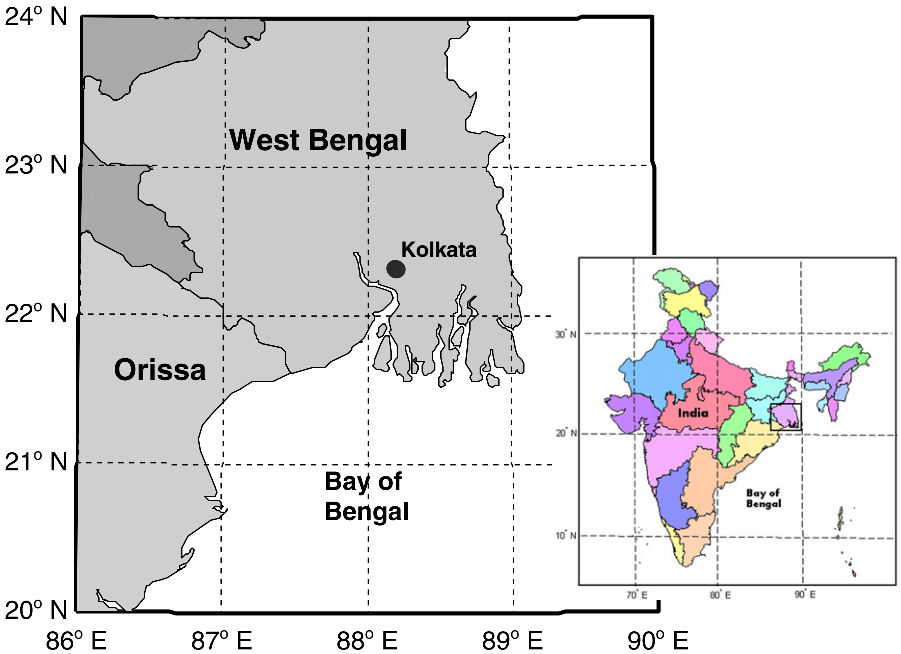

Fig. 1. Political map of India, the zoomed portion in a square box is shown outside the map presenting the geographical location of Kolkata showing the area of interest (black circle) for thunderstorm data from IMD (India Meteorology Department, Kolkata).

period. The data of pressure, temperature and dew point temperature at different heights are available up to a height of 15 km. According to the Salonen model (Salonen et al, 1990; Salonen and Uppala, 1991), the liquid water density as a function of height (h) is given as

$$\begin{aligned} w(h) &= w_0\{(h-h_b)/h_r\}^a exp(ct) \qquad t>0_\circ C \\ &= w_0\{(h-h_b)/h_r\}^a exp(ct) p_w(t) \quad t<0_\circ C \end{aligned} \tag{1}$$

where, t is the temperature at height h, $w_o = 0.17$ g/m^3, $c = 0.04$ per °C, $h_r = 1500$ m, $h_b =$ cloud base height in m, a ($=1.0$) is the parameter for height dependence. The cloud water is completely in liquid phase when temperature, t, is greater than 0 °C and completely in solid phase when $t < -20$ °C. The fraction of liquid water, $p_w(t)$, that exists when -20 °C $< t < 0$ °C is given by,

$$p_w(t) = 1 + t/20, \qquad -20_\circ C<t<0 \;_\circ C. \tag{2}$$

These relations were also used by Maitra and Chakraborty (2009) to study liquid water content and cloud attenuation at the present location. Total cloud LWC of cloud is given by,

$$LWC = \int_0^H w(h)dh, \; H \text{ being the cloud thickness.} \tag{3}$$

Integrated Water Vapor (IWV) is the measure of the amount of water vapor present in the atmosphere at a time instant. The vapor concentration is obtained by using the following relation

$$v_c = 1.739 \; x \; 10^9 x R_h x \; 100 \; x\theta_f \; xet \tag{4}$$

where, v_c is the vapor concentration, R_h is the relative humidity of the location, θ_f is the potential temperature of the air parcel over the region, t being the temperature in degree centigrade of the location for the study. Now IWV is calculated by integrating the vapor concentration (v_c) through the path from the sea-level upto the available height.

The data of vertical as well as horizontal wind have been collected upto pressure level from surface to 200 hPa from NCEP/NCAR Reanalysis database (Kalnay et al., 1996) provided by the ESRL PSD, Boulder, Colorado, USA (http://www.esrl.noaa.gov/psd.html). Vertical Wind Shear (VWSH) and Deep Layer Shear (0–6 km AGL) are obtained from that wind data which are also important in the determining the severity of convective activities. VWSH or the change of vertical wind speed with altitude interacts dynamically with thunderstorms to either enhance or diminish vertical draft strengths and is determined by the difference in upper and lower-level wind shears. Deep Layer Shear through 0–6 km above ground level (AGL) discriminates strongly between supercell and non-supercell thunderstorm environments and is calculated by vector subtraction of the changes in horizontal wind speed with altitude within 0–6 km AGL. Upper-level Wind Shear (ULWS) is the change in vertical wind speed with the change in altitude at the pressure levels 200 hPa and 500 hPa respectively, and has been computed by using the relation

$$ULWS = \frac{VWS_{200} - VWS_{500}}{Z_{200} - Z_{500}}. \tag{5a}$$

Similarly, Low-level Wind Shear (LLWS) is the change in vertical wind speed with the change in altitude at the pressure levels 700 hPa and 1000 hPa (surface) respectively which is computed by using the relation

$$LLWS = \frac{VWS_{700} - VWS_{1000}}{Z_{700} - Z_{1000}}. \quad (5b)$$

Thus, VWSH is computed from the difference between upper and lower level vertical wind speeds as follows:

$$VWSH = ULWS - LLWS\left(s^{-1}\right). \quad (5c)$$

VWS_x is the vertical wind speed at *x*hpa pressure level; Z_x indicates the altitude at *x*hpa pressure level.

