MAUSAM, **60**, 4 (October 2009), 461-474

551.515.4

Characteristics of thunderstorms and squalls over Indira Gandhi International (IGI) airport, New Delhi - Impact on environment especially on summer's day temperatures and use in forecasting

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(*Received 11 June 2007, Modified 8 July 2009*)

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सार – इस शोध–पत्र में हाल के पिछले ग्यारह वर्षों (1995-2005) के आँकड़ों के आधार पर आई. जी. आई हवाई अड्डा पालम, नई दिल्ली में गर्ज के साथ आए तूफानों (टी. एस.) और चंडवातों के आने के समय और उनकी अवधि का विशलेषणात्मक अध्ययन किया गया है जिससे इनके आने के समय का पता लगाया जा सके। इस आँकड़ा आधार की विमानन चेतावनी में उपयोगिता के बारे में भी बताया गया है। चंडवातों के प्रभाव का पता लगाने के लिए उनके आने से होने वाले पर्यावरणीय परिवर्तन का भी इसमें विश्लेषण किया गया है। दिल्ली में मई 2007 का महीना बहुत ठंडा रहा। इसमें दिन के बढ़े हुए तापमान को नियंत्रित करने में गर्ज के साथ आए तुफानों की भूमिका का भी अध्ययन किया गया है। परिणामों से पता चला है कि गर्ज के साथ तूफान जून में सबसे अधिकतम आए और उसके बाद जुलाई का महीना रहा जबकि चंडवात मई में सबसे अधिकतम आए और उसके बाद जून का महीना रहा। इससे पता चला है कि प्रत्येक ऋतु में 80 प्रतिशत गर्ज के साथ आए तूफानों की अवधि तीन घंटे से कम रही और शेष मुख्यतः तीन से छह घंटे तक रहे। दिन के समय गर्ज के साथ आए तफानों और चंडवातों दोनों के आरंभ होने की चरम समय अवधि महीनों के साथ–साथ बदलती रही। मानसून पूर्व महीनों के लिए 1200-1500 यू. टी. सी. गर्ज के साथ आए तूफानों और चंडवातों का अनुकूल समय है। जबकि मानसून ऋतु में यह जल्दी आरंभ हो जाते हैं। इस अवधि के दौरान लगभग 37 प्रतिशत कुल गर्ज के साथ तूफान चंडवातों के साथ आए। आई हवाई अड्डे में चंडवात की औसत अधिकतम पवनगति लगभग 68 कि.मी. प्रति घंटा रही जिसमें अधिकतम पवनगति 139 कि.मी. प्रति घंटा रही। औसनतन चंडवातों की घटनाओं के फलस्वरूप पर्यावरणीय तापमान 5.6° सें. गिरा, आर्द्रता स्तर 17.8 प्रतिशत बढ़ा और माध्य समुद्र दाब 1.6 हेक्टापास्कल तक बढ़ा। इस अध्ययन से यह भी पता चला है कि गर्ज के साथ आए तूफानों की घटनाओं के कारण दैनिक अधिकतम तापमान नियंत्रित रहा। 1995 से हवाई अड्डे में मई के महीने में अधिकतम गर्ज के साथ तूफान आए और दिल्ली के मई 2007 सबसे अधिक ठंडा महीना रहा। 1950-1980 के दौरान गर्ज के साथ आए तूफानों की आवृत्तियों की तुलना से पता चला है कि उनकी वार्षिक गतिविधियों में 12 प्रतिशत वृद्धि हुई है जिसमें जून में 51 प्रतिशत और मई में 26 प्रतिशत बहुत ही असामान्य वृद्धि हुई। 1995 से आँकड़ों के विशलेषण से पता चला है कि गर्ज के साथ आए तूफान ग्रीष्म तापमान से विलोमतः परन्तु सुदृढ रूप से सहसंबद्ध है। 1975 से लम्बी अवधि के तापमान के आँकड़ों से यह भी पुष्टि होती है कि अधिक प्रदूषण, भूमंडलीय उष्णनन और तेजी से बढ़तें हुए शहरीकरण के फलस्वरूप मई और जून के भीषण गर्मी के महीनों में जैसा कि अपेक्षित होता है, अधिकतम तापमान में विशेष वृद्धि नहीं हुई। अतः समय-समय पर उस क्षेत्र में गर्ज के साथ आए तूफानों की घटनाएँ तापमान में वृद्धि के नियंत्रण का मुख्य कारक रही।

ABSTRACT. In the present study, commencement timings and duration of thunderstorms (TS) and squalls at IGI airport, Palam, New Delhi have been analysed critically based on most recent eleven years data of 1995-2005 to find their favourable time of occurrences. Then utility of such data base in the aviation warning has been demonstrated. Environmental changes associated with these squalls have also been further analysed to understand their impact. Being recent May 2007 a very cool month over Delhi, the role of TS on controlling the day's soaring temperature has also been studied from their data. Results show TS are maximum in June followed by July whereas squalls are maximum in May followed by June. It shows more than 80% of TS in each season are of duration less than 3 hours with remaining are mostly 3 to 6 hours. The peak time period of commencement of both TS and squalls in the day differ with the progress of the months. For pre monsoon months, the most favourable timing of TS and squalls are 1200-1500 UTC while for monsoon, it starts earlier. Around 37% of the total TS during the period were associated with squalls. The average maximum wind speed in squall at IGI airport is about 68 kmph with highest maximum wind speed 139 kmph. On an average the environmental temperature falls by 5.6° C, humidity levels rises by 17.8% and mean sea level pressure rises by 1.6 hPa due to the occurrences of squalls. Study also shows daily maximum temperature rise is highly controlled by TS occurrences and May 2007, being a month of highest TS occurrences at the airport since 1995, became one of the coolest month in May over Delhi. The comparison of TS frequencies shows 12% increase in their annual activities since 1950-1980 with very high unusual increase of 51% in June and 26% in May. Since analysis of data from 1995 shows occurrences of TS are reversely but strongly correlated with summer temperatures and longer period temperature data since 1975 also confirms absence of significant trend in maximum temperature and higher temperature days in peak summer months of May and June till recent as expected due to high pollution, global warming and fast urbanization in the city, so it is the higher number of TS occurrences over the region from time to time which might have been main factor for controlling its significant rise.

Key words – Thunderstorms (TS), Squalls, Duration and Commencement timings, Environmental effect.

1. Introduction

Thunderstorms (TS) and squalls are the main channels of energy exchange in the atmosphere thereby causing drastic change in the environment of the place where they occur. These sudden changes in various meteorological parameters and atmospheric stability are very much hazardous to the aviation activities. Therefore, study of these activities at airport is very much important. In the absence any objective methods for their advance forecast except their nowcasting which we mainly do on the basis of current observation and RADAR echoes, study of climatological variation of their characteristics based on their longer period data would help in giving a better advance prediction related to their time of occurrences and associated squall characteristics for safe and efficient aviation weather warnings. There have been many studies on climatological aspects of TS and squalls over different parts of India. The frequency distributions of TS and squalls in different months for Indian region have been discussed in the past by Rao and Raman (1961) and recently by Tyagi (2007). For Delhi region, some climatological studies about squalls and dust storms at Delhi have been carried out by Bhalotra (1954) and Joseph *et al.*, (1980) respectively which are based on very old data period going back 1940s or 1970s, *e.g.*, Bhalotra, (1954) used data of 1943 to 1952 at Safdarjung airport while Joseph *et al*., (1980) used data during the period 1972-1977 at IGI airport, Delhi. With climate change playing a very important role on all types atmospheric phenomenon, it is very much necessary to updates their climatological characteristics based upon latest data.

