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Objective forecast of thundery and non-thundery days using conventional indices over Bangalore during pre-monsoon season

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सार – गर्ज वाले तूफानों का पूर्वानुमान देना पूर्वानुमानकर्त्ता के लिए एक चुनौतीपूर्ण कार्य है क्योंकि इनके स्थानिक पैमाने छोटे और अवधि अल्प होती है। इस शोध पत्र का उद्देश्य बंगलुरू के ऊपर गर्जवाले और बिना गर्ज वाले दिनों के पूर्वानुमानों के संबंध में विशिष्ट थ्रेशोल्ड्स के साथ स्थायित्व घातांकों की दक्षता का मूल्यांकन करना है। वर्ष 1991 - 2003 के दौरान बंगलुरू के रेडियों सौंदे / रेडियो पवन डेटा से कुल नौ घातांक प्राप्त किए गए हैं जिसे प्रागुक्त (प्रीडिक्टर्स) माना गया है और उनके सांख्यिकीय प्राचलों की गणना की गई है। महत्वपूर्ण प्रीडिक्टर्स का पता लगाने के लिए जेड टेस्ट (Z_{xy}) विधि को लागू किया गया है और महत्वपूर्ण प्रीडिक्टर्स में से थ्रेशोल्ड मान का पता लगाने के लिए स्किल स्कोर को बढ़ाते हुए चयनित प्रीडिक्टर्स के थ्रेशोल्ड मान प्राप्त किए गए हैं। प्राप्त परिणाम दर्शाते हैं कि महत्वपूर्ण घातांक K (>33° से.) और SHIm (<3° से.) 0000 यू टी सी के लिए अति दक्ष प्रीडिक्टर्स हैं जबकि SLI (<−4° से.) एवं DCI (>44° से.) 1200 यू टी सी के लिए अति दक्ष प्रीडिक्टर्स हैं। इन परिणामों को बंगलुरू में वर्ष 2004 - 2006 के मॉनसूनपूर्व अवधि में सत्यापित किया गया है।

ABSTRACT. Prediction of thunderstorms is a challenging task for a forecaster as their spatial scale is small and lifespan is short. This study aims at evaluating the skill of stability indices with specific thresholds in relation to forecasting thundery and non-thundery days over Bangalore. A total of nine indices derived from radiosonde/radiowind data of Bangalore during 1991-2003 are treated as predictors and their statistical parameters were computed. The Z test (Z_{xy}) was applied to find out significant predictors and the skill score method was used for finding the threshold value amongst the significant predictors. The threshold value of selected predictors is obtained by maximising normalised skill score. The results show that significant indices K (> 33 °C) and SHI_m (< 3 °C) are most efficient predictors for 0000 UTC while SLI (< - 4 °C) and DCI (> 44 °C) are most efficient predictors for 1200UTC. These results were verified for pre-monsoon period of 2004-2006 over Bangalore.

Key words – Thunderstorm, Stability indices, Forecasting.

1. Introduction

Thunderstorms are localised events that are a threat to aviation, agricultural operations, day to day activities as they are associated with severe weather like squall, dust-storms, heavy rain and flash floods, turbulence, hail and lightning. These form due to the non-linear interaction between the synoptic and small scale flows. Dry thunderstorms can lead to the outbreak of wild fires due to generation of heat by cloud to ground lightning. Thunderstorm forecasts pose a great challenge for a forecaster owing to their small spatial (1-25 km) and temporal scale (1-4 hrs). The average lead time for issuing warnings is generally small and the forecasters issue these warnings only when there is a very strong evidence of their occurrence. These forecasts are of utmost importance for preparedness and mitigation of the damage. All forecasting centres use a variety of tools like synoptic charts, satellite pictures and weather radar, analysis of direct numerical model output (Rajeevan *et al*., 2010) or post processed output (Schmeits *et al*., 2005), analysis of data from lightning detectors or hail reports, data from dense network of observatories and evaluation of several stability indices derived from radiosonde/radiowind (RS/RW) data of a station while issuing a thunderstorm forecast. The numerical models have to be run at a very high horizontal resolution to be able to capture the thunderstorm initiation and intensification and associated features (Litta *et al*., 2012), the coarse resolution models sometimes fail to predict them (Meißner *et al*., 2007). The computing resource can be a handicap in running the models at such a high resolution operationally. All of the above mentioned tools have to be used with caution by a forecaster operationally. One of the simplest and very effective techniques used for short range forecast is the use of suitable stability index (Huntreiser *et al*., 1997; Kunz 2007; Yamane *et al*., 2010; Tajbakhsh *et al*., 2012). The analysis by Chaudhari and Middey (2012) reveals that a composite stability index, called thunderstorm prediction index (TPI), which is formulated by combining lifted index (LI), convective inhibition energy (CIN) and convective available potential energy (CAPE) is most effective as compared to individual indices in the predicting thunderstorms over Kolkata during the pre-monsoon season (March-May). Haklander and Van Delden (2003) have shown that lowest 100 hPa LI scores best for Netherlands while Jefferson index is found to be most appropriate index for Greek peninsula (Marinaki *et al*., 2006). All the above studies have brought out that that each region is characterised by a unique set of indices with definite thresholds that have to be used for prediction of a thundery day (TD) or a non-thundery day (NTD).

