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Some aspects of squall over Indira Gandhi International airport, New Delhi

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सार – इस शोध-पत्र में दिल्ली में आए अल्पकालिक झंझा (चंडवात) के कारणों तथा इनके पूर्वानुमान के पूर्वगामी विभवों का पता लगानें के लिए विशलेषण किया गया है। इस कार्य के लिए इंदिरा गाँधी अंतराष्ट्रीय हवाई अडड्ा (आई. जी. आई. एयरपोर्ट) के चंडवात – आँकड़ों के साथ–साथ भारत मौसम विज्ञान विभाग द्वारा वर्ष 2001–2010 की अवधि में अभिलेखित प्रत्येक माह के सतह के तथा उपरितन वायु आँकड़ों पर भी विचार किया गया है। चंडवात की अवधि, तीव्रता, कालावधि, बारम्बारता और चंडवात की प्रकृति, लक्षणों के अलावा चंडवात के आने से वातावरण में होने वाले परिवर्तन तथा तापगतिकीय लक्षणों एवं चंडवात को उत्पन्न करने वाले कारणों (इनडाइसेज) का विशलेषण किया गया है।

दिल्ली में चंडवात आने की अनूकुल स्थितियाँ मार्च, अप्रैल तथा जून में निचले क्षोभमंडल का 700 है.पा. स्तर तक और मई में 925 है.पा. पर सामान्य से अधिक उष्ण होने के साथ ही ठंडी शुष्क वायु के अभिवहन से मध्य एवं उपरी स्तरों में (मार्च, मई एवं जून में 500–300 है.पा., अप्रैल में 400–300 है.पा.) सामान्य ओसांक के कम होने से बनती है। केवल मार्च और अप्रैल महीने में निचले स्तर में प्रतिलोमन भी चंडवात के होने में मदद करता है। मानसून के महीने में जूलाई से सितंबर तक मध्य और उपरी क्षोभमंडलीय स्तरों में (जूलाई में 400–300 है.पा. पर सामान्य ओसांक से 8 से 15 डिग्री से. नीचे, अगस्त में 300–200 है.पा. पर सामान्य ओसांक से लगभग 15 डिग्री सें. नीचे और सितंबर में 500–300 है.पा. पर सामान्य ओसांक से 17–24 डिग्री सें. नीचे) ठंडी एवं शुष्क वायु अभिगमन दिल्ली से चंडवात के होने की अनुकूल स्थितियाँ हैं। दिल्ली के मानसून के महीनों में चंडवात के आने में मानसून पूर्व के महीनों से भिन्न निचले स्तर की नमी की कोई भूमिका नहीं होती है। मार्च से सितंबर तक 0000 यू.टी.सी. पर सामान्य से काफी अधिक स्वेट सूचकांक को उस दिन दिल्ली में चंडवात की घटना के सूचक के रूप में प्रयोग किया जा सकता है। जून को छोड़कर बाकी सभी महीनों के लिए कुल सूंचकांक उपयुक्त पूर्व सूचक (प्रीकर्जर) है।

ABSTRACT. A study is undertaken to analyse the characteristics of squall over Delhi and to find out the potential precursors for its prediction. For this purpose, the squall data of Indira Gandhi International (IGI) airport along with the surface and upper air meteorological parameters recorded by India Meteorological Department have been considered for all individual months over the period of 2001-2010. Apart from the characteristics like period of occurrence, intensity, duration, frequency and nature of squall, the environmental changes due to squall and thermodynamic features and indices leading to squall have been analysed.

Higher than normal warming of lower troposphere upto 700 hPa level in March, April & June and at 925 hPa in May accompanied with cold dry air advection leading to lower than normal dew point in middle and upper levels (500-300 hPa in March, May and June, 400-300 hPa in April) are favourable for occurrence of the squall over Delhi. The lower level inversion in March and April only also helps in the occurrence of squall. In monsoon months of July-September, cold and dry air advection in middle and upper tropospheric levels (8- 15° C below normal dew point at 400-300 hPa in July, about 15° C below normal dew point at 300-200 hPa in August and 17- 24° C below normal dew point at 500-300 hPa in September) favours occurrence of squall over Delhi. Unlike pre-monsoon months lower level moisture does not play any role for the occurrence of squall over Delhi in monsoon months. Significantly higher than normal SWEAT index in March to September at 0000 UTC can be used as predictor of squall over Delhi on that day. Total totals index is the next suitable precursor for all the months except June.

Key words – Squall, Thermodynamic index, Pre-monsoon, Monsoon, Delhi.

1. Introduction

Squall is a weather hazard caused by thunderstorm. As per India meteorological department (IMD) criteria (IMD, 1982), squall is defined as "a sudden increase of wind speed by at least three stages on Beaufort scale, the speed rising to force 6 (24 knot) or more and lasting for at least one minute". The sudden increase of wind speed is due to downdraft coming from thundercloud (Cumulonimbus cloud). It is one of the natural hazards which cause damage to the life and property over affected region. It is hazardous to aviation, as an aircraft crossing the squall affected area can loose altitude due to downdraft and can loose speed due to rapid change in wind direction and strength of wind speed. It also affects the visibility of air field due to dust raised by downdraft. Squall also affects the aircraft parked on ground and the services and facility at the aerodrome.

Considering all the above hazardous impact of squall and expectation of disaster managers, there are many studies on climatological aspect of thunderstorm (TS) and squall in different parts of India. According to Rao and Raman (1961) and Tyagi (2007), the frequency of thunderstorm is higher during pre-monsoon season. New Delhi receives 42.3 thunderstorm days during a year including 4.1 days in winter, 10.5 days in pre-monsoon, 25.8 days in monsoon and 1.9 days in post monsoon seasons (Tyagi, 2007). Detailed statistical analysis about squall over Delhi has been carried out by Bhalotra (1954), Joseph *et al.,* (1980), Lal (1989), Seshadri and Jain, (1989), and Jenamani *et al., (*2009). According to climatological table (IMD, 1999), based on data of 1951-80, Squall in Delhi occurs mostly in pre-monsoon and monsoon seasons. Based on ten years (1943-1952) data of Safdarjung airport, Bhalotra (1954) found that about 60% of squalls during the years occurred between 1500-2100 hrs (IST), showing important role of insolation in development of squall. According to him, 80% of squalls during the year come from southwest to north, 85% of squalls have duration of one hour or less. Long duration squalls are mostly in hot weather season. About 70% of squalls attain peak velocity within 10 minutes of the commencement time. Based on the data for the period of 1995-2005, Jenamani *et al.,* (2009) have found that the average frequency of thunderstorm (TS) and squall over IGI airport are 47.2 and 17.6 per annum respectively. TS are maximum in June followed by July whereas squall is maximum in May followed by June. The peak time of commencement of both TS and squall are 1200-1500 UTC, while in monsoon it starts early because of availability of moisture. Considering the meteorological characteristics associated with TS/squall, Bhalotra (1954) has found that the rise of pressure in squall is most predominant and cases of fall are very few. The fall of temperature in squall is most common occurrence and rise of temperature occurs in a few cases. The rise and fall of humidity has also been observed similar to temperature variation.