3. Results and discussion

3.1. Trends in thunderstorm frequencies over Kolkata during 1997–2008

The yearly variation of severe, ordinary and total thunderstorm frequencies over Kolkata shows an interesting pattern (Fig. 2). There is a decreasing trend for the severe thunderstorm frequency (Fig. 2a) with correlation co-efficient, r = 0.602 whereas an increasing trend for both the ordinary (r = 0.762) and total (r = 0.636) thunderstorm frequencies for the period 1997–2008 (Fig. 2b and c). It may be noted that, the frequency and intensity of these severe thunderstorms are controlled by large scale atmospheric flows and synoptic systems present during the pre-monsoon period. In the lower troposphere, pressure troughs, low-pressure areas and wind convergence lines are important. In the upper troposphere, a trough in westerlies and jet-stream are commonly associated with Nor'westers. Superposition of favorable upper and lower tropospheric conditions will result in generally widespread outbreaks of Nor'westers (Lal and Pawar, 2010). Three necessary ingredients needed for the initiation of a thunderstorm event are sufficient moisture in lower troposphere with high surface temperature, conditional instability (an unstable air mass) and a source of lifting force to initiate the convection. It is well known that in the tropics, air parcels raised from

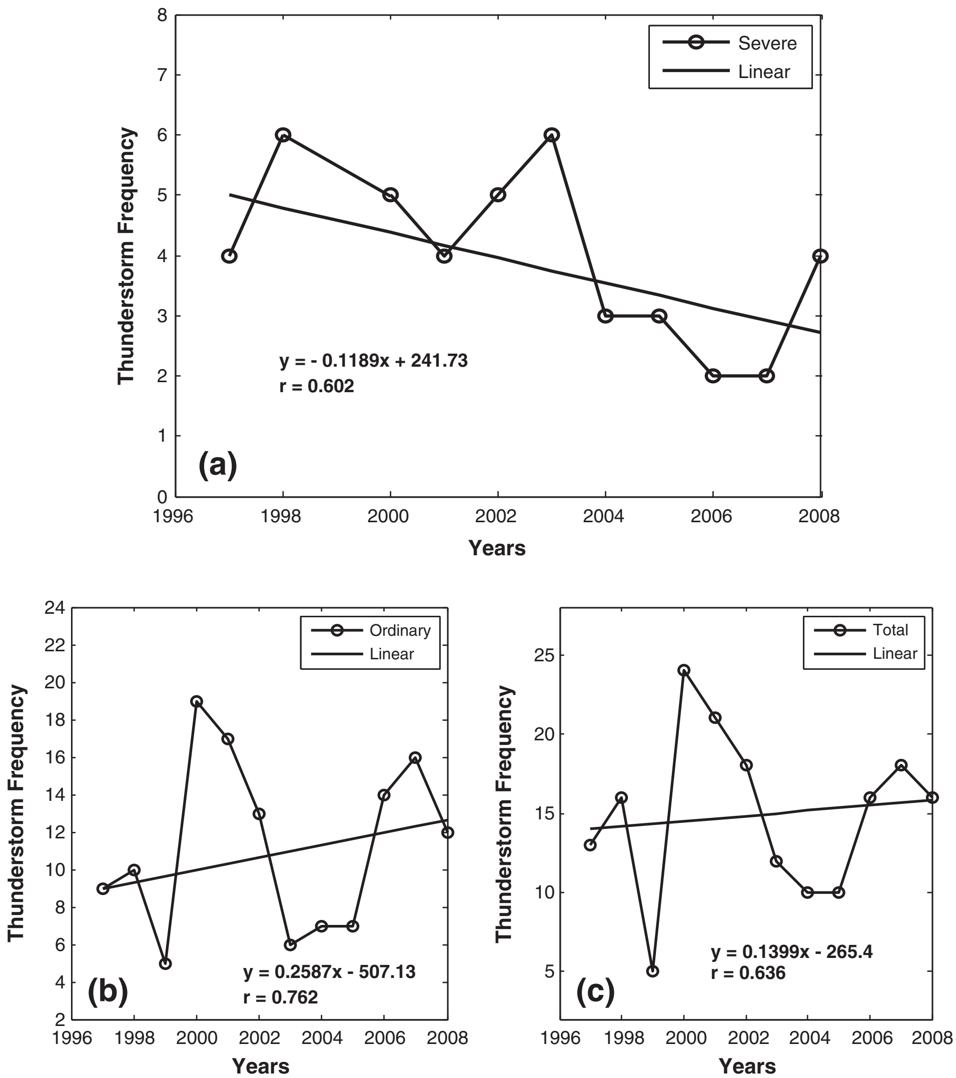

Fig. 2. Trends in (a) severe (b) ordinary and (c) total thunderstorm frequencies over Kolkata during 1997–2008.

above 900 hPa rarely become buoyant (Holton, 1992; McBride and Frank, 1999). Hence the surface based CAPE was chosen to represent the convective potential of the atmosphere. CAPE represents the amount of buoyant energy available to accelerate a parcel vertically from the level of free convection (LFC) to equilibrium level (EL) and a CAPE value greater than 1500 J kg^{-1} is suggested by Rasmussen and Wilhelmson (1983) as being necessary for supercell to form.

$$CAPE = \int_{EL}^{LFC} g\left(\frac{Tvp - Tve}{Tve}\right) dz \quad (6)$$

where, LFC and EL are respectively the heights of Level of Free Convection and Equilibrium Level; T_{vp} is the virtual temperature of the parcel at pressure level P through which parcel rises; T_{ve} is the virtual temperature of the environment at pressure level P through which parcel rises; g is acceleration due to gravity. The LFC is the height on or above LCL, where the parcel temperature is greater than environment temperature and it is found by raising a parcel moist adiabatically. EL or Level of Neutral Buoyancy (LNB) is the height above the LFC where the parcel temperature is less than the environment temperature or becomes equal. This means the unstable air is now stable at EL where the convection ceases. If the environment is stable and there is no LFC, there is obviously no EL (Venkat et al., 2013). Lifted index (LI) measures the difference between a parcel's temperatures compared with the environmental temperature at 500 hPa, after the parcel has been lifted from the lifting condensation level (AWS, 1990).

$$LI = T_{500} - T_{parcel} \quad (7)$$

where, T_{500} is the temperature of the environment at 500 hPa and T_{parcel} is the temperature of the air parcel. The temperature of the air parcel is also measured at the height of 500 hPa.

