An objective method for predicting occurrence of pre-monsoon (March-May) thunderstorm events over Delhi using stability indices

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सार – इस शोध पत्र में वर्ष 1999 – 2004 के मानसून पूर्व आँकड़ों का उपयोग करते हुए दिल्ली (28.35° उ. ⁄77.12° पू.) के लिए इन सूचकांकों के विवेचनात्मक मानों को निर्धारित करने के लिए गर्ज के साथ तूफान की घटना के संबंध में विभिन्न स्थिर सूचकांकों की जाँच करने का प्रयास किया गया है। इस अध्ययन से यह पता चला है कि दिल्ली में गर्ज के साथ तूफान के लिए शॉवाल्टर सूचकांक (एस. आई.), लिफ्टिड सूचकांक (एल. आई.), के सूचकांक (के. आई.), टोटल टोटल्स सूचकांक (टी. टी. आई.), और स्वेट सूचकांक (एस. डब्ल्यू. आई.), के विवेचनात्मक मान क्रमश < 2 °से. < 0 °से., >24 °से., >44.5 °से., और >100 °से. रहे हैं। लिफ्टिड कंडंसेशन स्तर (एल. सी. एल.), मुक्त संवहन का स्तर (एल. एफ. सी.), संतुलित स्तर (ई. एल.) और वर्षण जल (पी. डब्ल्यू.) की अनुवर्ती सामान्य विवेचनात्मक दूरियाँ क्रमश: 923 hPa − 695 hPa 856 − 504 hPa −, 545 hPa −109 hPa और 18 मि. मी. – 54 मि. मी. रही है। सूचकांकों के विवेचनात्मक मानों की जाँच और वर्ष 2005 और 2006 के मानसून पूर्व ऋतुओं के दौरान एल.सी.एल, एल.एफ.सी., ई.एल. और पी. डब्ल्यू के अनुवर्ती सामान्य विवेचनात्मक दूरियों से यह पता चलता है कि गर्ज के साथ तूफानों के अधिकांश दिनों में ये अपनी–अपनी विवेचनात्मक मानों ⁄ दूरियों के साथ सही मेल खाती है।

ABSTRACT. In this paper an attempt has been made to investigate different stability indices in relation to the occurrence of thunderstorms in order to determine the critical values of these indices for Delhi (28.35° N / 77.12° E) using pre monsoon data for the years 1999 - 2004. The study shows that the critical values of Showalter Index (SI), Lifted Index (LI), K Index (KI), Total Totals Index (TTI), and Sweat Index (SWI) are respectively < 2 °C, < 0 °C, > 24 °C, > 44.5 °C and > 100 for the thunderstorm to occur over Delhi. The corresponding common critical ranges of Lifted Condensation Level (LCL), Level of Free Convection (LFC), Equilibrium Level (EL) and Precipitable Water (PW) are respectively 923 hPa – 695 hPa, 856 hPa – 504 hPa, 545 hPa – 109 hPa and 18 mm – 54 mm. Testing of critical values of indices and the corresponding common critical ranges of LCL, LFC, EL and PW during pre-monsoon seasons of the years 2005 and 2006 shows that they are matching well with the respective critical values/ranges in most of the thunderstorm days.

Key words – Showalter Index, Lifted Index, Total Totals Index, K- Index, Sweat Index, Lifted condensation level, Level of free convection, Equilibrium level, Precipitable water (mm).

1. Introduction

Thunderstorm is an electro meteor and is defined as "one or more sudden electrical discharges, manifested by a flash of light (lightening) and a sharp or rumbling sound (thunder)". Thunderstorm is an important meso-scale system. Thunderstorms during the pre-monsoon season (March – May) are severe in nature. It is a major cause of natural disasters and a major hazard to aviation.

1.1. Conditions favorable for occurrence of thunderstorms are:

(*i*) Conditional and/or convective instability in the atmosphere.

(*ii*) Adequate supply of moisture particularly in the lower tropospheric levels.

(*iii*) A mechanism to release the instability present in the atmosphere. The air parcel have to be lifted to the LFC to release the instability present in the atmosphere. This may be dynamical (provided by synoptic systems), orographical or provided by thunderstorm down draft itself.