In the present paper, authors have studied the climatological aspects of the both squalls and TS activity over IGI airport, Palam, New Delhi using data of most recent 11 years of 1995 to 2005 which includes diurnal, monthly and intra-annual changes of their frequencies, durations and commencement timings for use in aviation. We have also studied environmental impacts of TS on trend of maximum temperatures both in day to day and in inter-annual scale mainly for summer months and impact of squalls on various environmental parameters *e.g.*, environmental temperature, humidity, mean sea level pressure and maximum wind speed. Finally we have used these information's for developing climatological forecasting guidelines based upon which different types squall warning can be appended in various thunderstorm warnings over IGI airport depending upon the particular month in which it occurs.

2. Data & methodology

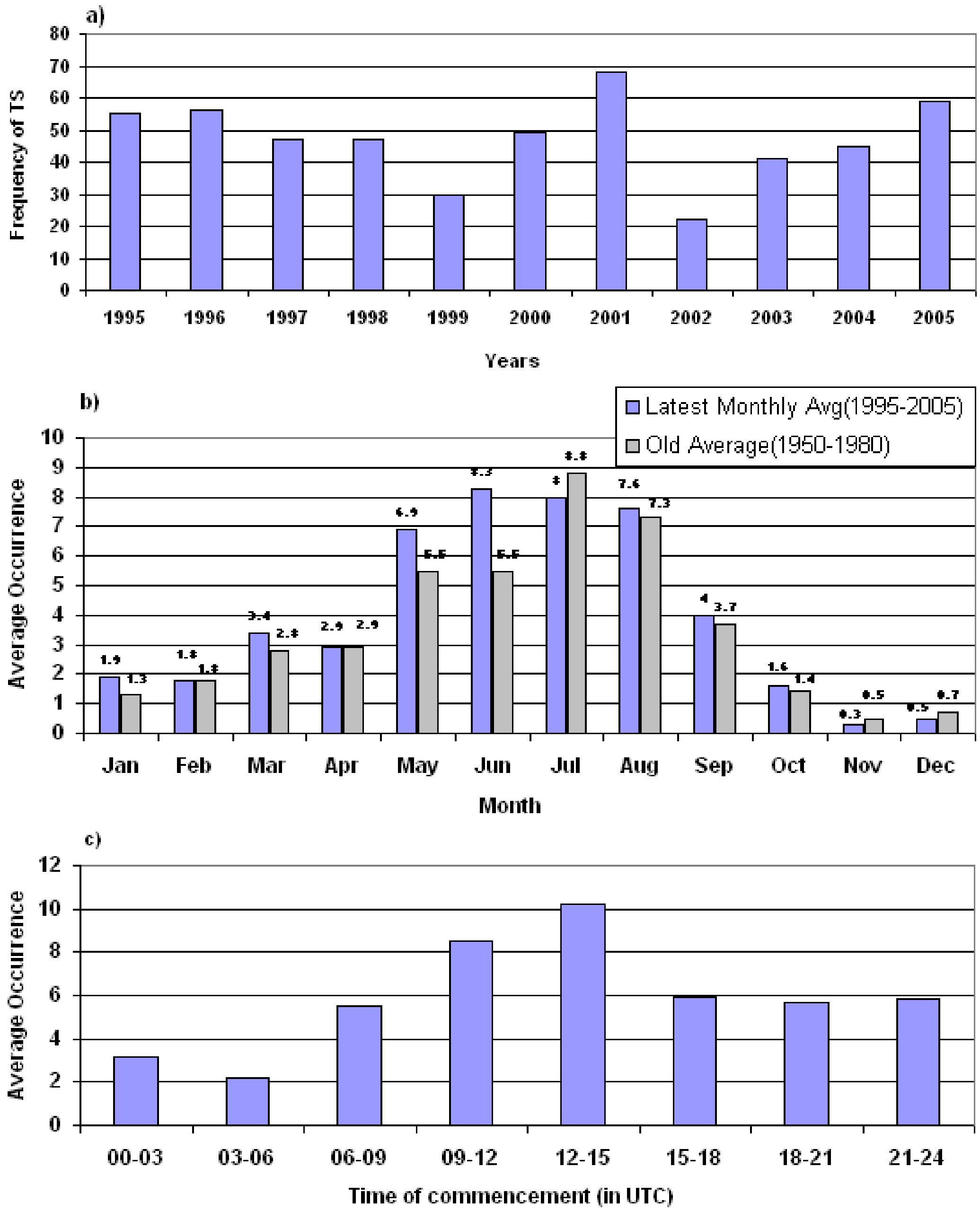
The data of TS and squalls over IGI airport, Palam, New Delhi from MMRs (Monthly Meteorological Registers) of Palam observatory for the period 1995-2005 and the temperature data from National Data Center, Pune for the period 1970-2007 have been used for the present study.

3. Results and discussion

3.1. *Climatological characteristics of TS*

The IGI airport, Palam on an average experienced 47.2 TS per year. The annual frequency of TS vary from the lowest of 22 in 2002 to the highest of 68 in 2001 during 11 years (1995-2005) as shown in Fig. 1(a) while their monthly averages variation in Fig. 1(b) shows the lowest with below 1 in November and December with the highest of 8 in first three monsoon months. The comparison between IMD climatology of TS during 1951-1980 [Fig. 1(b)] and that of 1995-2005 revealed that there is around 12% increase in their annual activities with very high unusual increase of 26% in May and 51% in June months. Most of the TS have occurred in pre-monsoon and monsoon season (between the period March to September) *i.e*., 86.9% with highest in monsoon 59% and 27.9% in pre-monsoon. TS activity in winter season is 8% and in post-monsoon season, it is quite low, *i.e*., nearly 4%.

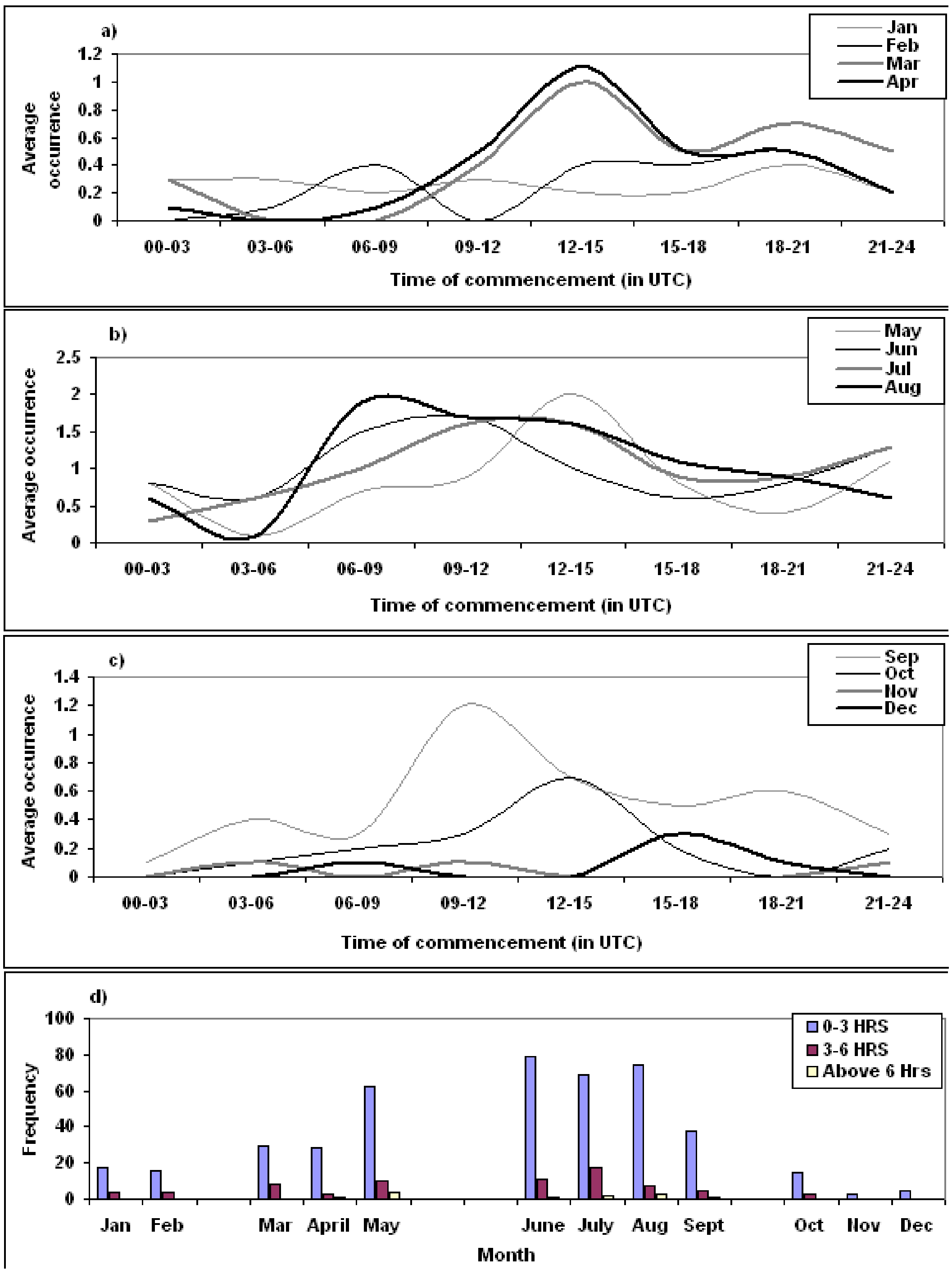
Fig. 1(c) shows the time of average commencement of TS when timing of all TS for the total period for all years are considered. It is highest with 10.2 *i.e*., around 21.6% occurrences during afternoon/evening of 1200-1500 UTC followed by 8.5 (18.1%) in 0900-1200 UTC with lowest of 2.1, *i.e*., nearly 4.6% during 0300-0600 UTC of morning. In monthly time scale, Fig. 2(a) shows no clear cut peak timing for both winter months while for all three pre-monsoon months, it shows very high frequency of thunderstorms (31%) commencing during 1200-1500 UTC with June to August not having single timings when TS commencement is highest [Fig. 2(b)]. In fact in these three monsoon months together, about 52 % of TS occurred during if a very long time period of 6-15 UTC has been considered. It is interesting to see shifting of thunderstorm peak timings with progress of months from Fig. 2(c), with very high peak commencements during 0900-1200 UTC for September followed by 1200-1500 UTC for October and 1500-1800 UTC for