CAPE and LI are proved useful for indicating the likelihood of severe thunderstorms. This is because air rising in these situations is much warmer than its surroundings and can

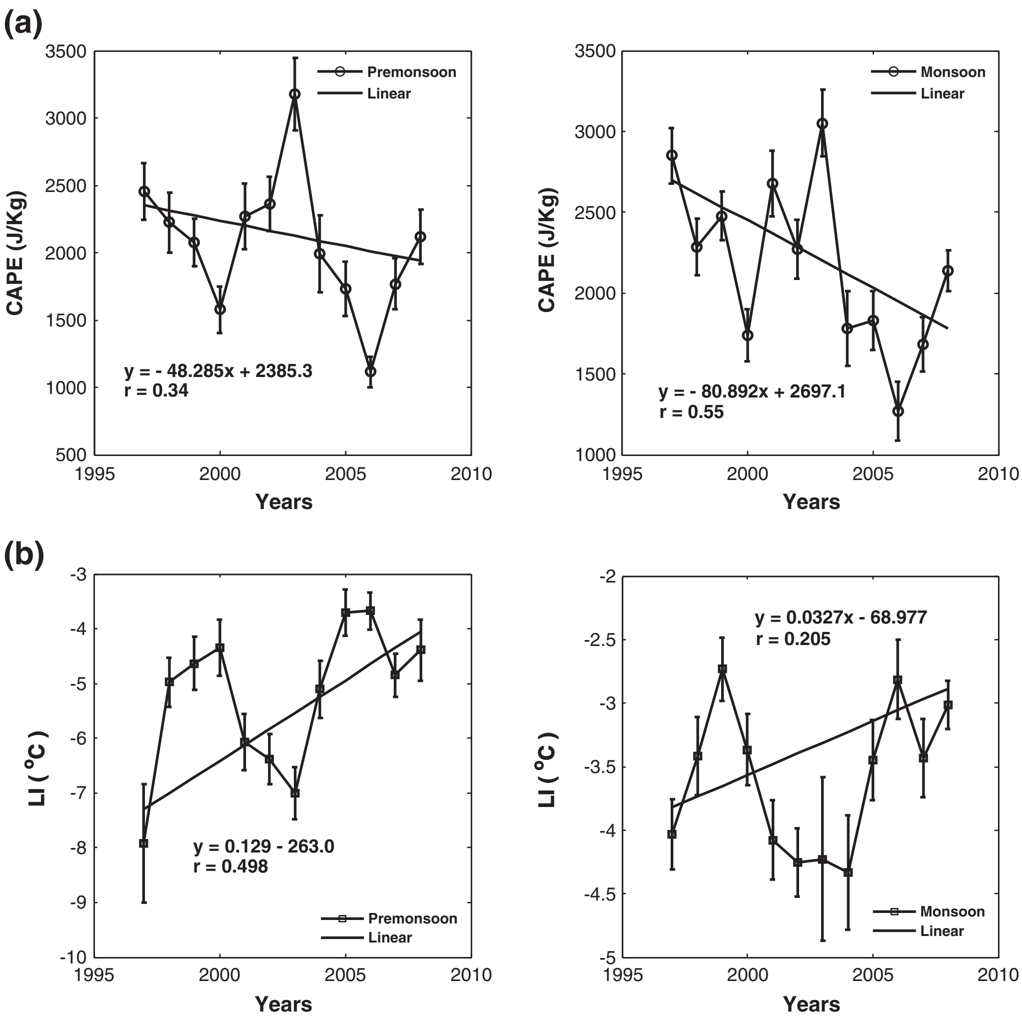

Fig. 3. Trends in (a) Convective Available Potential Energy (CAPE), (b) Lifted Index (LI), (c) Vertical Wind Shear (VWSH) and (d) Deep Layer Shear (0–6 km AGL) in pre-monsoon and monsoon seasons during 1997–2008.