1.2. Delhi (28.35° N / 77.12° E) is an important metropolis of India. It has an international airport (Palam airport) and considerable amount of industrial/ commercial activity goes on in and around Delhi. The gusts/squall associated with thunderstorms pose a series

hazard to aviation as well as to other commercial activities such as transportation, agriculture, constructions, communication and power transmission etc. The forecast of thunderstorm activity would help in taking precautionary measures for protection of life and property and to avoid aircraft accidents. Hence, a detailed study of different stability indices in relation to the occurrence of thunderstorms in order to determine the critical values of these indices favorable for the formation of thunderstorms over Delhi has been attempted.

1.3. Stability index is a measure of the potential of the atmosphere over a specified region (Karmarkar and Alam, 2006). Since such an indicator can be calculated hours prior to the actual development of any convective activity, it acts as timely identifier of areas within an air mass which are capable of supporting convective activity. Once these potential areas are identified, the forecaster can then take a closer and more precise examination of these areas, incorporating all available parameters, tools and experience into making final forecast (Thomson and Lin, 1985).

1.4. Prediction of thunderstorms using stability indices have been extensively attempted by many researchers. Stone (1985) discussed the performance of stability indices over Eastern United States and their relation to thunderstorm activity. Schultz (1989) compared several stability indices to study convective weather events over north east Colorado using data for summer of 1985. Fuelberg and Bigger (1994) made a comprehensive study on pre convective environment of summer thunderstorm over Florida Panhandle.

1.5. Showalter (1953) and George (1960) have explained methods for calculating numeric values of Showalter index (SI) and K Index (KI) respectively to determine the stability of the atmospheric state between 850 hPa and 500 hPa for purpose of forecasting thunderstorm. Galway (1956) studied the lifted index as a predictor of latent instability.

1.6. Over the Indian region several studies on thunderstorm forecasting have been carried out in the past. The frequency of thunderstorm in different months over India has been discussed by Rao and Raman (1961). Kotteswaram and Srinivasan (1958) discussed the synoptic conditions favorable for the development of thunderstorm and inferred that the simultaneous presence of low level convergence and upper air divergence is the important factor for thunderstorm development. Synoptic features associated with pre-monsoon thunderstorms over Assam have been studied by Sen and Basu (1961). Lal (1990) has examined the role of Showalter Index for forecasting of thunderstorm activity over Lucknow. Lal

(1989) studied the usefulness of Total Totals Index to forecast thunderstorm activity. Kar and Bandyopadhyay (1998) have analyzed the occurrence of the thunderstorm over a few stations in West Bengal during the pre-monsoon season. Very recently, Tyagi (2007) made a climatological study of thunderstorm over Indian region. Mukhopadhyay *et al*. (2003) suggested an objective method using stability indices for occurrence of the thunderstorm over north east India. Khole and Biswas (2007) studied role of total total stability index in forecasting of thunderstorms over Kolkata. Basu and Mondal (2002) attempted to find out suitable parameters for forecasting thundersqualls that hit Kolkata in pre-monsoon seasons.

1.7. Recently, installation of Doppler Weather Radar (DWR) at Chennai (2002), Kolkata (2003), Machilipatanam (2004), Vishaphapattnam (2006), Delhi (2010) and Hyderabad (2010) has highlighted the better prospect of thunderstorm prediction in the nowcast to very short-range time scale over Indian region (Sinha and Pradhan, 2006; Sen Roy *et al*., 2010; Medina *et al*., 2010). Particularly, with the assimilation of DWR observations along with other conventional and non-conventional observations, Numerical Weather Prediction (NWP) models have acquired a greater skill and are playing increasingly important role in mesoscale weather prediction (Srivastava *et al*., 2009 and 2010; Routray *et al*., 2010).

1.8. In the present paper the stability indices have been investigated for large number of thunderstorms in order to find out the critical values of different indices favorable for the occurrence of thunderstorms over Delhi. Stability indices those have been studied are: Showalter stability index (SI), Lifted Index (LI), K Index (KI), Total Totals Index (TTI) and Sweat Index (SWI). The low level data at the lowest 500 meter of atmosphere have been used to calculate above indices.

In the light of newly installed DWR at Delhi and at other parts of the country, this study is expected to form a useful reference for all future works using DWR.