The occurrence of thunderstorms with varying numbers and intensity is a characteristic feature over Indian region during the pre monsoon season. The most violent form of thunder activity occurs primarily over north-eastern India and adjoining Bangladesh region during this period. As a result, a number of studies are available that address various aspects of thunderstorm prediction in this part of the region (Karmakar and Alam 2011; Tyagi *et al*., 2011; Mukhopadhyay *et al*., 2003). Very limited amount of work is available regarding thunderstorm prediction using stability indices over the southern peninsula, though it is the second highest zone in India to experience thunderstorms. The seasonal frequency of thundery days over south-western part of India ranges between 40 and 20 (Tyagi, 2007). The area under investigation is Bangalore which is an important city in peninsular India. It is located in the south-eastern part of Deccan plateau and is also called as the Silicon Valley of India. It has 3 major airports out of which one is an international airport. Considerable amount of industries have their base in and around this city. This city experiences 41% of thunder activity during pre-monsoon season. Also, the percentage contribution of rainfall due to thunderstorms is maximum during April (67%) followed by September (57%) and May (55%) showing that these months have higher potential to produce rainfall (Agnihotri *et al*., 2013). Hence, the present study aims at evaluating the skill of various stability indices with prescribed thresholds in relation to forecasting a TD and a NTD during pre-monsoon season over Bangalore. The stability indices that are used as predictors in this study are K (George, 1960), total total index (TTI) (Miller 1972), surface lifted index (SLI) (Means, 1952), humidity index (HI) (Litynska *et al*., 1976), deep convective index (DCI) (Barlow, 1993), Showalter (SHI) (1953) and modified Showalter index (SHI_m), (Steinnacker, 1977), Boyden (BI) (1963) and severe weather threat (SWEAT) (Miller, 1972) respectively. The wind cum weather finding radar is not functional at this station for a number of years now and the observational network required for thunderstorm prediction is also not very dense. Hence this study will be of a great help to forecasters in their day to day operations and will enable them to issue a warning with more accuracy and sufficient lead time.

2. Data

The daily surface data at 3 hourly interval from 1991-2006 of two stations, *i.e.*, Bangalore City (12.98° N / 77.58° E, 921 m amsl) and Bangalore airport (12.51° N / 77.31° E, 888 m amsl) which are about 15 km apart have been examined for categorising a day into a TD or a NTD. A day is considered as a TD if any of these two stations report thunder. The surface data of both of these stations has been collected from the Meteorological Centre, Bangalore. Further, if thunder is reported between 0530-1729 hrs (IST), then 0000 UTC RS/RW data is considered for calculation of the above mentioned indices. If thunder is reported between 1730 hrs (IST) of day 1 and 0529 hrs (IST) of day 2, then 1200 UTC sounding data of day 1 is considered for the computation of the stability indices. On examining the MMR's, it was found that on a number of occasions, there was more than one spell of thunder in a day and in those cases both 0000 UTC and 1200 UTC RS/RW data is considered for calculation of stability indices. The daily upper air data of Bangalore City during 1991-2003 and 2004-2006 has been collected from the National Data Centre, Pune and Met. Centre Bangalore. The data for 1991-2003 is used for identification of suitable index and its threshold whereas data during 2004-2006 is used for verification. It is assumed that this data is representative of the pre convective environment of 50 km around the city.