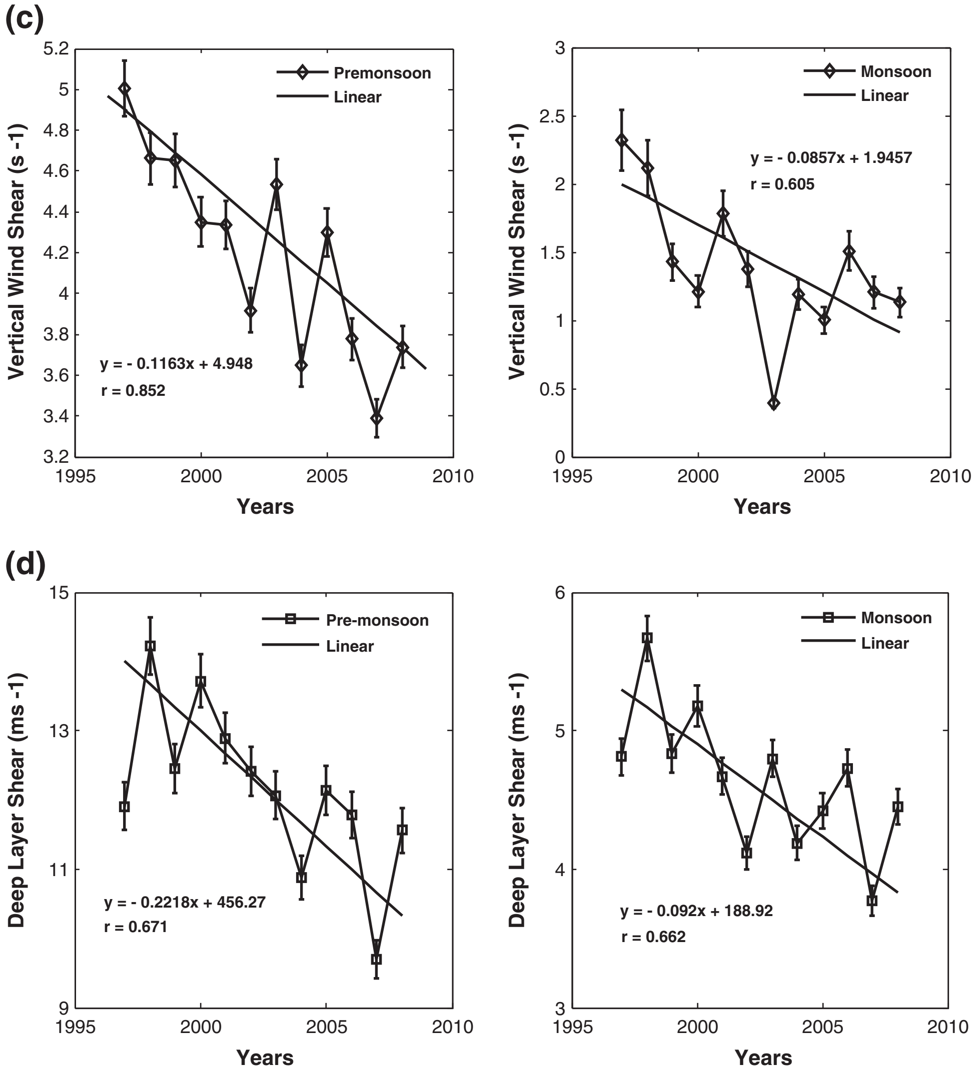

Fig. 3 (*continued*).

accelerate rapidly and create severe thunderstorms (Litta et al., 2012b). There was sufficient moisture in the atmosphere during the period of study, which leads to an increase in the number of ordinary thunderstorm events as well. But the severity of the thunderstorms decreases significantly, which may be due to the decrease of atmospheric instability, such as CAPE and LI. The generation of severe thunderstorm occurs only when CAPE is sufficiently high and there is a sharp fall of LI. During 1997–2008, the CAPE has a decreasing trend and LI has an increasing trend (Fig. 3a and b), which ensures the decrease in severity of thunderstorm events over this region. Nevertheless, VWSH and Deep Layer Shear also show a significant decreasing trend during the study period over this region (Fig. 3c and d), which also supports the suppression of convective activities over Kolkata in the last decade. The decrease in severe thunderstorm frequency during this period is also associated with increased pre-monsoon LWC over Kolkata (Fig. 4).

3.2. Trends in pre-monsoon and monsoon rainfall amounts over Kolkata during 1997–2008

The yearly variation of pre-monsoon rainfall over Kolkata shows a decreasing trend ($r = 0.944$) and monsoon rainfall shows an increasing trend ($r = 0.755$) for the period 1997–2008 (Fig. 5a and b). Though south-west monsoon is the major rain producing season over the country, other seasons have also significant contribution in some specific areas. The pre-monsoon cloud LWC is a representative of the cloud condensation process. Although, an increase in the evaporation during the warmer pre-monsoon months enhances the effective seeding of the cloud resulting in the increased amount of cloud LWC (Fig. 6), the rainfall during the pre-monsoon is decreasing. This pre-monsoon rainfall occurrence is predominantly controlled by western disturbance and convective activities. The decreasing trend of CAPE, VWSH, Deep Layer Shear (0–6 km AGL) and an increasing

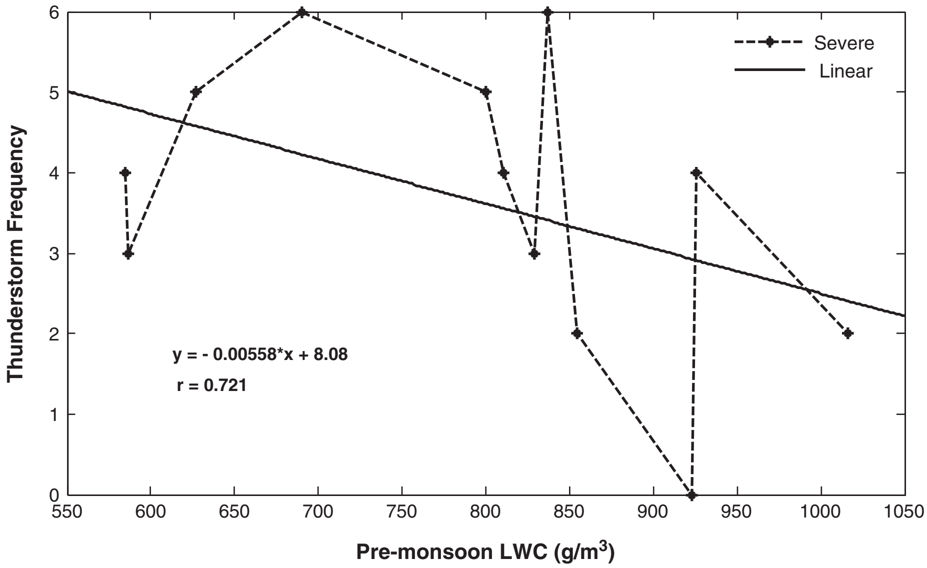

Fig. 4. Variation of severe thunderstorm frequency with pre-monsoon total cloud Liquid Water Content (LWC) over Kolkata during 1997–2008.

trend of LI (Fig. 3a–d) suggest that the pre-monsoon convective activity is decreasing, causing a decrease in the associated rainfall amounts over the region. The magnitude of Deep Layer Shear during monsoon is less than the pre-monsoon in our tropical region, since the presence of overhead clouds restricts the convective wind flow during monsoon season. Monsoon rain is of a different genre. It has a multi-decadal variability over the Indian region. The alternating sequence of multi-decadal periods of thirty years having frequent droughts and flood years are observed in the all India monsoon rainfall data. The decades 1961–70, 1971–80 and 1981–90 were dry periods. The first decade (1991–2000) in the next 30 years period already experienced a wet period. Therefore, there is a possibility of wet period for the subsequent two decades viz. 2001–2010 and 2011–2020 (Guhathakurta and Rajeevan, 2008), which is also supported by our study indicating an increase in monsoon rainfall during 1997–2008.