Many studies have attempted to predict the occurrence of TS over Delhi based on suitable indices. Srinivasan *et al.,* (1973) have suggested the empirical threshold value of total totals index (TTI) as 48 for occurrence of thunderstorm. Lal (1989) based on data of 10 years (1971-80) has found that higher the TTI value more favorable becomes the conditions for occurrence of TS during March to June. He also found that dew point at 850 hPa, *i.e.*, lower level moisture incursion plays a crucial role in occurrence of TS. Seshadri and Jain (1989) calculated the Showalter index and lifted index during summer monsoon months based on the data of seven years (1958-60, 1963-66) and found that lifted index is better predictor than Showalter index over Delhi. Kumar (1972) had developed a technique for forecasting monsoon TS activity over New Delhi region by using Showalter index, convective condensation level (CCL), difference in height between the CCL and freezing level (FL), direction of thermal wind between 700 and 500 hPa levels and the wind direction at height of 900 meter above mean sea level over Delhi. Dhawan *et al.,* (2008) have suggested that exceedence of critical value of four parameters, *viz*., Showalter index (greater than or equal to 0 to less than -9), Equivalent potential temperatures (θ_e) at 850 hPa (greater than 340 °K), meridional component of wind at 850 hPa (greater than 10 knot) and dew point at 850 hPa (greater than 13° C) can cause TS.

All the above studies indicate that, though there has been number of studies on climatological and thermodynamical aspects of thunderstorm over Delhi, such studies on squalls are limited. Considering this, a study is undertaken on the characteristics of occurrence, duration and intensity of squall and its thermodynamical aspect over Indira Gandhi International (IGI) airport, New Delhi. The radiosonde/radiowind (RS/RW) data at 0000 UTC on day of occurrence of squall during 2001-2010 has been analysed for this purpose. An attempt has been made to find out a simple and quick check on meteorological parameters and thermodynamic indices for possibility of squalls. It may help forecasters in monitoring and prediction of squall over Delhi.

2. Data and methodology

The study has been carried out on the basis of most recent data of ten years (2001-2010). The data on day of occurrence of squall, time of commencement of squall, direction of squall at station, intensity of squall, nature of squall etc. are collected from the squall reports available at Meteorological office, IMD, IGI airport, New Delhi. Monthly and annual frequencies of occurrence, time of commencement and duration of squall have been analysed. The characteristics of squall (nature of squall) have been analysed as per IMD criteria. As per this criteria, squalls are of various type, *viz*., (*i*) calm wind followed by squall, (*ii*) light wind followed by squall, (*iii*) calm wind followed by succession of squall, (*iv*) light wind followed by succession of squall, (*v*) gusty weather followed by squall, (*vi*) gusty weather followed by succession of squall, (*vii*) squall followed by gusty weather, (*viii*) general gusty weather with squall at interval and (*ix*) line squall. The direction of squalls at IGI airport has been analysed in 16 points of compass and its month-wise frequency has been calculated. The intensity of squall in terms of maximum wind has been analysed on the basis of Beaufort scale. The change in temperature, pressure and relative humidity in association with squall have also been analysed for different months. These data have been collected from Meteorological office, IMD, at IGI airport, New Delhi.

To find out the thermodynamical indices favourable for squall, the RS/RW data of 0000 UTC of the day of occurrence of squall has been considered except for the squalls which occurred during 0000-0700 hrs (IST). For these squalls, the 0000 UTC data of previous day has been considered. Various thermodynamincal indices as mentioned below have been calculated for each squall day following (a) http://weather.uwyo.edu/upperair/indices.html and (b) Ananthakrishnan & Yegnanarayanan (1949). The monthly means of indices are also calculated and analysed to find out suitable predictor of squall.

(*i*) Temperature (k) and Pressure (hPa) of lifting condensation level (LCL).

(*ii*) Level of free convection (LFC) – Level at which a parcel from the lowest 500 m of atmosphere is raised dry adiabatically to LCL and moist adiabatically to a level above which the parcel is positively buoyant. If more than one LFC exists, the lowest level is chosen.

(*iii*) Equilibrium level (EQLV) – Level at which a parcel from the lowest 500 m of the atmosphere is raised dry adiabatically to the LCL and moist adiabatically to a level above which the temperature of the parcel is the same as the environment. If more than one equilibrium level exists, the highest one is chosen.

(*iv*) Convective condensation level (CCL)

(*v*) Freezing levels (FL)

(*vi*) CCL - FL

(*vii*) Precipitable water (mm)

(*viii*) Showalter index (SI) = T_{500}-T_{P500}

T_{500} = Temperature in Celsius at 500 hPa

T_{P500} = Temperature in Celsius at 500 hPa of parcel lifted dry adiabatically from 850 hPa to 500 hPa.

(*ix*) Lifted index(LI) = T_{500}-T_{Parcel}

T_{Parcel} = 500 hPa temperature in Celsius of a lifted parcel with the average pressure temperature and dew point of the layer 500 m above the surface to 500 hPa.

(*x*) K- index (KI) = (T_{850}-T_{500}) + Td_{850}-(T_{700}-Td_{700})

T_{850} = Temperature in Celsius at 850 hPa

Td_{850} = Dew point in Celsius at 850 hPa

T_{700} = Temperature in Celsius at 700 hPa

Td_{700} = Dew point in Celsius at 700 hPa

(*xi*) Cross totals index (CTI) = Td_{850}-T_{500}

(*xii*) Vertical totals index (VTI) = T_{850}- T_{500}

(*xiii*) Total totals index (TTI) = (Td_{850}- T_{500}) + (T_{850}-T_{500})

(*xiv*) SWEAT index = 12 *Td_{850} + 20*Term2 + 2*SKT_{850} + SKT_{500} + Shear Term2 = Max (TTI - 49.0)

SKT_{850} = 850 hPa wind speed in knots

SKT_{500} = 500 hPa wind speed in knots

Shear = 125 [Sin (Dir500 - Dir850) + 0.2]

(*xv*) Convective available potential energy (CAPE)

(*xvi*) Convective inhibitions energy (CINE)

(*xvii*) Kinetic factor = (|CAPE|-|CINE|)/|CINE|

(*xviii*) Bulk Richardson Number (BRN) = CAPE / (0.5*U**2)

U = Magnitude of shear (u2-u1, v2-v1)

u1v1 = Average u, v in the lowest 500 m

u2v2 = Average u, v in the lowest 6000 m

3. Results and discussion

The climatological features associated with squall are presented and discussed in section 3.1 and thermodynamical characteristics associated with squall are presented and discussed in section 3.2. The broad conclusions of the study are presented in section 4. As the number of squall days during January-February and October to December (Table 1) are very less, the sample size for this statistical study may not be appropriate,

TABLE 1

Frequency of squall and number of squall days at IGI airport, New Delhi during (a) 2001-2010, (b) 1951-1980 and (c) 1995-2005

Months	2001-2010 a	1951-1980 b	1995-2005 c
January	0.0 (0)	(0.0)	0.2
February	0.1 (0.1)	(0.0)	0.2
March	0.8 (0.8)	(0.4)	0.8
April	2.3 (2.3)	(0.5)	2.1
May	5.7 (5.0)	(0.9)	5.5
June	5.2 (4.7)	(1.4)	5.1
July	1.3 (1.3)	(0.5)	1.7
August	0.9 (0.9)	(0.4)	0.6
September	0.6 (0.5)	(0.2)	0.7
October	0.2 (0.2)	(0.4)	0.4
November	0.3 (0. 1)	(0.0)	0.3
December	0.1 (0. 1)	(0.0)	0.0
Total	17.5 (16.0)	(4.7)	17.6

The figures inside the parenthesis indicate the number of squall days

Hence, the thermodynamic parameters associated with the squall has been presented and discussed for the period of March to September.