Figs. 1(a-c). (a) Year to year variation of TS frequency during 1995-2005, (b) Monthly climatological frequency of TS based upon data of 1995-2005 and 1950-1980 and (c) Diurnal variation of commencement timings based on their total occurrences in 1995-2005

November with December having very few occurrences which are non-uniformly distributed during the day.

Annual averages show that during the 11 years period, 83.7% of the total TS are of duration less than 3 hours, 13.8% are of duration 3-6 hours and 2.1% are of duration 6-9 hours that too in pre-monsoon and monsoon seasons while seasonal data shows no TS of duration 6-9 hours occurred in the post-monsoon and winter seasons. The TS activity of duration more than 9 hours is negligible at IGI airport, New Delhi and only one case in 11 years of TS of duration 9-12 hours was noticed. The frequency distribution of duration of TS in different months is shown in Fig. 2(d). It shows very high

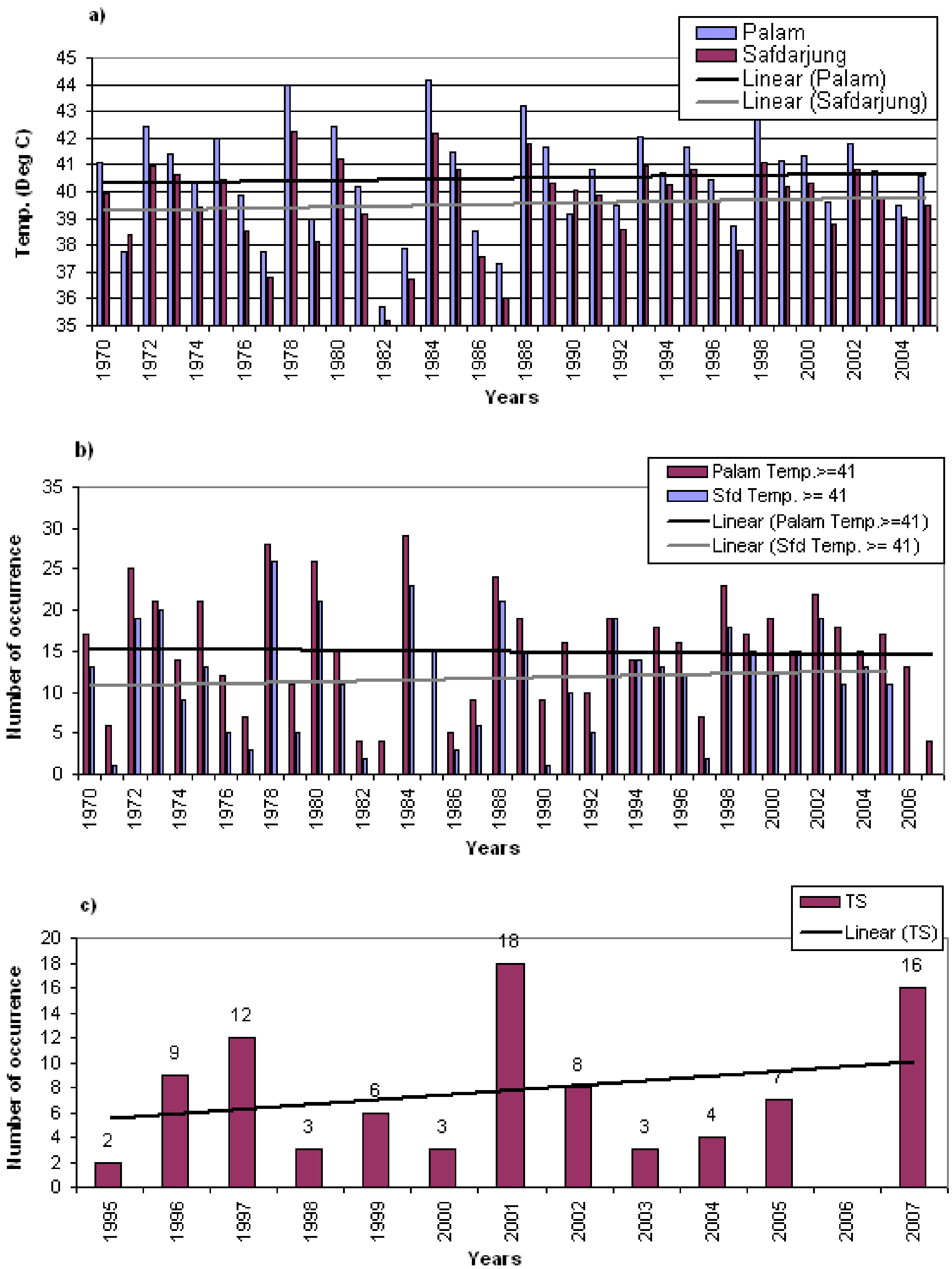


Figs. 2(a-d). Diurnal variation of commencement timings of TS activity and their durations during different months (a) January to April, (b) May to August, (c) September to December and (d) Duration of TS during different month

frequencies of duration < 3 hours for all months with duration of 3-6 hours occurring at very low frequencies in all months except November and December while very few frequency of TS of duration 6-9 hours are in April, May and June to September with higher in May & August and relatively less in remaining months.