2. Data source

Radiosonde data of 0000 UTC of pre-monsoon season (March, April & May) for 6 years (1999-2004) of Delhi (Safdarjung VIDD) have been used in this study. The data for the years 2005 and 2006 are used to verify the forecast skill of the indices for Delhi. The radiosonde data are scrutinized carefully and data from such ascent are used where the meteorological parameters, *viz*., wind, dry bulb temperature, dew point temperature at standard pressure levels are available. In some cases the RS ascent

TABLE 1

Frequency distribution of synoptic conditions associated with the occurrence of thunderstorm event over Delhi for the period 1999-2004

Type of synoptic feature	Number of days associated with occurrence of thunderstorm *	Percentage (Total number of events = 51)
i	42	82
ii	5	10
iii	6	12
iv	45	88

* in several occasions when synoptic conditions (i) and (iv) co-existed

TABLE 2

List of stability indices examined in this study

Indices	Code	Reference(s)	Expression	Explanation	Comments
K Index	KI	George (1960)	(T850-T500)+ TD850-(T700-TD700)	T850 = Temp. in Cel. at 850 hPa T500 = Temp. in Cel. at 500 hPa TD850 = Dew point Temp. in Cel. at 850 hPa T700 = Temp.in Cel. at 700 hPa TD700 = Dew point Temp. in Cel. at 700 hPa	Combination of 850 hPa – 500 hPa lapse rate, 850 hPa moisture, levels of saturation at 700 hPa
Lifted Index	LI	Means (1952)	T500-Tparcel	T500 = Temp. in Cel. of the environment at 500 hPa Tparcel = 500 hPa temp. in cel. of a lifted parcel with the average pressure, temperature and dew point of the layer 500 meter above the surface	Thermal stability of the atmosphere at 500 hPa in terms of environmental temperature and parcel temperature
Total Totals Index	TTI	Miller (1967)	(T850-T500)+ TD850-T500	T850= Temp. in Cel. at 850 hPa TD850 = Dew point Temp. in Cel. at 850 hPa T500 = Temp. in Cel. at 500 hPa	Lapse rate between 850 hPa and 500 hPa and measure of saturation at 850 hPa
Sweat Index	SWI	Bidner (1970)	12*TD850 + 20*TERM 2+ 2*SKT850 + SKT500 + SHEAR	TD850 = Dew point Temp. in Cel. at 850 hPa TERM 2 = MAX(TOTL-49,0) TOTL = Total Totals Index SKT850 = 850 hPa wind speed in Knots. SKT 500 = 500 hPa wind speed in Knots. SHEAR = 125*[SIN(DIR500 – DIR 850) + .2] DIR500 = 500 hPa wind direction. DIR850 = 850 hPa wind direction.	Combination of Thermal and Thermo mechanical stability
Showalter Index	SI	Showalter (1953)	T500-Tparcel	T500 = Temp. in Cel. of the environment at 500 hPa Tparcel = Temp. in cel. at 500 hPa of a parcel lifted from 850 hPa.	The 850 hPa parcel (mountain area stations use a higher level) is lifted dry adiabatically to saturation and then pseudo adiabatically to 500 hPa. The lifted 500 hPa temperature is then subtracted algebraically from the observed 500 hPa temperatures

is incomplete or there are cases when the ascent has reached upto the lower troposphere (700hpa or so) only. These ascents are not considered. The current weather registers of Delhi {(Safdarjung VIDD), Palam (VIDP)} for the period (1999-2004) were consulted. Thunderstorm days from records were noted down with full details.

2.1. *Synoptic conditions*

For the evaluation of synoptic scale features associated with the occurrence of thunderstorm over Delhi following synoptic conditions are identified.

(*i*)   Western Disturbances in the form of low pressure area and/or trough/cyclonic circulation embedded in the westerlies lies over any one of the following places and adjoining areas with a tendency of eastward movement:

North Pakistan, Jammu & Kashmir, Himachal Pradesh, Uttarakhand, Punjab, north Haryana, west Uttar Pradesh.

The trough/cyclonic circulation generally extends upto 4.5 km above sea level and sometimes upto 5.8. km above sea level. The trough in the westerlies often get extended to the south upto the Arabian sea causing the incursion of moist south westerlies/southerlies from the Arabian sea.

(*ii*)   Trough in westerlies in mid and upper troposphere with its axis generally at 500/300 hPa runs along any one of longitudes between 62° E and 72° E to the north of latitude 20° N with a tendency of eastward movement.

(*iii*) Low pressure area with associated cyclonic circulation generally extends upto 3.1 km above sea level and lies over any one of the following places and adjoining areas :

Central Afghanistan, Central Pakistan, Rajasthan, Haryana, Punjab, west Uttar Pradesh.