3.1. *Climatological features associated with squall over IGI airport.*

3.1.1. *Frequency of occurrence of squall*

The squall has occurred on 175 occasions over a 10 years period with an average of 17.5 events per year over IGI airport, New Delhi (Table 1). It endorses the earlier finding of Jenamani *et al*., (2009). The average frequency of squall is maximum during month of May (5.7) followed by June (5.2) & April (2.3). October has experienced two squalls days**,** whereas one squall day has been experienced in November, December and February and January is free from squall during period of study (Table 1). Considering different seasons, about 50% of squalls occurred during pre-monsoon season (March-May) followed by 46% in monsoon season (June-September), 3% in post-monsoon (October-December) and only 1% in winter season (January- February). As per climatology, based on data of 1951-80 (IMD, 1999), 1.4 days of squall has occurred in the month of June followed by 0.9 days in May, 0.5 days in April and July. Hence, comparing with climatology during 1951-80, we find that frequency of squall has significantly increased during March to September covering pre-monsoon and post-monsoon seasons. The rise has been maximum in the month of May followed by June. The mean frequency of squall in recent years (2001-2010) during the period of March to September is about 4 times that during 1951-1980.

3.1.2. *Direction of occurrence of squall*

The monthwise frequency distribution of direction of occurrence of squall is given in Table 2 as per 16 points of compass. Maximum 54 number of squalls occurred from north-west (NW) direction followed by 32 from west (W), 24 from south-west (SW) and 19 from west-northwest (WNW) direction. About 80% of total squalls occurred from SW to NW direction against the earlier findings of squall from SW to north (Bhalotra, 1954). About 10% of squalls also occurred from north of north west to north direction. Maximum number of squalls during month of May and June occurred from NW direction and in month of April it occurred from WNW and SW direction. The movement of squall is associated with the movement of thunderclouds. The direction of movement of thunderstorms is the average of the wind directions from the gradient wind level to 500 hPa level. That is, the speed and direction of movement of thunderstorm is the vector mean wind of the layer in which the cloud is embedded (Asnani, 2005). The movement of thunderstorm cloud also depends upon the stages of its life cycle. In growing stage when updrafts dominate, winds in lower level are more influential than those of upper level whereas in dissipating stage when downdrafts dominate, winds in upper level are more influential than those of lower level in determining the direction of movement of thundercloud. However, on some occasions, sudden change may be observed due to vertical transport of horizontal momentum by the strong vertical draft inside the thunderstorm. Since, the squalls result from downdraft coming out from the thunderclouds, the movement of squalls fully depends on the wind in upper levels (Asnani, 2005). The dominant direction of squall (SW to NW) over Delhi may be attributed to the fact that most of theses squalls occurred in association with the mid latitude westerlies at middle and upper tropospheric levels (Srinivasan *et al*., 1973).

3.1.3. *Intensity and duration of squall*

The intensity of squall has been found out by considering speed of squall as per Beaufort scale (Table 3). About 62% of total squalls have maximum speed between 34 to 63 knot (kt) and only 2% of total squalls have speed more than 63 kt. During period of study, 4 squalls were reported with speed more than 63 kt (118 kmph). The maximum speed of squall was 75 kt (138 km/h) reported on 07 April, 2005 followed by 74 kt (138 km/h) on 16 June, 2006. Pre-monsoon squalls (April to June) are more severe than monsoon season squalls as

TABLE 2

Direction of occurrence of squall at IGI airport New Delhi during 2001-2010

Months	Direction of squall															
	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	N	NNE
January	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
February	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-
March	-	-	-	-	1	-	1	-	2	-	2	2	-	-	-	-
April	-	-	-	-	1	-	1	-	5	1	8	3	3	1	-	-
May	1	1	1	-	-	-	-	-	7	4	12	6	20	2	2	1
June	2	-	1	-	1	-	1	-	9	3	4	5	22	1	3	-
July	1	-	-	-	-	-	-	-	-	2	2	2	3	-	3	-
August	-	-	1	-	2	1	-	-	1	-	-	1	1	-	2	-
September	1	-	-	-	1	-	-	-	-	-	2	-	2	-	-	-
October	-	-	-	-	-	-	-	-	-	-	-	-	2	-	-	-
November	-	-	-	-	-	-	1	-	-	-	1	-	1	-	-	-
December	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-
Total	5	1	3	-	6	1	4	-	24	11	32	19	54	4	10	1

most of squalls with intensity of Beaufort scale of 10 or more (48 kt or more) occur during April to June (>90%). The squalls in winter and post-monsoon seasons are mild in nature. The higher severity in summer month may be attributed to the fact during summer months atmosphere is highly unstable and the vertical development of thunder cloud is maximum (Srinivasan *et al.,* 1973). Considering the duration of squall maximum number of squalls (136) have sharp gust for one minute duration, 37 squalls for two minute duration and only two squalls for three minute duration (not shown).

3.1.4. *Nature of squall*

Considering the nature of the squall (Table 4), the squalls have two dominant characteristics, *viz*., (*i*) light wind followed by squall and (*ii*) gusty weather followed by squall. These two types together contribute about 80% of the total squalls. On 18 occasions (about 10%) squall is followed by gusty weather. Considering the individual months, similar is the case in May to September. In month of February, October, November & December, squalls are characterized as light wind followed by squall or calm wind followed by squall. The third category of squall (squall is followed by gusty weather) occurs mainly during March to June while light wind/gusty weather followed by succession of squall occurs only in May and June.

3.1.5. *Days of frequent squalls*

The statistics of days of frequent squalls (two or more in 24 hours) are shown in Table 5. The frequent squall in a day usually occurs during May and June (6 and 5 respectively out of total 14 days). Considering the time interval of occurrence of frequent squalls in a day, it is seen that the subsequent squalls occurred with fresh developments (after 2 hours) in 7 out of 14 days. The occurrence of frequent squalls in a day even spanning from morning to afternoon may be attributed to the persistence of favourable conditions in association with synoptic situations like western disturbances (Srinivasan *et al.,* 1973).

3.2. *Environmental changes due to squall*

3.2.1. *Change in surface pressure during squall*

The rise of surface pressure in squall is most predominant and only a few cases of fall of pressure have been observed (Table 6). It endorses the earlier findings of Bhalotra (1954) for Safdarjung airport. As per Asnani (2005), whenever thunderstorm accompanied by squall passes over a station, the pressures value changes abruptly and this changed can be noticed in the barograph. It may be either cup type pressure curve or dip that is first by fall of pressure and then by rise of pressure or a

TABLE 3

Intensity of squall (max. wind speed) at IGI airport, New Delhi during 2001-2010

Months	Beaufort scale						
	6	7	8	9	10	11	12
January	-	-	-	-	-	-	-
February	1	-	-	-	-	-	-
March	3	-	3	2	-	-	-
April	3	2	11	5	-	-	2
May	6	14	14	9	8	6	-
June	4	12	14	8	8	4	2
July	-	6	5	1	1	-	-
August	2	4	1	1	1	-	-
September	2	2	-	2	-	-	-
October	-	-	1	1	-	-	-
November	1	-	2	-	-	-	-
December	1	-	-	-	-	-	-
Total	23	40	51	29	18	10	4

Beaufort scale

6 = Wind speed from 22-27 kt 7 = Wind speed from 28-33 kt,
8 = Wind speed from 34-40 kt, 9 = Wind speed from 41-47 kt,
10 = Wind speed from 48-55 kt, 11 = Wind speed from 56-63 kt,
12 = Wind speed >64 kt,

TABLE 4

Characteristics of squall (nature) classification at IGI Airport, New Delhi during 2001-2010