3.3. Relationship of the ordinary and total thunderstorm frequencies with monsoon and pre-monsoon rainfall amount over Kolkata during 1997–2008

The yearly pre-monsoonal rainfall variation with both of the ordinary and total thunderstorm frequencies over Kolkata clearly indicates that there exist significant positive

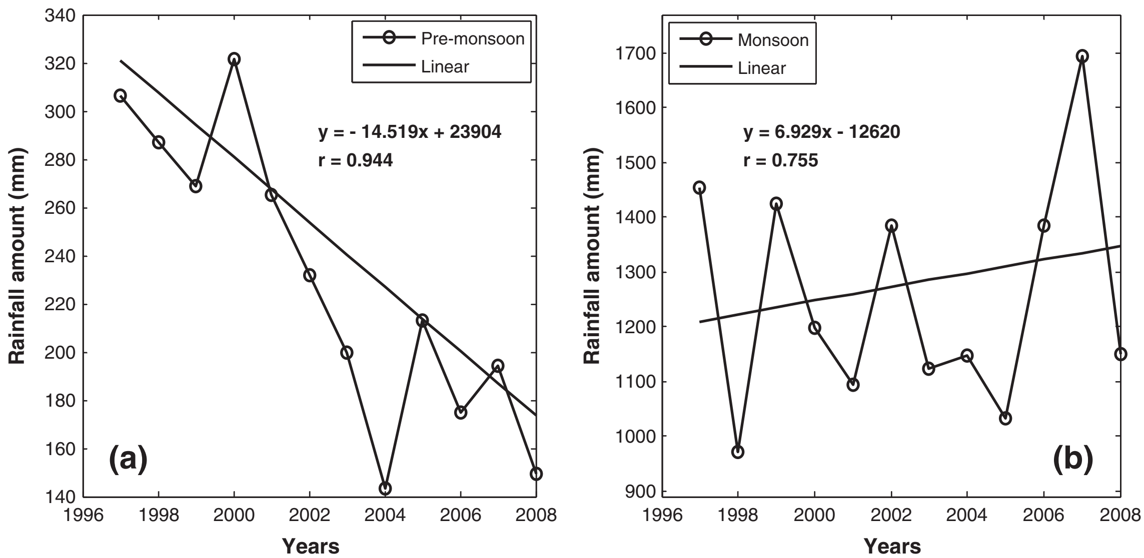

Fig. 5. Trends in (a) pre-monsoon and (b) monsoon rainfall amount during 1997–2008.

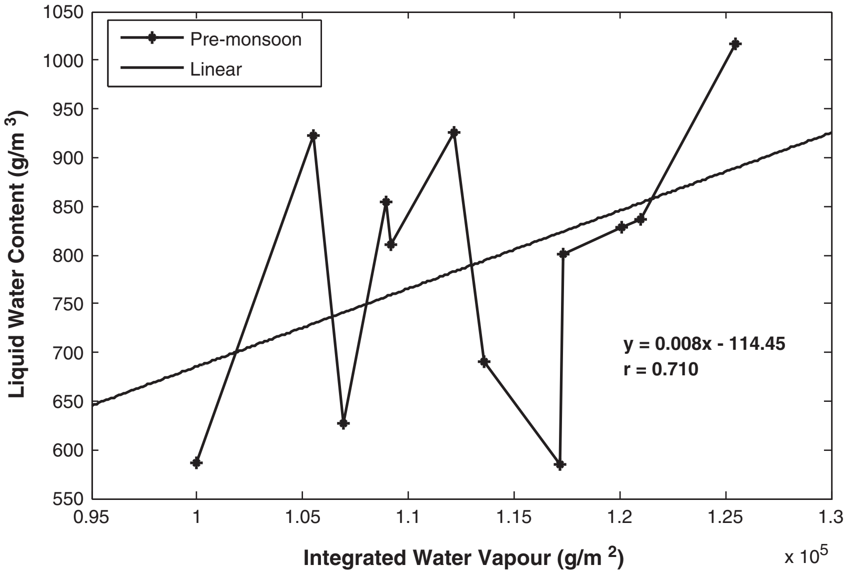

Fig. 6. Variation of cloud Liquid Water Content (LWC) with Integrated Water Vapor (IWV) over Kolkata during the pre-monsoon period of 1997–2008.

correlations (Fig. 7a–d) during the period 1997–2008. It may be noted that the pre-monsoon thunderstorm occurrences are mostly associated with the pre-monsoon rainfall amount. The pre-onset period of rainfall is mostly associated with an increase in the thunderstorm activity (Manohar et al., 1999). These higher and lower values of thunderstorm activity and rainfall occurrences can be explained as the rainfall associated with certain thunderstorms for the pre-monsoon season is mainly due to convection. Hence the rainfall yield confined to certain thunderstorm events depends upon the availability of moisture (Koteswaram and Srinivasan, 1958). The yearly monsoon rainfall shows an insignificant positive correlation with the ordinary thunderstorm frequency and an increasing trend over the same region (Fig. 7e–f), whereas an insignificantly poor anti-correlation with the total thunderstorm frequency and a feebly decreasing trend during this period over Kolkata (Fig. 7g–h). Table 1 shows the correlation among the types of thunderstorm frequency and the associated monsoon and pre-monsoon rainfall amount. The energy for the thunderstorm is provided by the humid air. Huge amount of heat energy is released, when water vapor inside a rising air mass cools and condenses, expanding the air which results in large buoyant forces and vigorous updrafts into the atmosphere. And finally, a trigger gives an upward push to the air to initiate primary condensation (Cook, 2010). Thus, the ordinary thunderstorm events have occurred in a temporal scale over Kolkata during this period due to the presence of sufficient amount of moisture and some instability in the atmosphere.

3.4. Relationship between the severe thunderstorm frequency with pre-monsoon and monsoon rainfall amounts over Kolkata during 1997–2008

The yearly variation of severe thunderstorm frequency over Kolkata with the pre-monsoon rainfall clearly indicates that there exist significant positive correlations. Severe thunderstorm frequency also increases with the increase in pre-monsoon rainfall amount during the period 1997–2008 (Fig. 8a–b). The positive correlation between the thunderstorm frequencies and the pre-monsoon rainfall is primarily due to the increase in surface sensible heat flux, which correspondingly increases the initial peak in the value of CAPE and frequency of conditionally unstable parameter, f_{cu} (Bhowmik et al., 2008). The severe thunderstorm frequency also increases with the pre-monsoon IWV (Fig. 9), as in the case with pre-monsoon rainfall (Fig. 8a–b).