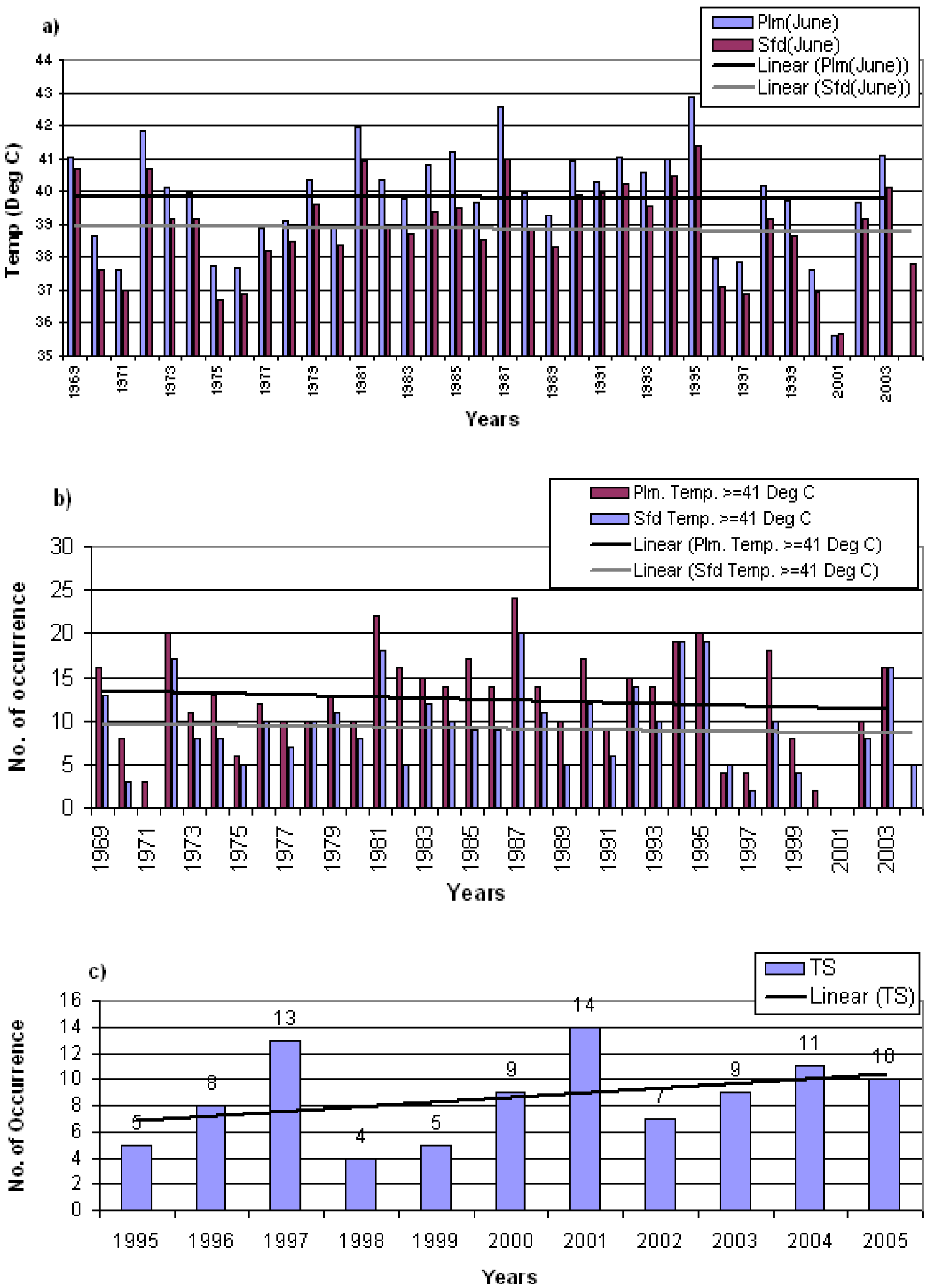
3.2. *Role of TS in controlling maximum temperature*

It is well known that people of the region get a temporary relief from the rising maximum temperature in the peak summer months of May and June mostly from



Figs. 3(a-c). (a) Trend of average Max. temp. in May at IGI and Safdarjung airport, (b) Trend of high temp. days in May and (c) Trend of frequency of TS activity in May

the development and occurrences of thunderstorms accompanied with rain and squalls. In fact it is believed that higher maximum temperatures or heat waves do not persist longer period over northwest India as these have been in eastern India recently. Orissa in 1998 and Andhra Pradesh and Orissa in 2003 and 2005 experienced severe prolonged heat wave spells causing high loses to human lives while north-western parts of India have no such severe impacts. It is because when temperature rises over the later, there is always a chance of development of dust storms or TS over the region. It has been also observed that in the absence of moistures in the region, if TS does not develop in some days then further rise of temperature may certainly cause dust storm



Figs. 4(a-c). (a) Trend of average Max. temp. in June at IGI and Safdarjung airport, (b) Trend of high temp. days in June and (c) Trend of frequency of TS activity in June

to develop from dry westerly. Thus, with floating dusts associated with dust storm in the atmosphere trapping incoming sunlight, temperature risings and heat wave are controlled to some extent. But in case of east coast of India, if TS does not occur in the absence of moistures incursion from adjoining seas by setting of sea breeze or any by other supported synoptic circulation pattern then there is a least chance of dust storm development due to which high maximum temperatures with heat waves continued to persist for longer period as has been observed in May and June of 1998, 2003 and 2005.

TABLE 1

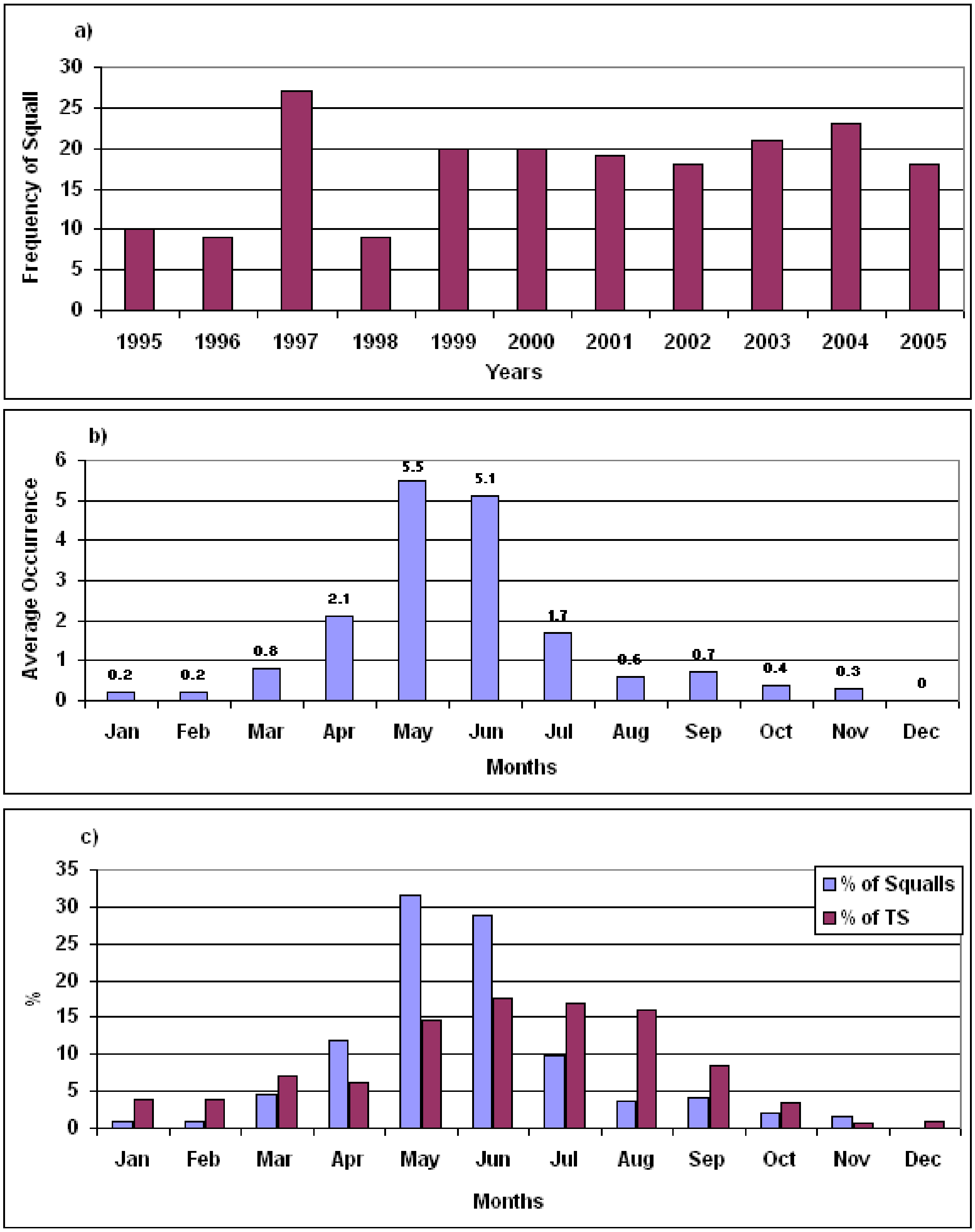
Correlation coefficients of temperatures with frequencies of TS