Months	Nature of squall								
	1*	2*	3*	4*	5*	6*	7*	8*	9*
January	-	-	-	-	-	-	-	-	-
February	-	1	-	-	-	-	-	-	-
March	-	3	-	-	3	-	2	-	-
April	3	5	-	-	9	-	6	-	-
May	-	24	-	2	24	1	6	-	-
June	5	21	-	-	21	2	3	-	-
July	-	7	-	-	6	-	-	-	-
August	1	6	-	-	2	-	-	-	-
September	-	2	-	-	3	-	1	-	-
October	-	1	-	-	1	-	-	-	-
November	1	1	-	1	-	-	-	-	-
December	1	-	-	-	-	-	-	-	-
Total	11	71	-	3	69	3	18	-	-

1*- Calm wind followed by squall,
2*- Light wind followed by squall
3*- Calm wind followed by succession of squall
4*- Light wind followed by succession of squall
5*- Gusty weather followed by squall
6*- Gusty weather followed by succession of squall
7*- Squall followed by Gusty weather
8*- General gusty weather with squall at interval
9*- Line squall

pressure jump line curve. This is because of the large quantity of cold air released by thunder clouds which produces an extensive dome of cold air over station. As a result, this creates a ridge of high pressure over station. This contributes to sudden rise of surface pressure. Higher pressure rises (>3 hPa) indicating more severe squall have been recorded during April to June. Highest pressure rise of 7.4 hPa was recorded in month of June (on 06 June 2005) when there was trace rainfall and the speed of the squall was 52 kt. All the cases of pressure fall have been reported during April-June. The maximum fall of surface pressure of 5.6 hPa was recorded on 4 June 2001 when 42.4 mm rainfall and 66 kt wind were recorded in association with squall. It indicates that there is no one to one relationship between intensity of squall and the rise/fall in pressure due to squall.

3.2.2. *Change in temperature during squall*

In 94% of squall cases, fall in temperature has been reported whereas there have been cases of rise or no change in temperature in remaining cases (Table 7). It endorses the earlier findings of Bhalotra (1954) for Safdarjung airport. Maximum fall of 16° C, was reported on 13 June 2010 when 4.8 mm rain was occurred in association with squall. The highest rise of 2.1° C was reported on 03 November 2005 when squall occurred at 0228 hrs (IST) and there was trace rain. The higher fall of temperature (more than 8° C) was observed mainly in summer month (April-June). Like pressure, there is also no one to one relationship between intensity of squall and the change in temperature due to squall.

3.2.3. *Change in relative humidity (RH) during squall*

From Table 8, in 90 % cases of squall, rise in RH is reported where as fall or no change in RH is reported in remaining cases endorsing the earlier findings of Bhalotra (1954) for Safdarjung airport. On 14% occasions, the rise in RH is more than 30% and it mainly occurs during March-June. The maximum rise of 62% has been reported on 20 March 2007 when there was 12 mm rain. The highest fall in RH (16%) was reported on 03 November

TABLE 5

Date and time of occurrence of frequent squall (2 or more) and associated maximum wind over IGI airport New Delhi during 2001-2010

Date	Frequency	Time of occurrence hrs (IST)	Maximum wind speed (knot) & direction	Nature of squall**
01 May 2001	2	1428	WNW/46	2
		1433	WNW/52	4
03 May 2001*	2	1251	NW/50	2
		2000	ENE/42	5
21 August 2003*	2	1255	SE/36	5
		1740	SW/28	1
27 May 2004*	2	1055	NW/31	2
		2143	SW/28	5
22 June 2004*	2	0524	WNW/50	2
		1558	N/35	5
07 May 2005	2	1822	SW/28	5
		1917	SW/43	5
05 June 2005	2	1521	NE/58	5
		1550	NW/56	6
03 November 2005*	3	0128	NW/38	2
		0758	W/27	1
		0828	S/38	4
31 May 2006*	3	1715	W/32	5
		1725	SW/45	6
		2350	NW/25	2
15 June 2006	2	1532	WNW/37	5
		1617	WNW/40	5
16 June 2006	2	1558	SW/30	2
		1603	SW/74	5
22 September 2006*	2	1548	W/45	2
		1855	W/26	2
06 May 2007	2	1501	NW/25	2
		1504	NW/40	6
10 June 2009	2	1340	N/40	2
		1510	NW/42	2

*Time interval between squalls is more than two hours.

Nature of squall**-

1 - Calm wind followed by squall, 2 - Light wind followed by squall, 4 - Light wind followed by succession of squall,

5 - Gusty weather followed by squall, 6 - Gusty weather followed by succession of squall.

TABLE 6

Change in surface pressure (hPa) in squall at IGI airport, New Delhi during 2001-2010

Months	Rise in Pressure (hPa)								Fall in Pressure (hPa)					
	0.1 - 1	1.1- 2	2.1- 3	3.1- 4	4.1- 5	5.1- 6	6.1- 7	7.1- 8	0.1 - 1	1.1- 2	2.1- 3	3.1- 4	4.1- 5	5.1- 6
January	-	-	-	-	-	-	-	-	-	-	-	-	-	-
February	-	1	-	-	-	-	-	-	-	-	-	-	-	-
March	6	1	1	-	-	-	-	-	-	-	-	-	-	-
April	17	4	-	1	-	-	-	-	1	-	-	-	-	-
May	29	16	6	2	1	1	-	-	2	-	-	-	-	-
June	35	11	2	-	-	-	-	1	2	-	-	-	-	1
July	11	2	-	-	-	-	-	-	-	-	-	-	-	-
August	7	2	-	-	-	-	-	-	-	-	-	-	-	-
September	4	1	1	-	-	-	-	-	-	-	-	-	-	-
October	2	-	-	-	-	-	-	-	-	-	-	-	-	-
November	3	-	-	-	-	-	-	-	-	-	-	-	-	-
December	1	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	115	38	10	3	1	1	0	1	5	0	0	0	0	1

TABLE 7

Change in temperature (°C) in squall at IGI airport, New Delhi during 2001-2010

Months	Fall in temperature (°C)								Rise in temperature (°C)		No Change
	0.1-2	2.1-4	4.1-6	6.1-8	8.1-10	10.1-12	12.1-14	14.1-16	0.1-2	2.1-4	
January	-	-	-	-	-	-	-	-	-	-	-
February	-	-	-	-	-	-	-	-	1	-	-
March	3	3	1	-	1	-	-	-	-	-	-
April	9	6	1	2	2	-	1	-	1	-	1
May	19	11	15	4	4	1	1	-	2	-	-
June	19	9	11	1	5	4	-	1	2	-	-
July	4	6	2	1	-	-	-	-	-	-	-
August	1	2	-	4	2	-	-	-	-	-	-
September	3	2	-	1	-	-	-	-	-	-	-
October	1	-	1	-	-	-	-	-	-	-	-
November	-	-	-	-	-	-	-	-	2	1	-
December	1	-	-	-	-	-	-	-	-	-	-
Total	60	39	31	13	14	5	2	1	8	1	1

TABLE 8

Change in relative humidity (%) in squall at IGI airport, New Delhi during 2001-2010

Months	Rise in relative humidity (%)							Fall in relative humidity (%)		No Change
	1 - 10	11 - 20	21- 30	31 - 40	41- 50	51 - 60	61 - 70	0 -10	11 - 20	
January	-	-	-	-	-	-	-	-	-	-
February	1	-	-	-	-	-	-	-	-	-
March	3	1	-	-	1	-	1	2	-	-
April	10	4	2	-	3	-	-	3	-	1
May	23	11	8	6	4	-	-	5	-	-
June	25	13	5	2	4	1	-	-	-	2
July	8	3	1	-	-	-	-	1	-	-
August	2	2	2	1	-	-	-	1	1	-
September	2	3	1	-	-	-	-	-	-	-
October	1	-	1	-	-	-	-	-	-	-
November	1	-	-	-	-	-	-	1	1	-
December	-	-	-	-	-	-	-	1	-	-
Total	76	37	20	9	12	1	1	14	2	3

2005 when squall occurred at 0228 hrs (IST) accompanied with trace rainfall and on 25 August 2001 when squall occurred at 2230 hrs (IST) without rain. On 17 occasions when there was fall or no change in RH, there was either no rainfall or trace rainfall. Comparing the intensity (wind) of squall and the RH observed after squall, there is also no one to one correspondence between them like that of temperature and pressure with the intensity of squall.