2.1. *General synoptic features during pre-monsoon season over the southern peninsula*

During March-May, the air over peninsular India is warm as the region experiences intense insolation resulting in the development of a shallow heat low over land area. This shallow heat low during March is over interior peninsula and lies over Madhya Pradesh and adjoining south Uttar Pradesh by end of May on account of increased insolation. This is seen very clearly in the synoptic charts of 1200 UTC. The two anticyclones, one over the Arabian Sea and the other over the Bay of Bengal are the source of moisture into southern peninsula. In the lower levels a wind discontinuity or north-south trough extends from the central India upto southern peninsula

TABLE 1

Description of various indices

S. No	Name of Index	Formula	Description	Remarks
1.	K in °C	$(T + T_d)_{850}$ - T_{500} - (T_{700} - T_{d700})	T and T_d are dry bulb and dew point temperature at 850, 700 and 500 hPa	Combination of 850 - 500 hPa lapse rate, 850 hPa moisture, saturation at 700 hPa
2.	Total Total Index (TTI) in °C	2 (T_{850} - T_{500}) - (T_{850} - T_{d850})	Notations same as above	Combination of 850 - 500 hPa lapse rate, saturation at 850 hPa
3.	Surface Lifted Index (SLI) in °C	Te_{500} - $Tp_{sfc\delta 500}$	T is environmental temperature (ºC) at 500 hPa. $T_{sfc\delta 500}$ is the temperature of the parcel at 500 hPa after it is lifted dry adiabatically from surface (sfc) to its condensation level and moist adiabatically thereafter	Thermal instability of atmosphere at 500 hPa
4.	Humidity Index (HI) in °C	$(T - T_d)_{850} + (T - T_d)_{700} + (T - T_d)_{500}$	Notations as above,	Combination of saturation at 850, 700 and 500 hPa
5.	Deep Convective Index (DCI) in °C	$(T + T_d)_{850}$ - SLI	Notations as above	Combination of lower temperature and thermal instability
6.	Showalter Index (SHI) in °C	Te_{500} - $Tp_{850\delta 500}$	Notations as above	Thermal instability of atmosphere at 500 hPa
7.	Modified Showalter Index (SHI_m) in °C	Te_{500} - $Tp_{700\delta 500}$	Notations as above	Thermal instability of atmosphere at 500 hPa
8.	Boyden Index (BI)	H_{700} - H_{1000} - T_{700} - 200	H is height of indicated pressure level (decamater)	
9.	Severe weather threat (SWEAT)	$12T_{d850}$ + 20(TTI -49) + $2Ws_{850}$ + Ws_{500} + 125 [sin(Wd_{500} - Wd_{850})] + 0.2	Ws and Wd are wind speed (kts) and direction	

across Maharashtra, Karnataka and Kerala. The wind discontinuity is seen at 850 hPa on most of the days and sometimes extends upto 700 hPa. The winds are light northerly to northwesterly to the east of trough and south-easterly to southerly to the west of the trough. The upper level winds (300 hPa and above) are westerlies which are dry (Rao and Ramamurti, 1972). The presence of shallow warm moist air from the Bay and dry winds aloft is a favourable situation for the occurrence of thunderstorms. The topography of this region with intense heating and advection of moisture under favourable wind regime contribute to initiation of thunderstorms over the southern peninsula. During the early part of the season, the southern peninsula is affected by movement of easterly waves. The pre-monsoon rainfall is within 50-5 cm which is about 25 - 30% of the annual rainfall (Srinivasan *et al*., 1973).