	Maximum		Minimum	
Months	IGI airport	Safdarjung airport	IGI airport	Safdarjung airport
May	-0.7*	-0.6*	-0.4**	-0.4**
June	-0.8*	-0.7*	-0.7*	-0.7*

*significant at 99%, ** significant at 97%

Impact of TS and squalls occurrences as temporary respite from rising heat waves in peak summer days leading to human conformability over a location have been already studied by Chakrabarti *et al.* (2007) by using their 6-years data of TS and temperature data from Kolkata. In the present study, because of both recent months of May 2007 and 2008 are very cool month over Delhi during when we experienced very few high temperature days when very high TS were occurred, an attempt was made to link TS occurrences with maximum temperature by analysing climatological trends from their longer period data of IGI airport, Palam and Safdarjung. Figs. 3(a-c) and Figs. 4(a-c) show trends and monthly variation of average maximum temperatures, number of higher temperature days than (≥ 41° C) and frequencies of TS for both the months of May and June from longer period data available since 1970 and 1995 respectively for Delhi (both TS and daily temperature data are available for IGI, Palam while only temperature data for Safdarjung). The mean frequency based on 1950-1980 climate data of IMD shows a 12% increase in their numbers during recent of 1995-2005 with very high increase in May and June. The lowest average maximum temperature during May of 1970-2007 [Fig. 3(a)] was recorded in 1982 (35.2° C for IGI) over both stations while after 1990, it was lowest for May in 1997 (38.7° C for IGI) followed by 2004 and recent of 2007 (39.5° C each for IGI) and then 2001 (39.6° C for IGI). It may be noted that the daily temperatures was equals or higher than 41° C [Fig. 3(b)] for 4 days, 7 days and 8 days in 1982, 1997 and recent of 2007 respectively over IGI and similar less days were observed over Safdarjung during these years. It may be noted from Fig. 3(c) that after 1995, the coolest May months of 1997, 2001 and 2007 are too experienced very high number of TS with 12 in 1997 and 18 in 2001 and highest of 19 in recent of May 2007. In fact, during 1988-2007, 2007 is the 2nd coolest day temperature after 1997 due to highest TS frequencies in the month. It is also 10th in rank in order of coolest day temperatures since 1970. Though in May 2001, similar highest TS occurred, days in 2001 were warmer than 1997 while average day temperature of 2001 were same as 2007. Similarly, the warmest months during the period 1970-2007 is 1984, 1978 and 1988 in May for both the stations with average day's temperatures as 44.2° C, 44.0° C and 43.2° C respectively recorded at IGI while higher temperature equals or crossing 41 at IGI are 29, 28 and 24 days in these months respectively *i.e.*, almost in all days. Since 1995, for which TS data are available in Fig. 3(c), the warmest month for May in both station of the city is 1998 when for 23 days, IGI experienced maximum temperature crossing 41ºC and average was 42.7° C with only 3 TS. Figs. 4(a&b) also show similar relationship between TS and day temperatures for the month of June. Correlation Coefficients (CC) between them in Table 1 shows very high negative CC which are nearly same for both the stations for respective months, *e.g.*, -0.7 (-0.6) and -0.4 (-0.4) respectively for May and -0.8 (-0.7) and -0.7 (-0.7) for June for IGI (Safdarjung) which shows TS really plays an important role in keeping both maximum and minimum temperature in both part of the city under controlled. As discussed before being the city experiencing population boom and fast urbanization resulting high pollution, long period linear trend analysis of both maximum temperatures and TS frequencies have been performed in Figs. 3 and 4 to understand whether both observatories, *i.e.*, one located at outskirt and one located at centre of Delhi have been experienced any change in both extreme temperature days and average maximum temperatures from impact of pollutions and fast urbanization leading climate change during both peak summer months.

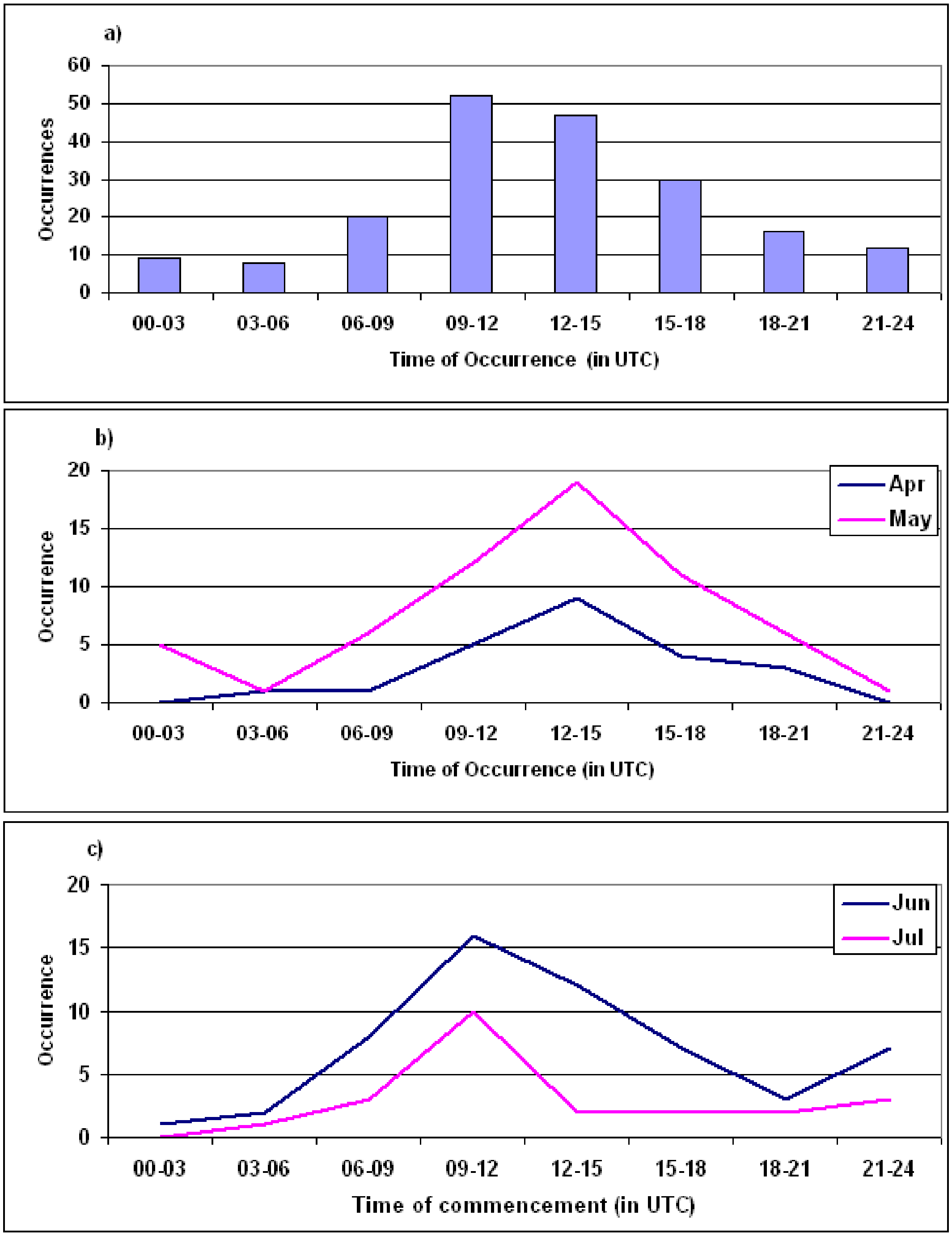
It is interesting to note all trend lines related to temperatures in Figs. 3 and 4 are almost parallel to base lines (*i.e.*, no significant trends) for both station in both months. In case of June rather, a slight fall in average maximum temperatures and their higher days have been noticed over both station from Figs. 4(a&b). The main cause can be well explained by looking the trends TS frequencies as have been noticed in both months from Fig. 3(c) and Fig. 4(c) which have been increased nearly from 6 to 10 days for both months. Data from climatological table of 1950-1980 of IMD compared to 1995-2005 also shows an increase of 29% and 54% respectively in their frequencies for May and June which indicates the expected rise of day maximum temperature and high temperature days due to impact of climate change and urbanization after 1970 in Fig. 3 and Fig. 4(a) have surely been controlled by rising of such TS frequencies.