3.3. *Thermodynamical features leading to squall over IGI airport*

3.3.1. *Fundamental parameters*

The mean values of environment temperature, dew point and RH over IGI airport at 0000 UTC of day of occurrence of squall from surface to 200 hPa level along with the corresponding normal values are shown in Table 9 and departure from normal value of dew point depression are shown in Fig. 1. Significantly higher than normal (by 2-4 °C) environment temperature in lower tropospheric levels (upto 850 hPa) accompanied with rise in surface dew point by about 4 °C and decrease in dew point by 7-10°C from the normal and RH by the order of 20 to 30% from the normal in middle levels (500-300 hPa) in the morning [Table 9(a)] indicates occurrence of squall at IGI airport in subsequent hours of the day in month of March. Similarly, in month of April, rise in environment temperature by 2-3 °C from the normal in lower levels (upto 850 hPa) accompanied with the rise in dew point by 2 to 4 °C, in lower troposphere (upto 700 hPa) and increase in RH by 5 to 10% upto 700 hPa and decrease in dew point by 5-9 °C at 400-300 hPa levels in morning are favorable for occurrence of squall on that day.

In month of May, warmer than normal (by 1.5-2 °C) environment temperature at 300-200 hPa levels, increases in the dew point from the normal by 3 to 5 °C in lower troposphere (upto 700 hPa), fall by 4 to 7 °C at 500-300 hPa and increases in RH by 15 to 20% in lower troposphere (upto 700 hPa) and decrease by about 15% at 500-300 hPa at 0000 UTC of day are favorable for occurrence of squall on that day. Unlike, the month of March and April, surface/lower level temperature in the month of May do not play significant role in the occurrence of squall in May. On the other hand, lower level moisture incursion plays more significant role in May than in March and April. All the above results confirm the earlier findings Srinivasan *et al.,* (1973) of favourable and unfavourable environmental conditions for occurrence of squall. However, this study quantifies the

TABLE 9 (a)

Mean temperature (°C), dew point (°C), relative humidity (%) and their difference from normal values at 0000 UTC of the day of occurrence of squall over IGI airport New Delhi during March-June

Months	Levels (hPa)	Temperature (°C)			Dew point (°C)			Relative humidity (%)		
		S	N	D	S	N	D	S	N	D
March	Surface	**19.4**	16.9	2.5	**12.9**	9.2	3.7	67	60	7
	925	**22.4**	19.5	2.9	5.1	6.3	-1.2	38	42	-4
	850	**19.3**	15.2	4.1	1.3	-0.5	1.8	33	34	-1
	700	6.2	3.5	2.7	-11	-8.5	-2.5	33	41	-8
	500	-14.3	-14.7	0.4	**-34.6**	-24.9	-9.7	**20**	42	-22
	400	-25.3	-26.7	1.4	**-46.7**	-34.9	-11.8	**14**	46	-32
	300	-40.5	-41.3	0.8	**-55.4**	-48.1	-7.3	**23**	48	-25
	250	-49.2	-49.1	-0.1	-63	-	-	22	-	-
	200	-54.3	-55.2	0.9	-67.5	-	-	22	-	-
April	Surface	**25.2**	23.2	2	**12.5**	10.3	2.2	50	44	6
	925	27	25.5	1.5	10.1	8.5	1.6	**44**	34	10
	850	**23.1**	20.5	2.6	**5.5**	2.1	3.4	**37**	29	8
	700	**9.3**	7.2	2.1	**-2.2**	-6.2	4	**49**	38	11
	500	-11.5	-12.1	0.6	-26	-23.3	-2.7	43	39	4
	400	-23.9	-24.3	0.4	**-39**	-33.9	-5.1	35	42	-7
	300	-39.5	-39.4	-0.1	**-55.7**	-47	-8.7	**26**	44	-18
	250	-47.8	-47.4	-0.4	-63.3	-	-	23	-	-
	200	-53.1	-54.2	1.1	-67.5	-	-	20	-	-
May	Surface	27.5	27.3	0.2	**18.1**	12.8	5.3	**59**	41	18
	925	**27.8**	28.9	-1.1	**15.5**	12.7	2.8	**50**	37	13
	850	23.6	24	-0.4	**10.4**	6.7	3.7	**46**	33	13
	700	10.7	10.5	0.2	**0.3**	-2.4	2.7	**53**	40	13
	500	-8.8	-9.1	0.3	**-25.6**	-21.2	-4.4	**34**	52	-18
	400	-20.3	-20.3	0	**-39.6**	-31	-8.6	**23**	38	-15
	300	**-32.7**	-34.4	1.7	**-50.7**	-44.2	-6.5	**21**	36	-15
	250	**-40.5**	-42.4	1.9	-58.2	-	-	17	-	-
	200	**-50.1**	-51.5	1.4	-67	-	-	15	-	-
June	Surface	**28.2**	28.9	-0.7	19.4	19.1	0.3	**60**	55	5
	925	29	28.9	0.1	**15.2**	18.4	-3.2	49	53	-4
	850	24.3	24.4	-0.1	11.1	12.7	-1.6	49	48	1
	700	**11.4**	12.2	-0.8	1.7	2.7	-1	56	52	4
	500	**-6.5**	-5	-1.5	**-24.6**	-14.9	-9.7	**35**	46	-11
	400	**-15.4**	-13.8	-1.6	**-34.4**	-24.1	-10.3	**25**	41	-16
	300	-27.5	-27.4	-0.1	**-47.1**	-36.7	-10.4	**20**	41	-21
	250	**-37.6**	-36.6	-1	-55.7	-	-	19	-	-
	200	-48.5	-48.1	-0.4	-66.6	-	-	16	-	-