(*iv*)   Cyclonic circulation generally extends upto 4.5 km above sea level and lies over any one of the following places and adjoining areas :

Rajasthan, Punjab, Haryana, Himachal Pradesh, Uttarkhand, west Uttar Pradesh, north Madhya Pradesh and Pakistan.

Table 1 presents frequency distribution of synoptic systems associated with the occurrence of thunderstorm over Delhi. During the study period (1999-2004) associated synoptic systems have been identified on 51

occasions of thunderstorm events over Delhi. There are several occasions when synoptic conditions (*i*) and (*iv*) co-existed. The Table shows that the synoptic conditions (*i*) Western Disturbances in the form of low pressure area and/or trough/cyclonic circulation embedded in the westerlies and (*iv*) Cyclonic circulation generally extends up to 4.5 km above sea level over Punjab, Haryana and adjoining states are the two dominant synoptic features which cause thunderstorm over Delhi.

3.   Methodology of stability analysis

Stability Indices LCL, LFC, EL and PW have been investigated for large number of thunderstorm days in order to determine the critical values of these indices and the corresponding common critical ranges which are favorable for occurrence of thunderstorms over Delhi. For these stability indices the low level data at lowest 500 meter has been used. The indices were calculated by using the data at 0000 UTC of Safdarjung (VIDD) for this study. The indices with their physical meaning are explained in Table 2.

4.   Results and discussion

In order to study the degree of the instability of the atmosphere for the occurrence of thunderstorm over Delhi, five different stability indices of the atmosphere prior to occurrence of the thunderstorm (*i.e.*, at 0000 UTC) have been computed. The different stability indices namely, SI, LI, KI, TTI and SWI with their frequencies are tabulated in the Tables 3-7 respectively. Attempts have been made to find out the critical values of the indices and the corresponding common critical ranges of LCL, LFC, EL and PW for the occurrence of thunderstorm over Delhi. The results are described in the subsequent sub-sections.

4.1.   *Stability Indices and their frequencies over Delhi in relation to the occurrence of the thunderstorm over Delhi*

4.1.1.   *Showalter Stability Index (SI) and its frequency*

From the Table 3, it is clear that for the most of the events (thunderstorms) the SI was between 2 to -7 at 0000 UTC. There were 5 out of 58 (*i.e.*, 8.62%) thunderstorms has been occurred when SI above 2 degree Celsius at 0000 UTC which indicates that the atmosphere was stable. For these events the instabilities might have been occurred due to insolation as well as the moisture influx extended to greater height. The Table also shows that 53 out of 58 (91.38%) of the thunderstorms occurred when SI < 2 °C.

TABLE 3

Showalter stability Index (SI) at 0000 UTC and its frequency at Delhi

Range of SI (°C) ¥	Frequency (f)	% of the total	Range of LCL (hPa)	Range of LFC (hPa)	Range of EL (hPa)	Range of PW (mm)
>5	2	3.45	891 - 789	749 - 656	462 - 407	30 - 38
5 - 2	3	5.17	923 - 747	850 - 593	352 - 235	23 - 37
(2) - (−1)	12	20.69	913 - 779	852 - 530	512 - 147	18 - 54
(−1) - (−4)	22	37.93	922 - 695	837 - 559	545 - 117	19 - 47
(−4) - (−7)	12	20.69	864 - 701	757 - 504	481 - 109	22 - 53
(−7) - (−10)	6	10.35	876 - 732	787 - 633	281 - 151	30 - 47
(−10) - (−13)	1	1.72	772.37	728.67	178.75	42.42
	58 #	100 #	922 - 695 *	852 - 504 *	545 - 109 *	18 - 54 *

Total, * common range

TABLE 4

Lifted Index (LI) at 0000 UTC and its frequency at Delhi

Range of LI (°C) ¥	Frequency (f)	% of the total	Range of LCL (hPa)	Range of LFC (hPa)	Range of EL (hPa)	Range of PW (mm)
>4	1	1.75	789.18	656.65	407.06	30.15
4 – 0	7	12.28	922 - 792	852 - 559	545 - 213	19 - 38
(0) - (−4)	23	40.35	910 - 709	850 - 504	481 - 147	19 - 54
(-4) - (−8)	15	26.32	867 - 695	768 - 537	310 - 188	18 - 48
(-8) - (−12)	10	17.55	887 - 772	854 - 683	251 - 109	29 - 47
<−12	1	1.75	773.36	727.66	151.48	41.24
	57 #	100 #	910 – 695*	854 – 504*	481 – 109*	18 – 54*