The yearly variation of the severe thunderstorm frequency with the monsoon rainfall variation shows an anti-correlation ($r = -0.542$) indicating that the severity of the thunderstorm decreases with the monsoon rainfall during this period (Fig. 8b–c). The anti-correlation between severe thunderstorm frequency and the monsoon rainfall is evident from the decrease in CAPE index as well as a slight increase in LI value during monsoon (Fig. 3). The value of f_{cu} as well as CAPE decreases slightly during the monsoon season due to the convective mixing and decreased insolation on account of overhead cloudiness (Bhowmik et al., 2008; Rao and Ramamurti, 1968). There is also a decrease in the atmospheric temperature. But the humidity over this region goes on increasing, especially in the lower tropospheric levels, due to the northward movement of the ITCZ. Owing to the increase of humidity in the lower levels, the cloud base also lowers (at 900 hPa). Due to the decrease in the surface temperature during this season, the depth of the convectively unstable layer and the frequency of conditionally unstable parameter, f_{cu} decreases (Bhowmik et al., 2008). More the amount of IWV more will be the amount of cloud LWC, which can increase the rainfall amount in the region. The penetration of the moist monsoon air in the lower levels, and the accompanying convective mixing of the atmosphere, decreases the depth and strength of the inhibitory cap in the middle troposphere and organized convection is more frequent in the monsoon season (Bhowmik et al., 2008). Moreover, besides the convective instability, environmental shear that plays one of the most crucial parts in generation and sustenance of severe thunderstorm appears to depend on the amount of instability (Sinha and Pradhan, 2006). The strength and longevity of thunderstorms is influenced by the variation of wind shear (Chaudhari et al., 2010) which dictates whether rain falls straight down back through the thunderstorm and disrupts it, and also by microscopic particles of dust and debris in the atmosphere, called aerosols, which cloud droplets form around. A larger number of smaller cloud droplets forms when the aerosol concentrations are higher. The strong vertical wind shear as well as Deep Layer Shear (0–6 km AGL) is always needed for the generation of atmospheric instabilities. But after the formation of the system, the atmosphere becomes stable for some time. Now, if a strong VWSH and Deep Layer Shear sustains after the formation of the system, then during strong wind shear conditions, the increase in evaporative cooling (which is always larger than the increase in condensational heating) with increasing aerosols, leading to the suppression of

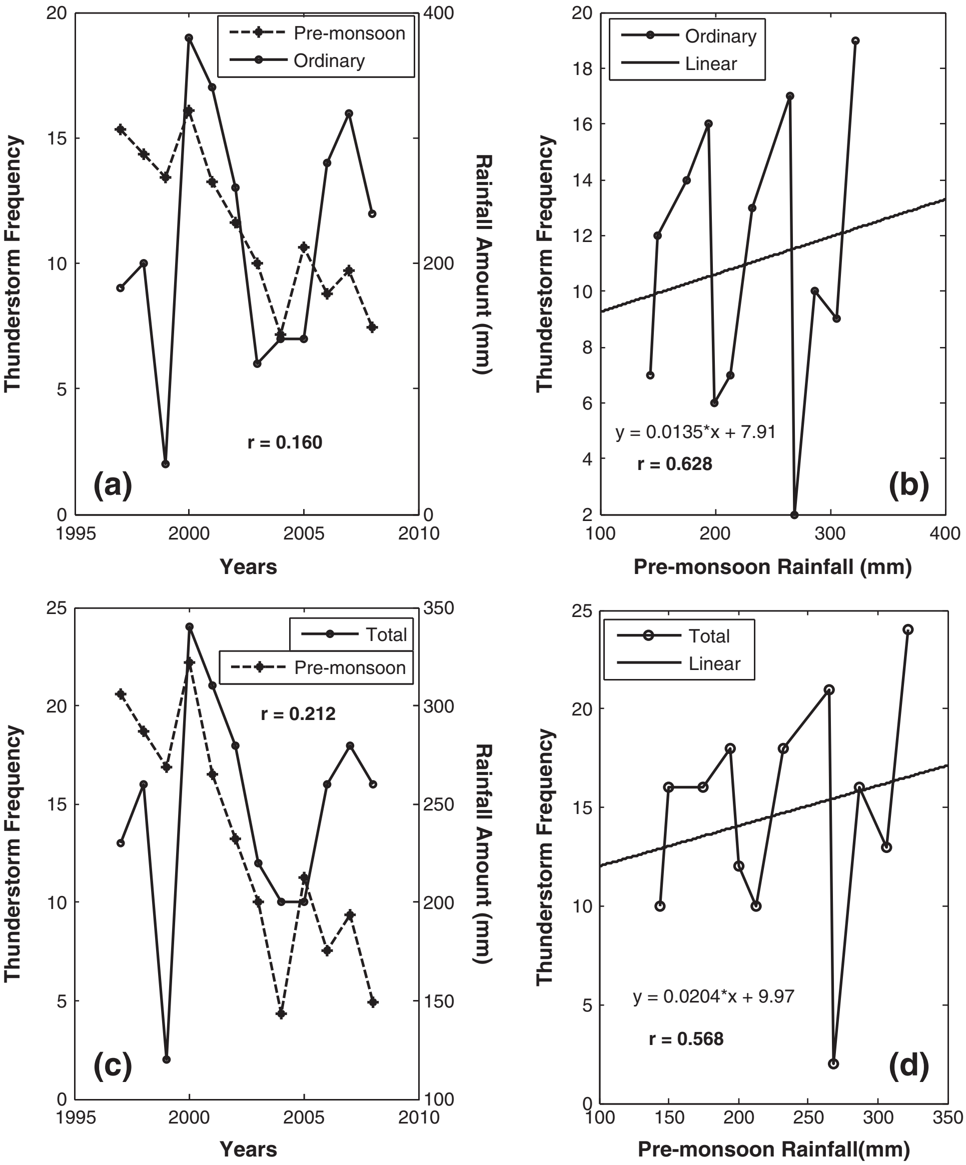

Fig. 7. (a) Yearly variation of ordinary thunderstorm frequency with pre-monsoon rainfall amount and (b) trend variation of Ordinary thunderstorm frequencies with the pre-monsoon rainfall over Kolkata during 1997–2008. (c) Yearly variation of total thunderstorm frequency with pre-monsoon rainfall amount and (d) trend variation of total thunderstorm frequencies with the pre-monsoon rainfall over Kolkata during 1997–2008. (e) Yearly variation of ordinary thunderstorm frequency with monsoon rainfall amount and (f) trend variation of ordinary thunderstorm frequencies with the monsoon rainfall over Kolkata during 1997–2008. (g) Yearly variation of total thunderstorm frequency with monsoon rainfall amount and (h) trend variation of total thunderstorm frequencies with the monsoon rainfall over Kolkata during 1997–2008.