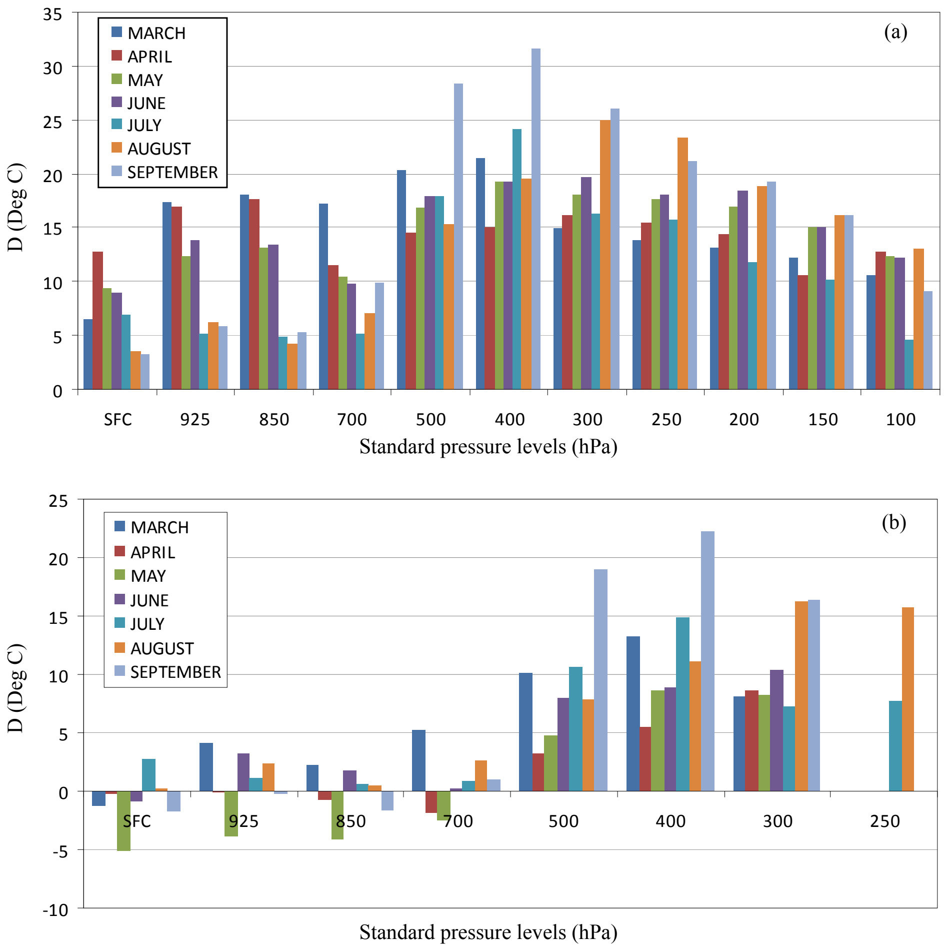
"-" Data not available, S: Value on squall day, N: Normal value, D = S - N
The values significantly different than normal at 95% level of confidence are highlighted

TABLE 9 (b)

Mean temperature (°C), dew point (°C), relative humidity (%) and their difference from normal values at 0000 UTC of the day of occurrence of squall over IGI airport New Delhi during July- September

Months	Levels (hPa)	Temperature (°C)			Dew point (°C)			Relative humidity (%)		
		S	N	D	S	N	D	S	N	D
July	Surface	**29.9**	27.7	2.2	23	23.5	-0.5	69	78	-9
	925	27.5	26.4	1.1	22.4	22.4	0	75	79	-4
	850	23.7	22.3	1.4	18.8	18	0.8	75	77	-2
	700	11.8	12.4	-0.6	6.6	8.1	-1.5	73	75	-2
	500	-1.7	-2.1	0.4	-19.6	-9.4	-10.2	**38**	57	-19
	400	-11.4	-11.2	-0.2	**-35.5**	-20.4	-15.1	**22**	47	-25
	300	-26.5	-25.3	-1.2	**-42.8**	-34.4	-8.4	33	42	-9
	250	-36.8	-35.1	-1.7	-52.6	-43.1	-9.5	29	44	-15
	200	-49.8	-47.4	-2.4	-61.6	-	-	35	-	-
August	Surface	27.2	26.8	0.4	23.7	23.5	0.2	81	82	-1
	925	25.9	25.4	0.5	19.6	21.5	-1.9	70	79	-9
	850	**22.3**	21.4	0.9	18.1	17.7	0.4	78	79	-1
	700	12.8	12	0.8	5.7	7.5	-1.8	65	74	-9
	500	-3.5	-2.2	-1.3	-18.8	-9.6	-9.2	46	57	-11
	400	-12.9	-11.9	-1	-32.4	-20.3	-12.1	34	50	-16
	300	-25.5	-26.3	0.8	**-50.4**	-35	-15.4	**10**	43	-33
	250	-36.4	-36.1	-0.3	**-59.8**	-43.8	-16	**9**	45	-36
	200	-50.1	-48.6	-1.5	-69	-	-	13	-	-
September	Surface	**26.4**	25.4	1	**23.1**	20.4	2.7	83	74	9
	925	25	24.8	0.2	19.2	18.7	0.5	71	69	2
	850	21.1	20.5	0.6	15.8	13.6	2.2	72	65	7
	700	10	10.1	-0.1	0.1	1.2	-1.1	59	54	5
	500	-7.6	-4.7	-2.9	**-35.9**	-14	-21.9	**11**	48	-37
	400	-16.3	-14.6	-1.7	**-47.9**	-24	-23.9	**6**	45	-39
	300	-30.1	-29	-1.1	**-56.1**	-38.6	-17.5	8	39	-31
	250	-41.1	-38.8	-2.3	-62.2	-	-	10	-	-
	200	-51.7	-50.7	-1	-70.9	-	-	12	-	-

"-" Data not available, S: Value on squall day, N: Normal value, D = S - N
The values significantly different than normal at 95% level of confidence are highlighted



DPDS :-Dew Point Depression on Squall days DPDN:-Dew Point Depression on Normal days D = DPDS – DPDN

Figs. 1 (a&b). (a) Dew point depression and (b) departure of dew point depression from normal at 0000 UTC of the day of occurrence of squall over IGI Airport during March to September during 2001-2010

favourable and unfavourable factors so that they can be used as precursors for the occurrence of squall over IGI airport.

Comparing the dew point depression during squall days (DPDS) and normal days (DPDN), the departure of dew point depression during squall days from normal (DPDS-DPDN) is negative upto 700 hPa levels during April and May indicating lower level moisture incursion, while in March it does not show such evidence except for the surface level. The dew point depression is significantly higher than normal at middle and upper levels indicating cold and dry air advection over the region which is favourable for occurrence of thunder squall. The departure of dew point depression from normal is maximum either at 400 hPa or 300 hPa level for occurrence of squall in different months. It is more than 10° C during monsoon months (June-September). Such type of condition prevails over Delhi during monsoon season, when there is a weak monsoon condition and there exist a deep trough in mid latitude westerly at middle and upper tropospheric levels (Rao, 1976). As in normal monsoon condition the dew point depression is less, it becomes significantly higher during above mentioned weak monsoon condition. The lower level moisture does not undergo any significant changes in weak monsoon condition.

In June, colder environment temperature along with increase in RH at surface and colder temperature than normal by 1-2 °C at 700-400 hPa levels and colder dew point than normal by about 10 °C at 500-300 hPa levels and hence decrease in RH by 10-20% at 500-300 hPa levels are favourable for occurrence of squall.

TABLE 10

Mean values of CAPE, CINE, Bulk Richardson number, temperature and pressure of LCL equilibrium level etc. at 0000 UTC of the day of occurrence of squall over IGI airport, New Delhi during 2001-2010

Months	Indices											
	CAPE (J/kg)	CINE (J/kg)	Kinetic factor	Bulk Richardson No.	LCL		Equilibrum Level (hPa)	LFC (hPa)	CCL (hPa)	FL (hPa)	CCL-FL (hPa)	Precipi-table water (mm)
					Temp. (K)	Press. (hPa)						
March	156.1	-326.5	-0.5	8.0	278.5	783.4	281.7	562.7	652	632	20	19.9
April	821.1	-352.8	1.3	56.9	281.7	779.5	267.8	644.8	647	601	46	26.5
May	1104.6	-310.3	2.6	88.0	287.2	806.7	282.2	662.2	703	582	121	26.8
June	925.6	-216.5	3.3	396.7	287.6	798.7	310.8	687.0	694	565	129	38.7
July	1884.4	-123.3	14.3	567.8	294.5	865.5	170.3	754.1	792	522	270	56.4
August	995.6	-198.9	4.0	309.1	293.3	875.7	267.8	716.5	769	537	232	52.2
September	1820.5	-145.7	11.5	162.8	293.0	886.9	288.4	742.6	793	578	215	41.1