Total, * common range

TABLE 5

K Index (KI) at 0000 UTC and its frequency at Delhi

Range of KI (°C) ¥	Frequency (f)	% of the total	Range of LCL (hPa)	Range of LFC (hPa)	Range of EL (hPa)	Range of PW (mm)
<20	2	3.63	852 - 779	624 - 583	454 - 228	18 - 30
20 - 24	5	9.10	859 - 747	669 - 504	481 - 193	19 - 35
24 - 28	8	14.55	872 - 695	852 - 530	508 - 214	19 - 41
28 - 32	9	16.36	923 - 779	856 - 537	545 - 109	23 - 46
32 - 36	9	16.36	913 - 709	728 - 595	512 - 117	26 - 42
36 - 40	8	14.55	922 - 701	837 - 559	338 - 209	28 - 47
40 - 44	10	18.18	887 - 759	756 - 635	348 - 147	30 - 54
44 - 48	4	7.27	876 - 772	787 - 645	251 - 178	39 - 53
	55#	100 #	923 - 695*	856 - 530*	545 - 109*	19 - 54*

Total, * common range, ¥ Upper and Lower limits of range excluded

TABLE 6

Total Total Index (TTI) at 0000 UTC and its frequency at Delhi

Range of TTI (°C) ¥	Frequency (f)	% of the total	Range of LCL (hPa)	Range of LFC (hPa)	Range of EL (hPa)	Range of PW (mm)
20.5 – 24.5	1	1.75	852.99	764.67	324.49	24.41
24.5 – 28.5	1	1.75	695.2	571.8	309.66	21.79
32.5 – 36.5	1	1.75	890.69	748.89	461.44	37.74
36.5 – 40.5	1	1.75	922.59	849.77	351.24	39.19
40.5 – 44.5	1	1.75	747.42	592.92	333.36	23.35
44.5 – 48.5	5	8.77	886 – 826	756 – 530	454 – 147	29 – 54
48.5 – 52.5	16	28.08	913 – 757	852 – 535	512 – 193	18 – 47
52.5 – 56.5	16	28.08	922 – 709	837 – 559	545 – 109	19 – 53
56.5 – 60.5	8	14.04	876 – 701	787 – 504	508 – 155	19 – 47
60.5 – 64.5	6	10.53	887 – 762	734 – 633	268 – 151	28 – 46
64.5 – 68.5	1	1.75	772.37	728.67	178.75	42.42
	57 #	100 #	922 – 701*	852 - 504*	545 - 109*	18 – 54*

Total, * common range

TABLE 7

Sweat Index (SWI) at 0000 UTC and its frequency at Delhi

Range of SWI ¥	Frequency (f)	% of the total	Range of LCL (hPa)	Range of LFC (hPa)	Range of EL (hPa)	Range of PW (mm)
<100	3	5.17	856 – 747	647 – 593	334 - 228	18 – 31
100 – 200	12	20.69	922 – 771	856 – 535	512 – 117	20 – 40
200 – 300	20	34.48	922 – 695	837 – 530	545 – 147	19 – 54
300 – 400	14	24.14	859 – 701	710 – 504	481 – 109	19 – 53
400 – 500	6	10.35	887 – 765	787 – 633	281 – 151	34 – 47
500 – 600	3	5.17	836 – 772	729 – 683	218 – 178	30 – 43
	58 #	100 #	922 - 695*	856 - 504*	545 - 109*	19 – 54*

Total, * common range, ¥ Upper and Lower limits of range excluded

As per the study of Showalter (1953), negative number indicates instability (rising air warmer than its surrounding) and a positive number indicates stability. But the percentage of the occurrence is suggesting us to consider the critical value of SI is < 2 °C at 0000 UTC over Delhi. The Table 3 also shows that the corresponding critical ranges of LCL, LFC, EL and PW at 0000 UTC over Delhi as   922 hPa – 695 hPa, 852 hPa -504 hPa, 545 hPa -109 hPa and 18 mm – 54 mm respectively for the thunderstorm to occur over Delhi.