Figs. 5(a-c). (a) Year to year variation of squall frequency during 1995-2005, (b) Monthly climatological frequency and (c) Comparison of squalls occurs in a month to that of TS in that month in terms of % from their total occurrences

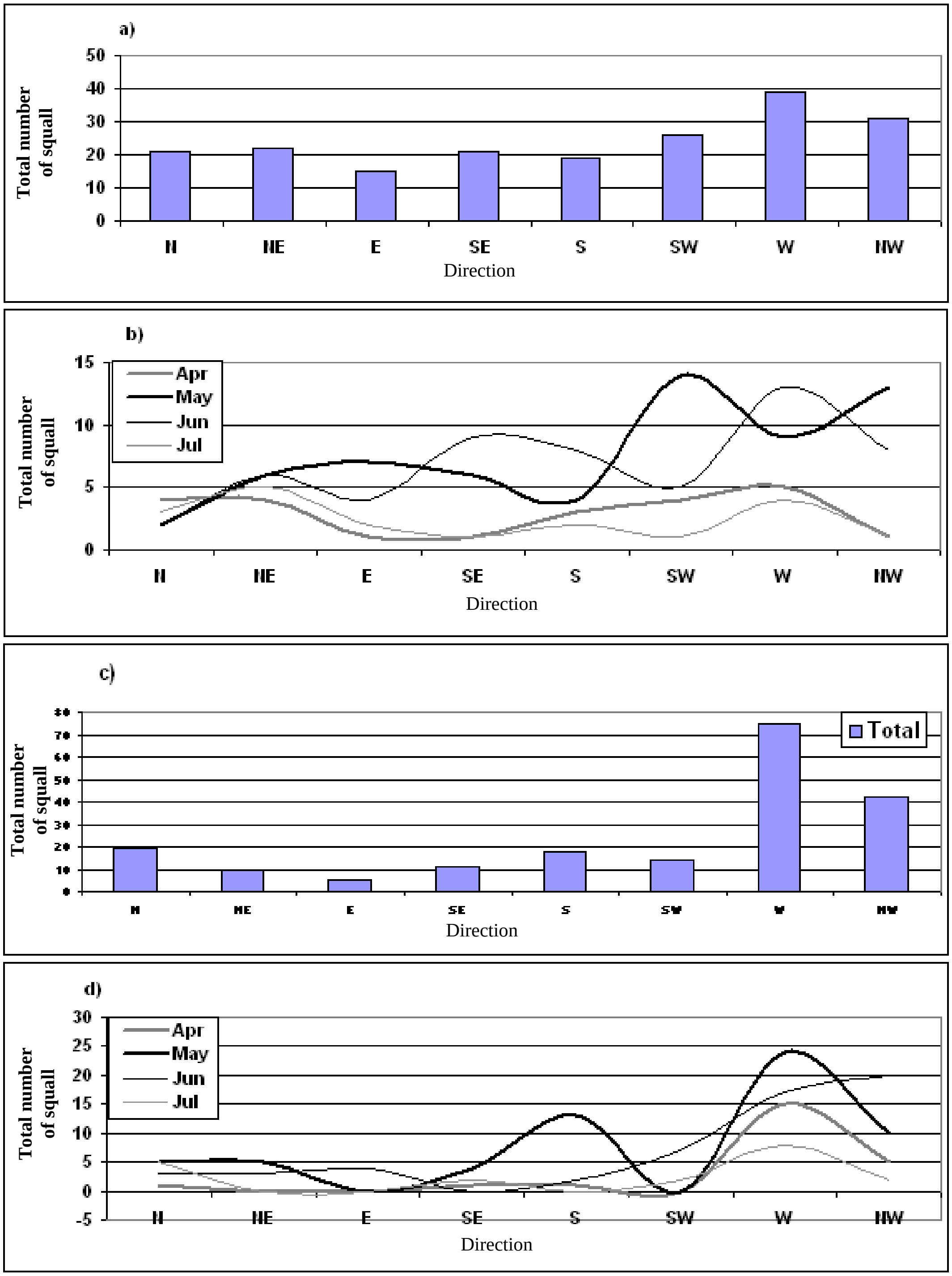
3.3. *Climatological characteristics of squalls frequency distribution of squalls and their relationship with TS occurrences*

The average annual frequency of squalls is found to be 17.6 with large variations. The year wise frequency distribution of squalls in Fig. 5(a) shows occurrences of highest squalls (27) in 1997 and lowest in 1996 and 1998 (9). Season wise average frequency distribution shows highest TS activity occurred during monsoon followed by pre-monsoon, *i.e.*, 92 in monsoon and 91 in pre-monsoon during 11 years (1995-2005). In post-monsoon there are 7 cases and in winter season 4 cases were observed during the 11 years. Month wise average



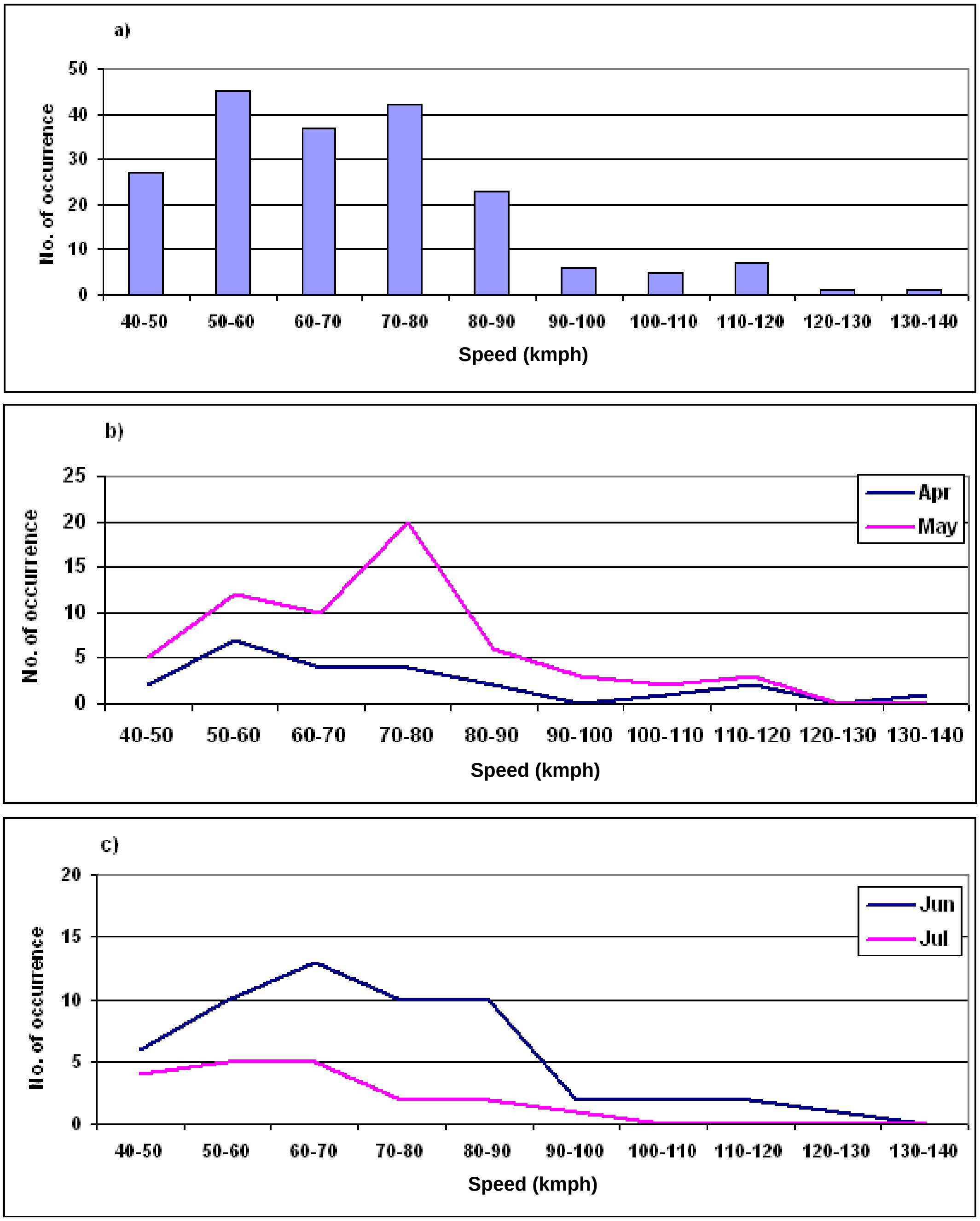
Figs. 6(a-c). Diurnal variation of occurrence of squalls (a) based on total occurrence, (b) based on monthly occurrences for the month of April and May and (c) for the month of June and July