TABLE 11

Mean values of thermodynamical indices at 0000 UTC of the day of occurrence of squall over IGI airport, New Delhi during 2001-2010

Months	Indices																				
	Showalter Index (SI)			K index (KI)			Lifted Index (LI)			Total totals index (TTI)			Vertical totals index (VTI)			Cross totals index (CTI)			SWEAT index		
	S	N	D	S	N	D	S	N	D	S	N	D	S	N	D	S	N	D	S	N	D
Mar	**0.7**	4.4	-3.7	17.6	17.4	0.2	**1.4**	5.6	-4.2	**49.2**	44.1	5.1	**33.6**	39.9	-6.3	15.6	14.2	1.4	**148.4**	0	148.4
Apr	**-0.1**	2.2	-2.3	**26.5**	21.3	5.2	**-1.4**	3.0	-4.4	**49.8**	46.8	3.0	34.0	32.6	1.4	15.8	14.2	1.6	**174.3**	25.2	149.1
May	**-1.9**	0.3	-2.2	**31.9**	26.9	5.0	**-3.7**	1.4	-5.1	**51.0**	48.9	2.1	32.5	33.1	-0.6	**18.5**	15.8	2.7	**256.0**	80.4	175.6
Jun	**-1.5**	-0.3	-1.2	32.2	32.6	-0.4	**-2.8**	-1.5	-1.3	48.5	47.1	1.4	**30.7**	29.4	1.3	17.8	17.7	0.1	**230.8**	152.4	78.4
Jul	-2.3	-1.4	-0.9	39.2	38.1	1.1	-2.8	-2.7	-0.1	**45.7**	44.5	1.2	25.4	24.4	1.0	20.3	20.1	0.2	**265.5**	216.0	49.5
Aug	**-2.9**	-0.8	-2.1	37.2	36.8	0.4	-2.8	-2.4	-0.4	**47.3**	43.5	3.8	25.7	23.6	2.1	**21.6**	19.9	1.7	**271.8**	212.4	59.4
Sep	**-4.2**	1.1	-5.3	34.7	29.9	4.8	**-5.6**	-0.7	-4.9	**52.1**	43.5	8.6	**28.7**	25.2	3.5	**23.4**	18.3	5.1	**298.1**	163.2	134.9

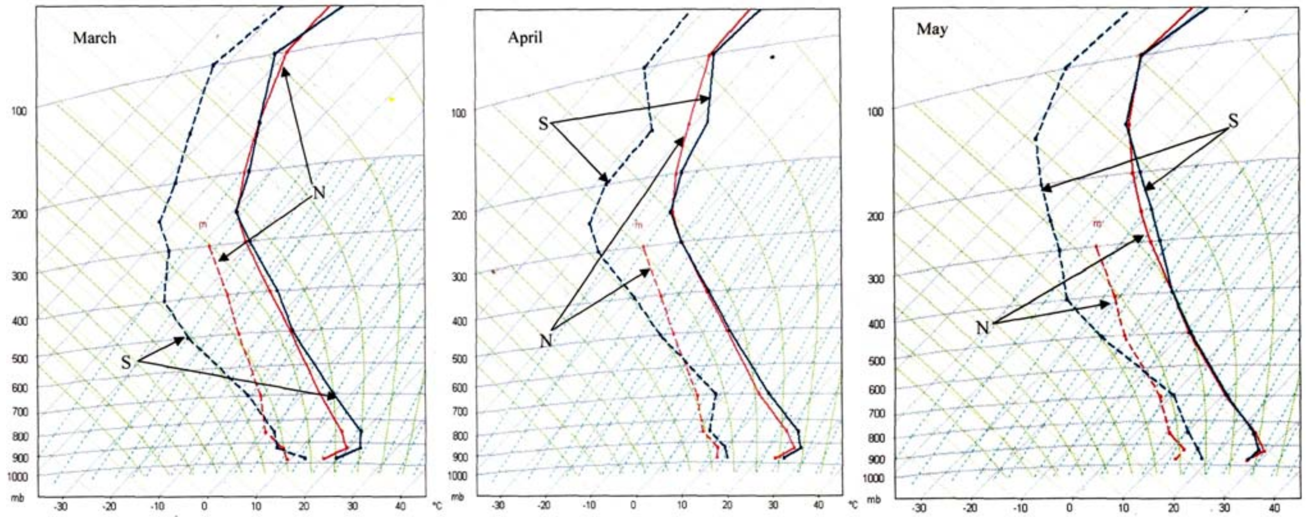
S : Value on squall day, N : Normal value, D = S - N

The values significantly different than normal at 95% level of confidence are highlighted

In month of July, August and September [Table 9(b)] similarly colder dew point and hence drier air at middle and upper level 400-300 hPa in July, 300-250 hPa in August and 500-300 hPa in September favours occurrence of squall. Unlike pre-monsoon month, lower level moisture (RH/dew point) do not play any role in the occurrence of squall in July-September as moisture is already available in lower levels due to prevailing monsoon condition. It is supported by the above normal dew point depression in these months in lower levels as shown in Fig. 1. Dew point depression is significantly higher than normal at middle and upper levels.

3.3.2. *Tephigram*

All the above results are also depicted in the form of Tephigrams in Figs. 2 & 3 for pre-monsoon and monsoon seasons respectively. It further indicates that an isothermal layer/inversion layer in lower levels in March and April



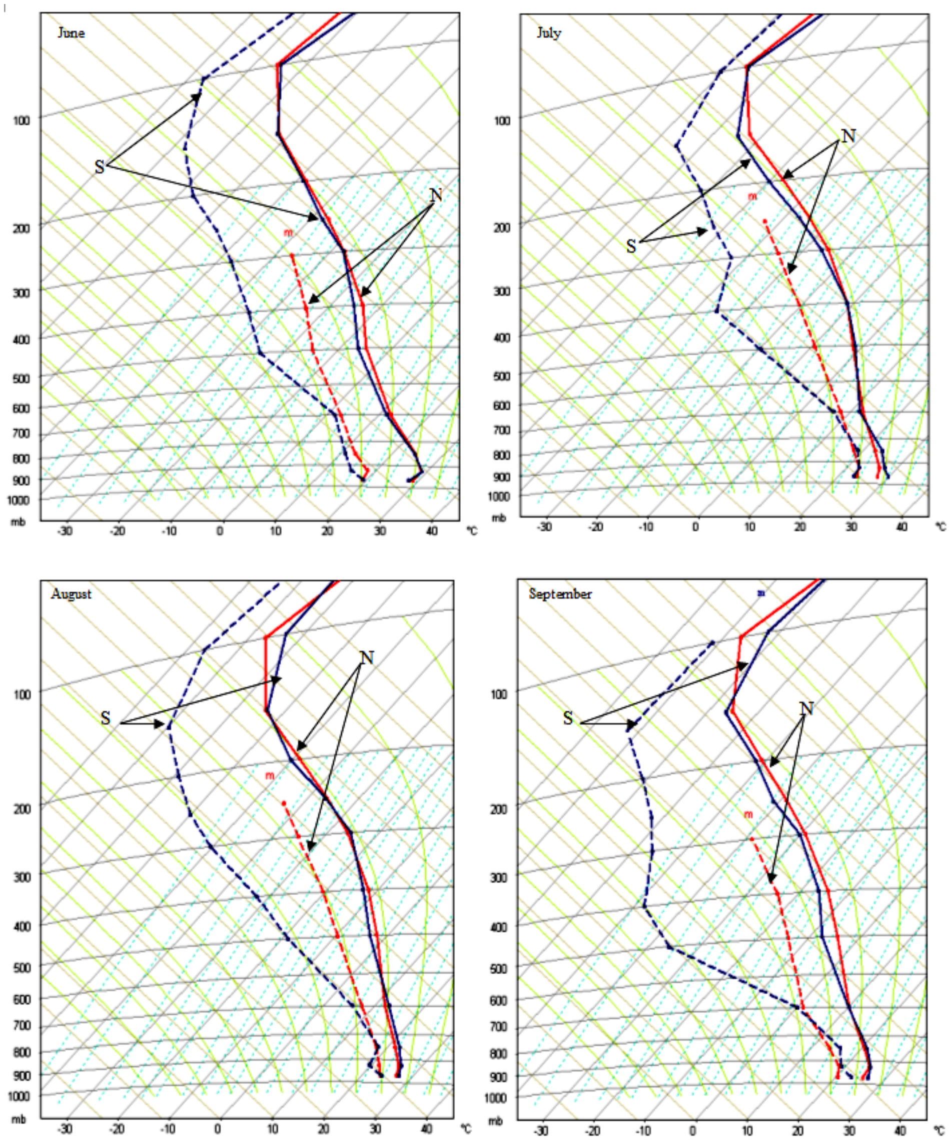
------- Temperature curve for normal & squall days, ……. Dew point curve for normal & squall days, m -Missing Dew point,
S- Environmental & dew point temperature on squall days, N- Normal Environmental & dew point temperature