TABLE 8

Critical values of indices

Name of the index	Critical value	Corresponding critical range of			
		LCL (hPa)	LFC (hPa)	EL (hPa)	PW (mm)
SI	< 2 °C	922 - 695	852 – 504	545 – 109	18 – 54
LI	< 0 °C	910 – 695	854 – 504	481 – 109	18 – 54
KI	> 24 °C	923 – 695	856 – 530	545 – 109	19 – 54
TTI	> 44.5 °C	922 – 701	852 – 504	545 – 109	18 – 54
SWI	> 100	922 – 695	856 – 504	545 – 109	19 - 54
Common critical ranges of LCL. LFC, EL & PW for all critical values of indices		923 – 695	856 – 504	545 – 109	18 - 54

TABLE 9

Testing of the forecast skill of the critical values of indices for Delhi during pre-monsoon season (March, April & May) of the years 2005 & 2006

Thunderstorm days	SI (°C)	LI (°C)	KI (°C)	TTI (°C)	SWI	LCL (hPa)	LFC (hPa)	EL (hPa)	PW (mm)
4 Mar 2005	-6.34^	-1.66^	37.30^	61.40^	403.20^	893.97+	623.87+	250.22+	30.8+
9 Mar 2005	1.90 ^	-1.24^	26.90^	47.40^	248.15^	884.1+	722.56+	243.97+	27.93+
23 Apr 2005	-5.15^	-7.27^	39.30^	59.20^	353.34^	749.88+	638.31+	194.14+	34.44+
24 Apr 2005	-9.05^	-7.83^	25.96^	65.66^	510.93^	835.23+	656.06+	212.23+	26.34+
1 May 2005	0.31^	-1.49^	30.70^	49.00^	121.40^	872.6+	665.16+	394.71+	28.77+
3 May 2005	-8.25^	-12.96^	42.30^	66.40^	465.80^	874.3+	780.84+	-	27.26+
14 Mar 2006	2.73$	-0.62^	29.90^	47.60^	71.60$	908.82+	730.58+	296.46+	28.23+
25 Mar 2006	1.75^	-1.15^	9.10$	48.00^	122.20^	837.06+	531.11+	315.82+	18.73+
19 Apr 2006	0.02^	-2.15^	25.30^	51.80^	154.80^	833.61+	675.22+	250.01+	47.9+
10 May 2006	-6.96^	-8.31^	40.90^	58.40^	406.39^	860.85+	759.35+	171.65+	40.32+
14 May 2006	-4.16^	-4.16^	35.70^	54.20^	296.20^	845.12+	643.61+	226.12+	39.59+
16 May 2006	-2.40^	-5.62^	39.40^	52.00^	236.80^	847.14+	687.23+	211.56+	43.99+
19 May 2006	-3.56^	-7.35^	42.00^	53.60^	244.82^	827.1+	730.24+	309.94+	40.41+
20 May 2006	-2.48^	-0.21^	33.90^	51.20^	242.61^	852.92+	635.14+	378.31+	40.95+
23 May 2006	1.90^	1.66$	36.00^	43.40$	180.42^	865.49+	673.23+	566.8@	46.06+
31 May 2006	-2.42^	-4.63^	25.50^	49.00^	224.01^	851.28+	684.54+	116.03+	41.83+

^ - matched well with critical value, + - matched well with critical range
$ - not matched well with critical value, @ - not matched well with critical range

4.1.2. *Lifted Index (LI) and its frequency*

The Table 4 shows that 8 out of 57 (14.03%) thunderstorms occurred when LI was above 0 °C at 0000 UTC, which indicates that the atmosphere was stable. This can be attributed to the fact that the atmosphere may remain stable in the morning, but as the day progresses this stability may be thought of being destroyed and instability develops because of the incoming solar radiation as well as moisture influx extending to greater height in the afternoon. The Table also shows that 49 out of 57 (85.97%) thunderstorms occurred when LI < 0 °C. The percentage of the occurrence suggesting us to consider the critical value of LI is < 0 °C at 0000 UTC over Delhi. The Table 4 also shows that the corresponding critical ranges of LCL, LFC, El and PW at 0000 UTC as 910 hPa - 695 hPa, 854 hPa - 504 hPa, 481 hPa - 109 hPa and 18 mm - 54 mm respectively for the thunderstorms to occur over Delhi.