3. Methodology

3.1. *Stability indices*

The stability indices namely, K, TTI, SLI, HI, DCI, SHI, SHI_m, BI and SWEAT were computed using RS/RW data of Bangalore city for a period of 1991-2003. The description of various indices is given in Table 1 for the sake of completeness. It is seen from the Table 1 that K considers the saturation at 700 hPa while TTI considers saturation at 850 hPa. Both K and TTI consider lapse rate between 850 to 500 hPa and hence indicate amount of heating of lower atmosphere. The indices like SLI, SHI and SHI_m represent thermal instability of atmosphere and indicate whether the parcel will be hotter or cooler than the atmosphere at 500 hPa starting from surface, 850 or 700 hPa. HI is a measure of saturation from 850 to 500 hPa levels and DCI is a combination of SLI and lower tropospheric temperature. SWEAT is a combination of all the essential parameters of low level moisture, convective environment, speed and directional shear required for a thunderstorm while BI includes only 700-1000 hPa layer thickness. Higher values of K, TTI, DCI, BI and SWEAT imply more instability whereas smaller values of SLI, HI, SHI, SHI_m imply more instability and hence higher thunderstorm probability. The above mentioned indices were computed using 0000 and 1200 UTC soundings for TD and NTD respectively. The basic statistics like mean, standard deviation, median, highest and lowest values for every index were obtained for all, TD and NTD respectively.

TABLE 2(a)

2 × 2 Contingency table

		Observation	
		Yes	No
Forecast	Yes	F_YO_Y (A/Hits)	F_YO_N (C/False Alarms)
	No	F_NO_Y (B/Miss)	F_NO_N (D/Non-event hits)

TABLE 2(b)

Description of different skill scores

S. No.	Skill score	Formula used	Limits
1.	Probability of detection (POD)	A/(A+B)	0 ≤ POD≤ 1
2.	False alarm rate (FAR)	C/(A+C)	0 ≤ FAR≤ 1
3.	Critical success index (CSI)	A/(A+B+C)	0 ≤ CSI≤ 1
4.	True skill statistic (TSS)	(A/A+B) - (C/C+D)	-1 ≤ TSS≤ 1
5.	Heidke skill score (HSS)	2(AD-BC)/[(A+B)(B+D)+(A+C) (C+D)]	-1 ≤ HSS≤ 1
6.	Normalised skill score (NSS)	0.5*TSS(α)/[TSS(max)+ HSS (α)/HSS(max)]	-1 ≤ NSS≤ 1

3.2. *Statistical significance*

There were about 82 and 196 TD and 980 and 803 NTD days for 0000 UTC and 1200 UTC during 1991-2003. The *Z* test (Z_{xy}) is used to find out if the difference between the means of TD and NTD are statistically significant (Wilks, 1995). This is computed as

$$Z_{xy} = \frac{(M_x - M_y)}{\sqrt{\frac{S_x^2}{n_x} + \frac{S_y^2}{n_y}}}$$

where, M_x, M_y, S_x, S_y, n_x and n_y are the mean, standard deviation and numbers of TD and NTD respectively. Larger absolute value of Z_{xy} indicates that the difference between the means of TD and NTD is statistically significant. The critical values of Z_{xy} are ± 1.96 and ± 2.58 at 95 and 99% confidence.

3.3. *Thunderstorm indices as dichotomous predictors*

The indices have continuous values and the range is large, but this study treats each of indices as a dichotomous predictor for thunderstorm. It is well known that the forecast of a dichotomous predictor is verified using a yes/no 2 × 2 contingency table (Wilks 1995). In Table 2(a), A is the number of events correctly forecasted, B is events missed, C is number of events forecasted, but not occurred and D is number of non-events correctly forecasted. The different skill scores that are derived from these four independent variables are given in Table 2(b). The probability of detection (POD) is the probability of expected events. The false alarm ratio (FAR) is the false event forecast and the critical success index (CSI) is the ratio of hits to the sum of total events and the false alarms. CSI does not consider correct forecasts of non events (D) and hence is a biased score (Scheafer, 1990). But the true skill statistic (TSS) takes correct non-event forecasts into account and is difference between the expected events and the unexpected non-events. Huntrieser *et al*. (1997) have used maximum TSS for determining the threshold or benchmark value for various predictors. The TSS equal to zero implies random forecast. The Heidke skill score (HSS) gives the credit to all the correct forecasts that are not due to chance. Haklander and Delden (2003) have used normalised skill score (NSS) which is a combination of TSS and HSS and obtains best of both the scores. This score has been used for finding out the threshold/ benchmark value for an index. The skill score method is an objective method that is used to determine the threshold value of the most suitable index representing the atmospheric conditions. The 2 × 2 contingency table was prepared for lowest value of index and skill scores as in Table 2(b) were computed. The value of the index was then incremented by a certain fixed value and scores were recalculated. This process was continued till the maximum value of index. The threshold/benchmark value of an index is taken as that value which results in max NSS.