Fig. 2. Thermodynamic characteristic for the month of March, April & May at 0000 UTC on day of occurrence of squall over IGI airport, New Delhi during 2001-2010

favours squall over Delhi. However no such distinction is observed in the Tephigram of squall days during monsoon months and May. There is clear difference of vertical distribution of dew point in squall days from normal days during all the months. Considering the CAPE and CINE (Table 10), CAPE is > 800J/kg at 0000 UTC of squall days during April to September and is maximum in the month of July. The lower value of CAPE in month of March indicates that the squall in this month can not be predicted based on the CAPE value of 0000 UTC. Accordingly, the kinetic factor is also negative in March. It gradually increases from March to become maximum in July. It is less again in August and higher in September. The Bulk Richardson number (BRN) is directly related with CAPE and inversely related with magnitude of wind shear between middle and lower levels. It gradually increases from March to July and then decreases towards September. The LCL lies around 780-890 hPa with the temperature of 3.5 °C to 21.5 °C from March to September The LFC lies between 560-760 hPa with equilibrium level of 170 hPa to 310 hPa in different months. The height of equilibrium level is maximum in July and minimum in June. Similarly the height of LFC is lowest in July and highest in March. The LFC and LCL are relatively lower in monsoon months.

3.3.3. *Thermodynamic indices*

The mean thermo-dynamical indices along with those associated with squall over IGI airport are shown in Table 11. The SI is the simplest measure of atmospheric stability. If SI is positive, so the parcel going upward is colder than its new environment and so the atmosphere is stable. The chance of convective activity increases when SI value decreases to zero or below as the instability increases. It is observed that Delhi experiences squall in association with significantly lower than normal SI in April to June and August to September. Similarly Delhi experiences squall in association with significantly lower than normal LI in March to June and September. The SI and LI are positive in the month of March in association with the squall unlike other months. Unlike the findings of Seshadri and Jain (1989) for thunderstorm, SI seems to be better predictor than LI for occurrence of squall during summer monsoon months while both have predictive value in pre-monsoon months. The KI is higher than normal in the month of April and May only. The mean total totals index (TTI) is in the range of 45 to 55 during squall days over IGI airport. Srinivasan *et al.,* (1973) has suggested the empirical threshold value of TTI as 48 for the occurrence of thunderstorm and Lal (1989) have suggested that the higher the TTI value, more favourable is the condition for occurrence of thunderstorm. The TTI is significantly higher than normal for all the months except June at 0000 UTC of the day of squall over Delhi. The VTI is significantly higher than normal in the months of March, June and September and CTI is significantly higher than normal in the months of May, August and September. The SWEAT index is the only index which is significantly higher than normal at 0000 UTC of squall days over Delhi for all the months and it can be used as predictor of squall over Delhi.



——— Temperature curve for normal & squall days, ------- dew point curve for normal & squall days
m-Missing Dew point, N- Normal Environmental & dew point temperature
S-Environmental & dew point temperature on squall days,

Fig. 3. Thermodynamic characteristic for the month of June, July, August & September at 0000 UTC on day of occurrence of squall over IGI airport New Delhi during 2001-2010

The CCL ranges between 647 hPa in April to 793 hPa in September while it lies between 650-700 hPa during March to June and between 750-800 hPa in July to September. The height of freezing level gradually increases from March to July and then gradually decreases. The difference in CCL and FL also gradually increases from March to become maximum in July and then decreases towards September. It is more than 120 hPa during May-September on the squall days against the threshold value of 53 hPa for occurrence of thunderstorm during monsoon months as found by Kumar (1972).

4. Conclusion

The following broad conclusions are drawn from the above results and discussion.

(*i*) The frequency of thunder squall has significantly increased in recent years during March to June. The average frequency of squall during 2001-2010 for the month of March to June (16.8) is about 4 times of that during 1951-1980 (4.3).

(*ii*) Pre-monsoon season (April-June) squalls are more severe as the squalls in these months reach severe gale force wind (48 knot or more).

(*iii*) The dominant characteristics of squalls are (a) light wind followed by squall and (b) gusty weather followed by squall. These two types together contribute about 80% of total squalls. Another 10% of squalls are followed by gusty weather. Light wind/gusty weather followed by succession of squall occur only during May and June.

(*iv*) About 90% of total squall occurs from southwest to north direction over Delhi. The squall mainly occurs from northwesterly direction in the months of May & June and from westerly/southwesterly direction during April.

(*v*) There is no one to one relationship of intensity (wind) of squall with the environmental changes like change in temperature, pressure, dew point, RH and rainfall following the squall.

(*vi*) The surface and lower level temperature in the month of March and April and lower level moisture incursion in the month of May play important roles in the occurrence of squall. Higher than normal warming of lower troposphere upto 700 hPa level in March, April and June and at 925 hPa in May accompanied with cold and dry air advection leading to lower than normal dew point in middle and upper levels (500-300 hPa in March, May and June, 400-300 hPa in April) are favourable for occurrence of the squall over Delhi. The lower level inversion in March and April only also helps in the occurrence of squall.

(*vii*) In monsoon months of July-September, cold and dry air advection in middle and upper tropospheric levels (8- 15 °C below normal dew point at 400-300 hPa in July, about 15 °C below normal dew point at 300-200 hPa in August and 17- 24 °C below normal dew point at 500-300 hPa in September) favours occurrence of squall over Delhi. Unlike pre-monsoon months, lower level moisture does not play any role for the occurrence of squall over Delhi during monsoon season.

(*viii*) Higher than 120 hPa difference in CCL and FL (CCL-FL) during May-September favours the occurrence of squall over Delhi.

(*ix*) An isothermal layer/inversion layer in lower levels in March and April favours squall over Delhi. However no such distinction is observed in the Tephigram of squall days during monsoon months and May.

(*x*) The SWEAT index is most suitable for prediction of occurrence of squall over Delhi. Significantly higher than normal SWEAT index in March to September at 0000 UTC can be used as predictor of squall over Delhi. The TTI is the next suitable precursor for all the months except June. The LI and SI can also be used during March-June and September. Threshold values of various thermodynamical parameters and indices presented in this paper may be used as precursors for daily prediction of occurrence of squall over Delhi.

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