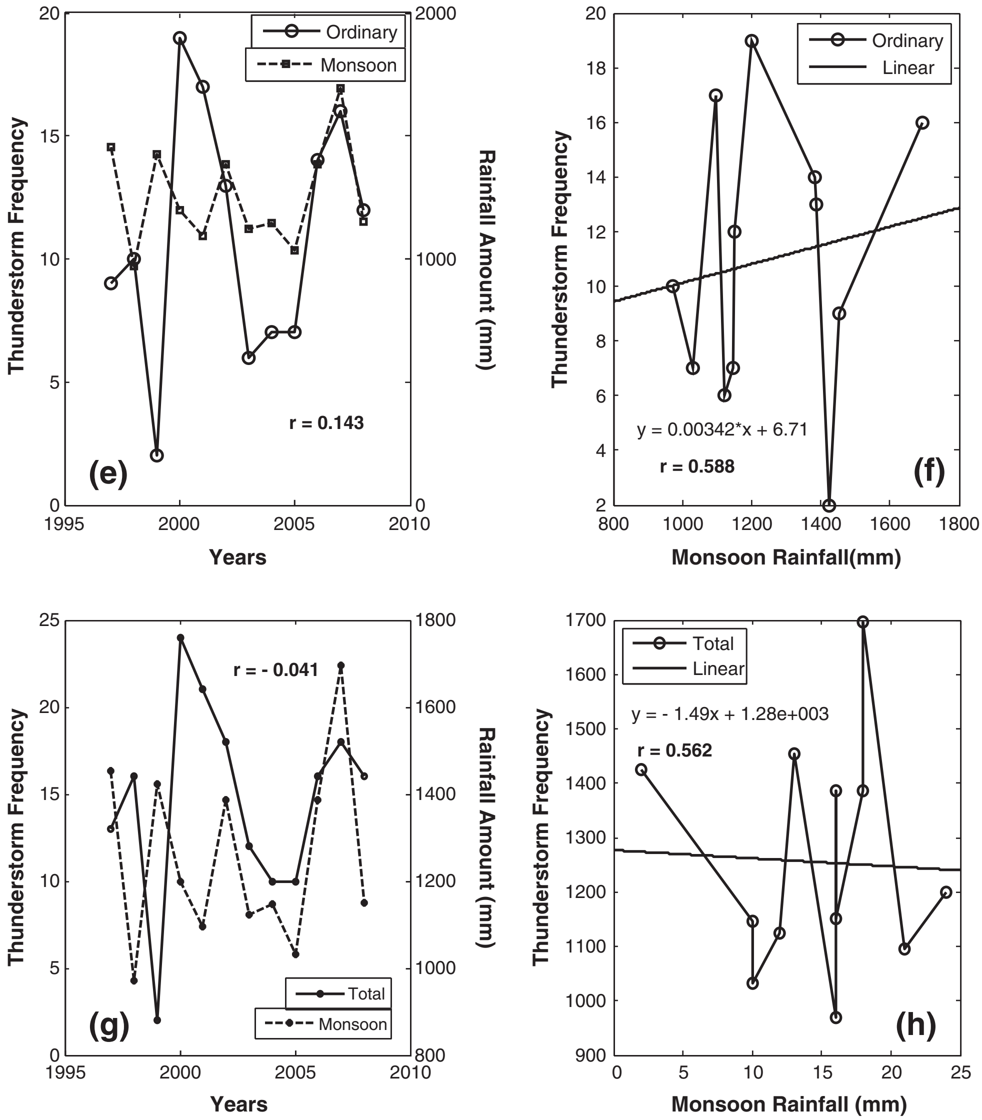

Fig. 7 (*continued*).

convection (Fan et al., 2009). Thus there may be the possible chances of ordinary thunderstorms in this season but a decrease in severe thunderstorm frequency with the monsoon rainfall amount for the period.

Table 1
Correlation among the types of thunderstorm frequency and the associated monsoon and pre-monsoon rainfall amount.

Types of thunderstorm	Rainfall period	Correlation co-efficient
Severe Ts frequency	Monsoon	r = −0.5415
Ordinary Ts frequency	Monsoon	r = 0.143
Total Ts frequency	Monsoon	r = −0.041
Severe Ts frequency	Pre-monsoon	r = 0.237
Ordinary Ts frequency	Pre-monsoon	r = 0.160
Total Ts frequency	Pre-monsoon	r = 0.212

4. Conclusion

The severity of the thunderstorms has decreased significantly over the region whereas the number of ordinary thunderstorms has increased during the last decade at the present location. The pre-monsoon rainfall has also decreased whereas the monsoon rainfall has increased over the region. A significant positive correlation is obtained for all the types of thunderstorm (severe, ordinary and total) events with the pre-monsoon rainfall amount. The increase in pre-monsoon instability in the atmosphere may be an indicator for the occurrence of convective phenomenon and associated rainfall events. The decrease in the CAPE, VWSH, Deep Layer Shear and increase in LI is responsible for the decrease of severe thunderstorm events during the twelve-year study period. The suppression of convective instabilities during pre-monsoon is the causal effect for a decrease in