squall frequencies in Fig. 5(b) shows no squalls in December and the highest average number of squall occurred in May as 5.5, *i.e.*, 61 followed by June as 5.1, *i.e.*, 56. Its average frequencies are 2.1 in April followed by 1.7 in July while it varies between 0.3 & 0.8 in remaining months. In Fig. 5(c), comparison of monthly percentage annual distribution of squalls with TS shows squalls are more in summer of May and June while TS are more in monsoon. Total number of squalls during the year 1995 to 2005 are 194 out of which 82% of the squalls occurred in the months April, May, June & July with May and June months alone having 60% of total annual squalls.



Figs. 7(a-d). Frequency of squall with respect to various directions (a) at the time of commencement based on total occurrences, (b) based on monthly occurrences for the month April to July, (c) after the cessation based on total occurrences and (d) based on monthly occurrences for the month April to July

Rest of the squalls is distributed in the remaining months with rare chances of occurrences in winter, September and no squalls in December. Fig. 5(c) also shows maximum TS activities are mainly from May to August, *i.e.*, around 65% while squalls are maximum in April to July with 83% of the total occurrences. The average frequency



Figs. 8(a-c). Frequency of squall in different speed ranges (a) Based on total occurrences, (b) based on monthly occurrences for the month of April and May and (c) For the month of June and July

of squalls in a year are 17.6 out of 47.2 TS (194 squalls out of 519 TS in 11 years), *i.e.*, around 37% of the total thunderstorms are associated with typical squalls from.

Time of occurrence of the squall

Fig. 6(a) considers timing of occurrences of total squalls which indicates a peak at afternoon till mid-night as the occurrences frequencies are very high of 52 squalls during 0900-1200 UTC followed by 47 squalls during 1200-1500 UTC, 30 squalls during 1500-1800 UTC and 20 squalls during 0600-0900 UTC with very less chance of 9 during morning 0000-0600 UTC. It also shows that 76% of the total squalls have occurred during the period 0600-1800 UTC. But their monthly occurrences, *e.g.*, April, May, June and July in Figs. 6 (b&c) indicates a very high peak squall activity at 1200-1500 UTC with occurrences during the other periods decreases gradually

TABLE 2

Environmental changes during the squall over IGI airport, Palam

	Temperature fall (°C)	Humidity rise (%)	Pressure change (hPa)	Peak wind (kmph)
Average	5.6	17.8	1.5	68
Maximum	19.7	39	3.9	139
Minimum	0.0	0.0	0.6	40

from peak on both the sides. But in June & July, their peak timings are earlier, *i.e.*, 0900-1200 UTC with gradual fall on both sides of the peak. Comparing the two seasons, *i.e.*, pre monsoon of April, May and monsoon of June, July from the Figs. 6(b&c), it is evident that the peak period of activity in April, May is between 1200-1500 UTC, *i.e.*, in the evening which shifts to the just afternoon period, *i.e.*, between 0900 & 1200 UTC. So from aviation point one should note this timing of occurrences shifting while issuing terminal aerodrome forecast. From Figs. 6 (b&c), average squall occurrence in May is more than in April.

Direction of commencement and dissipation of squalls

Squalls at Delhi airport were reported in general from all the directions of 8 points of compass as shown in Figs. 7 (a&c) when direction of commencement and dissipation have been considered. Fig. 7(a) shows at the time of commencement 36% squalls were reported from westerly and north-westerly direction whereas Fig. 7(c) shows at the time of cessation 60% squalls were noticed from westerly and north-westerly direction which indicates a change in the direction of squall with their progress. It was also noticed that on most of the occasions ground wind direction changes at the approach of squall and during their progress by as much as 145 degrees. Monthly variation from Fig. 7(b) shows commencement from SW to NW in May while from W to NW in June with SE squalls are more in June compared to May. Similarly, Fig. 7(d) shows direction at the time of cessation highest for all months from W to NW.

Squall wind speed

The speed of the squalls vary from 40 kmph to 120 kmph as depicted in Fig. 8 (a). A squall of the strongest wind speed of 138 kmph was observed on 27th April 2005 during this study period. Almost, 90% of total squalls are associated with wind speed of 40 to 90 kmph (20-45 knots) while 64% associated with 50-80 kmph (25-40 knots) and nearly 42% reported 50-70 kmph (25-35 knots). Analysis of monthly frequency of squall speed vs. number of occurrences in Figs. 8 (b&c) reveals that in May, the frequency of occurrence of squall within the wind speed range 70-80 kmph is higher, *i.e.*, 20 squalls out of 194 when compared to other months. This rise in speed seems as a result of more solar heating in May. In June & July the majority of squalls noticed between the speed ranges 50 to 90 kmph with highest no. of squalls of the speed 60-70. This cut off value is very helpful in deciding the wind speed warning in 50 to 90 kmph. The frequencies of high speed squalls in May & June are higher than April & July.

3.4. *Environmental changes associated with occurrences squalls*

The environmental changes associated with squalls are given in Table 2. Squalls bring out environmental temperature fall abruptly as the down drafts of towering CB spread from the cold air of middle and upper troposphere to the ground whereas relative humidity, mean sea level pressure and wind speed increases depending on the severity of the squall.

The highest fall of temperature was 19.7° C while average temperature fall is 5.6° C. The maximum rise in mean sea level pressure was found to be 3.9 hPa while average rise in pressure is 1.5 hPa. The rise in humidity was as high as 39% while the average rise in humidity is 17.8% with the occurrence of squall. The highest maximum wind speed during the squall has been noticed 139 kmph while the average wind speed due to squall is 68 kmph. Only one exceptional case of rise in temperature by 1 to 2° C in the squall in Nov, 2005 was noticed out of these total squall cases in 11 years. This may be on account of ground inversion which can be confirmed from the radiosonde ascent. It is found that the squalls occurring in the pre-monsoon season are more frequent and are most disastrous in nature & very much hazardous for aviation activities.