4.1.3. *K Index (KI) and its frequency*

From the Table 5, it is observed that most of the values of KI range between 24 and 44 °C when 80% of the thunderstorms occurred over Delhi. It can also be seen from the Table that maximum thunderstorms occurred in the range of KI = 40 – 44 °C which is about 18.18% of the total number of thunderstorms. The table shows that 87.27% of the thunderstorms occurred when KI > 24 °C. The critical value of KI may be taken as KI > 24 °C. The corresponding critical ranges of LCL, LFC, EL and PW at 0000 UTC are found as 923 hPa – 695 hPa, 856 hPa – 530 hPa, 545 hPa – 109 hPa and 19 mm – 54 mm respectively for the thunderstorm to occur over Delhi.

4.1.4. *Total Totals Index (TTI) and its frequency*

The Table 6 shows that maximum thunderstorms occurred in the range of TTI = 48.5 – 56.5 °C, which is about 56.16% of total number of the thunderstorms. 8.75% of the total no. of thunderstorm occurs when TTI was < 44.5 °C. About 91.25% of the thunderstorms occurred when the value of TTI is > 44.5 °C. The critical value of TTI may be taken as TTI > 44.5 °C. The corresponding critical ranges of LCL, LFC, EL and PW at 0000 UTC are found to be 922 hPa – 701 hPa, 852 hPa – 504 hPa, 545 hPa – 109 hPa and 18 mm – 54 mm respectively for thunderstorm to occur over Delhi.

4.1.5. *Sweat Index (SWI) and its frequency*

It is seen from the Table 7 that 3 out of 58 thunderstorms (5.17%) occurred when SWI was < 100. The table also indicates that 43 out of 58 (74.14%) thunderstorms occurred when SWI > 200. The table also

shows that 55 out of 58 (94.83%) thunderstorms occurred when SWI was > 100. Therefore, the critical value of SWI may be taken as SWI > 100 for thunderstorms to occur over Delhi. The corresponding critical ranges of LCL, LFC, EL and PW at 0000 UTC over Delhi are found as 922 hPa – 695 hPa, 856 hPa – 504 hPa, 545 hPa – 109 hPa and 19 mm – 54 mm respectively for thunderstorms to occur over Delhi.

The critical values of indices and corresponding critical ranges of LCL, LFC, EL and PW for the occurrence of thunderstorms over Delhi are summarized in the Table 8. It is clear from the Table that for all critical values of indices the corresponding common critical ranges of LCL, LFC, EL and PW may be taken as 923 hPa – 695 hPa, 856 hPa – 504 hPa, 545 hPa – 109 hPa and 18 mm – 54 mm respectively.

5. **Testing of critical values of indices and corresponding common critical ranges of LCL, LFC, EL and PW**

Critical values of indices and corresponding common critical ranges of LCL, LFC, EL and PW so determined are tested during pre-monsoon season (March, April and May) of the years 2005 and 2006 for each thunderstorm using observed values of indices and LCL, LFC, EL and PW. The results are presented in Table 9. Considering the size of the Table, the non-occurrence cases are not included in the Table. It is seen that during 15 out of 16 thunderstorm days the actual values of indices matched well with critical values and during 16 out of 16 thunderstorm days the actual values of LCL, LFC and PW matched well with their critical ranges. During 15 out of 16 thunderstorm days the actual value of EL matched well with its critical range.

6. **Conclusions**

On the basis of this study the following conclusion can be drawn:

(*i*) The passage of western disturbance is the most important favorable synoptic condition for occurrence of thunderstorm over Delhi.

(*ii*) The study of the frequency of different stability indices reveals that the atmosphere may be stable in the morning (about 10 -12 hours before the occurrence) on the date of occurrence of a few thunderstorms but this stability may be thought of being destroyed because of the increasing day length, more incoming solar radiations and influx of moisture with its extension to a greater height in the atmosphere.

(*iii*) The critical values of Showalter stability Index (SI), lifted Index (LI), K Index (KI), Total Total Index (TTI) and Sweat Index (SWI) at 0000 UTC over Delhi may be taken as < 2 °C, < 0 °C, > 24 °C, > 44.5 °C and > 100 °C respectively for the thunderstorms to occur over Delhi. For all critical values of stability indices the corresponding common critical ranges of LCL, LFC, EL and PW are found as 923 hPa – 695 hPa, 856 hPa – 504 hPa, 545 hPa – 109 hPa and 18 mm – 54 mm respectively for the thunderstorm to occur over Delhi.

(*iv*) Critical values of indices and corresponding common ranges of LCL, LFC, EL and PW in combination with synoptic features described in the section 2.1 may be considered as favorable conditions for occurrence of thunderstorms over Delhi during pre-monsoon season.

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