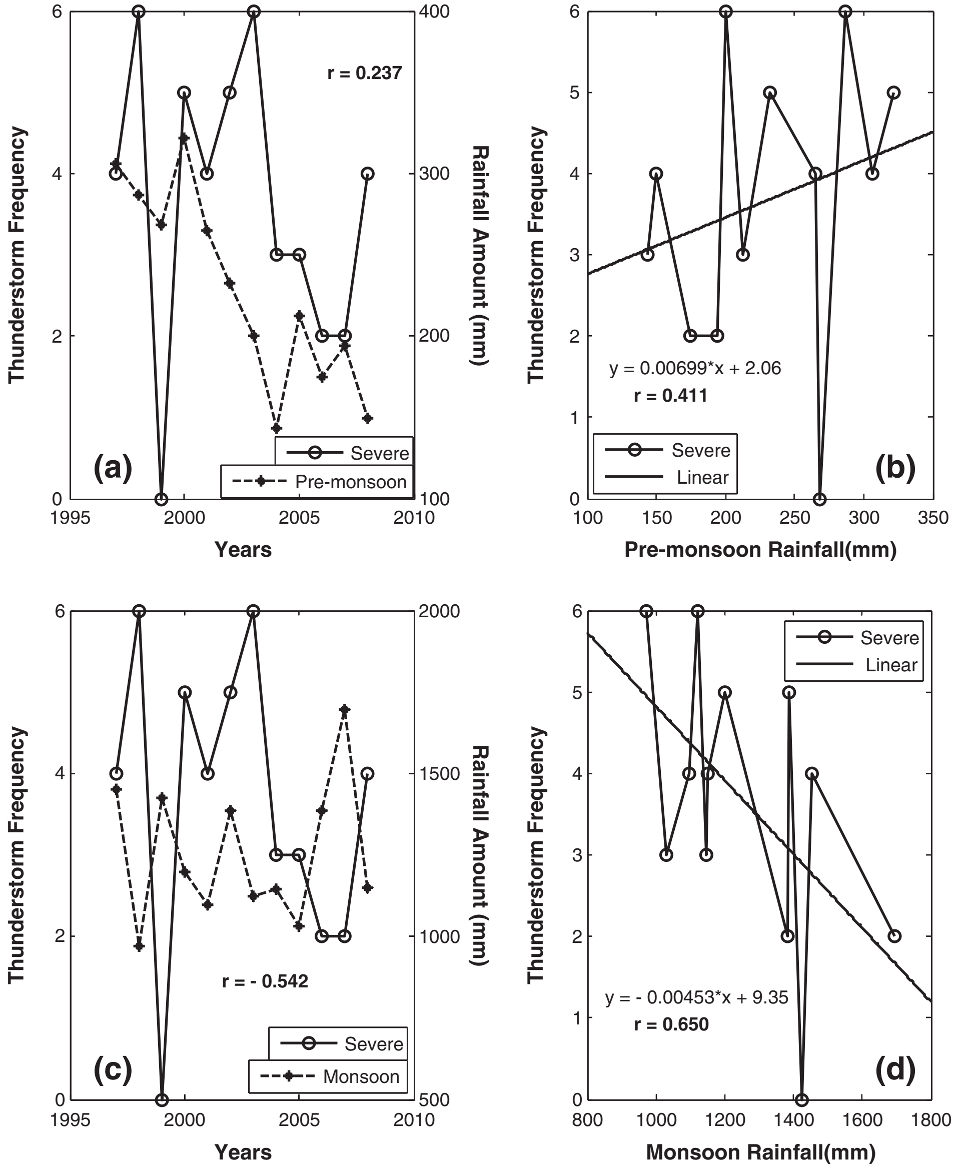

Fig. 8. (a) Yearly variation of severe thunderstorm frequency with pre-monsoon rainfall amount and (b) trend variation of severe thunderstorm frequencies with the pre-monsoon rainfall over Kolkata during 1997–2008. (c) Yearly variation of severe thunderstorm frequency with monsoon rainfall amount and (d) trend variation of severe thunderstorm frequencies with the monsoon rainfall over Kolkata during 1997–2008.

the associated rainfall. However, the monsoon rainfall has a multi-decadal variability. The present period belongs to wet period in the thirty-year variability which explains the increase in the monsoon rainfall. A significant anti-correlation is observed between the severe thunderstorm frequency and the monsoon rainfall amount over Kolkata. The water vapor during this season is mainly transported and not of local origin as in the case of pre-monsoon rain. As a result, the atmospheric conditions associated with monsoon rain are not congenial to generate instability as indicated by low CAPE, low VWSH, Deep Layer Shear and high LI values. The lessening of the instability indices inhibits the severe thunderstorm events during this season. The present study indicates a strong association of the thunderstorm frequency with the rainfall amount at the present location. The study has significant implications in understanding the changing pattern of the regional climate.

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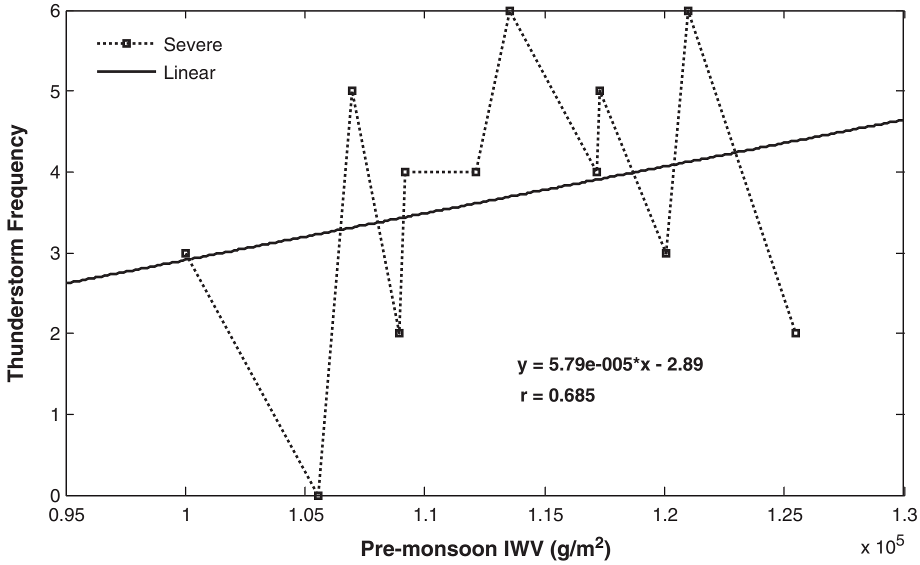

Fig. 9. Variation of severe thunderstorm frequency with pre-monsoon total Integrated Water Vapor (IWV) over Kolkata during 1997–2008.

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