3.5. *Use in forecasting*

It is very well known that exact timing of occurrences TS and squalls and its violent characteristics can not be predicted much in advance except now casting using RADAR echoes. But in aviation, one has to include

TABLE 3

Climatological guidance of TS forecast and associated squall warnings

Months	% of annual frequency	Most favourable TEMPO timings for TAF	Whether warning of TS to be issued if RADAR echoes	Expected duration in in TAF	Whether squall warning to be appended	Expected direction and strength (*i.e.*, wind speed) of squalls
Mar	7% (still less chance)	1200-1500 UTC	Yes if strong echoes	Mostly (78%) within 3 hours while 22% 3-6 hours	4.6% of annual. In case TS warning is issued, 25% chance in the month TS accompanied with squalls	NW(67%) Speed.-50-90 kmph (100%) 50-70 (78%)
Apr	6.2% (still less chance)	1200-1500 UTC	Yes if strong echoes	Mostly (87%) within 3 hours while 10% 3-6 hours and only 3% are 6-9 Hours	11.9 % (3rd highest month) of annual. In case TS warning, squall chance is very high and hence squall warning must be issued as 72% chance of TS (2nd highest chance in any month) in the month accompanied with squalls	S/SW/W-52%, N-NE (32%) Speed - 40-80 kmph (74 %) and 80-120 (22%) 130-140 (4%)
May	Very high chances (15%) – 4th highest month of TS	1200-1500 UTC	Yes, in case any echoes	Mostly (82%) within 3 hours while 13% 3-6 hours with only 4% are 6-9 hours and 1% 9-12 hours	Highest chance of 31.5 % of annual. In case TS warning, squall chance is very high and hence squall warning must be issued as 80 % chance of TS (Highest chance in any month) in the month accompanied with squalls	SW/W/NW-59%, NE/E/SE-31%.Speed.-40-80 kmph (77%) and 80-120 (22%)
Jun	Highest chances (17.5%)	0600-1500 UTC	Yes, in case any echoes	Mostly (87%) within 3 hours while 12% 3-6 hours and only 1% are 6-9 hours	28.9 % of annual (2nd highest in month). In case TS warning, squall chance is very high and hence squall warning must be issued as 62 % chance of TS (3rd highest chance in any month) in the month accompanied with squalls	S/SW/W/NW-61%, N/NE/E/SE-38% Speed - 40-80 kmph (69%) and 80-130 (31%) *Note* : June squalls are stronger than May
Jul	Very high chances 17% (2nd highest month in the year)	0600-1500 UTC	Yes, in case strong echoes	Mostly (78%) within 3 hours while 19% 3-6 hours with only 2% 6-9 hours	9.8 % of annual. In case TS warning, squall chance is marginal as 22% chance of TS in the month accompanied with squalls	N/NE/E/SE-58%, others in all dir. Speed. -40-80 kmph (84 %) and 80-100 (16%)
Aug	Very high chances (16.1%)3rd highest month in the year)	0600-1500 UTC	Yes, in case any echoes	Mostly (88%) within 3 hours while 8% 3-6 hours with only 4% 6-9 hours	3.6 % of annual. In case TS warning, squall chance is very less since only 8% chance of TS in the month accompanied with squalls	N/E-57% Speed 40-70 kmph (100 %)
Sep	High chances (8.4%)	0900-1200 UTC	Yes, in case strong supporting echoes	Mostly (86%) within 3 hours while 11% 3-6 hours with only 3% 6-9 hours	4.1 % of annual. In case TS warning, squall chance is moderate since 18% chance of TS accompanied with squalls	N/NE/E/SE-75% Speed 40-80 kmph (100 %)

both in TAF and aerodrome warnings including trend forecast in METAR/SPECI with latter one to be issued at least 30-minutes in advance. With unavailability of suitable climatological timing of occurrences for each month, many times, the duty offices faces a lot of problem *e.g.*, issue very longer TEMPO timing which is not advisable as per ICAO. However, one can apply the present study as statistically compiled in Table 3 from climatological data to short out many issues to improve aviation forecasting related to occurrences of TS and squalls and their warnings once RADAR echoes are received. Since Fig. 1(b) and Table 3 shows hardly any TS occurs over IGI in November and December (1.5% of total TS occurred) and very less chance in October, January and February (only 4% of TS occurring in each month), one must extremely careful and try to find sufficient evidences about certainty of occurrence of TS before issuing any warnings for airport areas for these months. TS mainly occur during March-September which accounts for 87% of annual occurrences observed while squalls mainly occur during April to July which accounts for 82% of their annual occurrences. Similarly present study also shows one need not hurry to include squalls if at all TS warning has been issued over Delhi in these 5 months (October to February) as squalls rarely occurs during all these winter and post-monsoon months (only

6% of total occurs in both the seasons). But during April to July one can include squall warnings as per Table 3 in TS warnings as during these months in total 81% of annual frequency of squalls over IGI occur. Table 3 also shows percentage of TS accompanied with squalls for each months when both TS occurrences and squall occurrences are higher for high squall month. Also, it is very important to note from Table 3 how duration of TS varies with progress of the month and their timings of occurrences (call TEMPO in TAF). In case of adding squall warnings when TS warnings are issued, much of the earlier confusion related to squall direction and strength of wind speed have been clarified in Table 3. It shows if S/SW/W/NW are most possible direction of squalls appended in TS warnings for June when 61% of squalls from these direction were observed then for September, it is N/NE/E/SE when 75% of squall are from these directions. In case of associated wind speed, when May and June squalls are most stronger (Table 3) with 20-30% crossing 80 kmph, all (100%) August squalls are with in 40-70 kmph according to which in the absence any tools, it is necessary to incorporate respective climatological wind speed and direction of the squalls in the forecast and warning for respective months as per Table 3.

4. Conclusions

The average frequency of TS and squalls over IGI airport, Palam New Delhi is 47.2 and 17.6 per annum respectively. TS activity is maximum in June followed by July, whereas squalls are maximum in May followed by June. Both TS and squalls are predominant in monsoon and pre-monsoon seasons. Out of the total TS, around 37% are associated with typical type of squalls. There is 12% rise in the TS activity at IGI in 1995-2005 compared to the IMD normal of 1950-1980. During the period, study shows about more than 80% of TS in each season are of duration less than 3 hours with remaining are mostly 3 to 6 hours. Only 2-4% of TS in pre-monsoon and monsoon have lasted more than 6 hours with post-monsoon and winter having no such TS.

The peak time period of commencement of both TS and squalls in the day differs with the progress of the months. For pre-monsoon months, the most favourable timings of TS and squalls are 1200-1500 UTC while for monsoon, it starts earlier because of availability of more moisture with establishment of monsoon. For June to August together, about 52 % of TS occurred during 0600-1500 UTC. Afterwards, it is interesting to see shifting of thunderstorm peak timings with progress of months from 0900-1200 UTC during September followed by 1200-1500 UTC for October and 1500-1800 UTC for November with December having very few occurrences. Majority of the direction of squalls are from south-westerly to north-westerly. The present study confirms significant rise of maximum temperature and extreme temperature days for both the peak summer months of May and June from 1970s till recent expected due to high pollution, global warming and fast urbanization in the city have been inhibited due to significant rise of TS occurrences over the region. Squalls occur at IGI airport, Palam from all directions, however, the majority of the commencement of squalls are from SW to NW. Direction of 60% of the squalls at the time of cessation is W and NW. The duration of the squalls at IGI airport remained 1-3 minutes during the study period. On an average, the environmental temperature falls by 5.6° C, the relative humidity rises by 17.8% and mean sea level pressure rises by 1.6 hPa. Climatological Forecasting Guidelines Table based upon which different types of squall warning can be appended in various thunderstorm warnings depending on individual month, show squall wind speed and direction varies with progress of the months.

Acknowledgements

This work is undertaken at Met. Office of IGI airport, Palam, New Delhi. We express our sincere thanks to Mrs Bharati Jha, Met. Office of IGI airport, Palam, New Delhi for helping in drawing of figures.

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