4. Results and discussion

The Tables 3(a&b) show the statistics of all the indices for 0000 and 1200 UTC cases. These tables show that the extremes of each of the indices are very large as compared to their individual means. Table 3(a) shows that the mean of all the indices excluding SHI_m and BI is higher for a TD as compared to the NTD. All the indices, except BI have higher Z_{xy} than ±2.58 and the largest value of Z_{xy} are found for SHI_m, DCI and SLI suggesting that these possess best potential to differentiate a TD from a NTD. Table 3(b) shows that all indices have greater mean on a TD as compared to NTD excluding SHI_m, BI and HI. Also, all indices are significant at 99% confidence level.

4.1. *Scatter plot*

The scatter plot of all the indices whose means are statistically significant was made for visualising the

TABLE 3(a)

Statistical parameters of thunderstorms for which 0000 UTC data is representative

S.No	Index	Extreme		All			Thundery days			Non Thundery days			Z_{xy}
		Max	Min	Mean	Median	SD	Mean	Median	SD	Mean	Median	SD	
1.	K (°C)	71	-6.9	31	32.3	10.7	35.8	36.5	7.9	30.6	31.9	10.8	5.54
2.	TTI (°C)	66.2	16.7	44.7	45.4	7.2	47.6	47.8	5.4	44.5	45.2	7.2	4.8
3.	SLI (°C)	17	-11.1	-2	-2.7	4	-3.8	-4	2.3	-1.8	-2.6	4.1	-7.2
4.	HI (°C)	69.4	-9.1	34.8	35.6	13.3	37.4	38.5	12.7	33.8	35	13.4	2.9
5.	DCI (°C)	60.5	1.1	36.6	38.5	9.5	41.4	41.9	5.4	36.2	38.2	9.6	7.8
6.	SHI (°C)	16.9	-16.3	-0.57	-1.2	5.1	-2.7	-3	3.7	-0.4	-1	5.2	-5.2
7.	SHI_m(°C)	13.7	-5.5	3.5	3.3	3.6	1.2	1.2	2.5	3.7	3.5	3.6	-8.2
8.	BI	101.7	89.8	96.5	96.6	1.5	96.4	96.7	1.2	96.5	96.6	1.5	1.1
9.	SWEAT	625.6	-868	109.2	137.5	227.3	191.4	196.8	165.5	102.7	131.5	230.3	4.3

TABLE 3(b)

Statistical parameters of thunderstorms for which 1200 UTC data is representative

S.No	Index	Extreme		All			Thundery days			Non Thundery days			Z_{xy}
		Max	Min	Mean	Median	SD	Mean	Median	SD	Mean	Median	SD	
1.	K (°C)	53.7	-3.1	33.3	34.9	9.1	39	39.2	6.2	31.9	33.1	9.2	13
2.	TTI (°C)	63.2	21.5	45.7	45.8	6.1	50	49.9	5.0	44.7	45	6	12.1
3.	SLI (°C)	18.9	-13.6	-2.6	-3	4.3	-5.8	-6	2.9	-1.7	-1.9	4.2	-16.3
4.	HI (°C)	64.9	1.6	29.7	29.6	11.6	24.1	22 .8	9.6	32.1	32.2	11.6	-8.7
5.	DCI (°C)	58.6	6.9	39.1	40.3	8.3	45.2	45.8	5.4	37.7	38.6	8.2	15.8
6.	SHI (°C)	26.8	-11.9	0.2	-0.1	4.1	-2.7	-2.8	3.3	0.9	0.7	4.0	-12.9
7.	SHI_m (°C)	15.4	-9.6	2.3	1.9	3.6	0.6	0.5	2.8	2.7	2.4	3.7	-8.3
8.	BI	107.5	93.7	101.1	101.4	1.6	100.5	100.9	2.0	101.2	101.4	1.5	-4.6
9.	SWEAT	551.6	-747	95.6	104.6	193.9	215.6	238.5	154.3	71.9	87.0	192.3	9.9

relation between the thunderstorm predictor and thunderstorm occurrence (predictand). Scatter plot of SLI for 1200 UTC (SLI12) during 1991-2003 is shown in Fig. 1(a) (rest figures not shown). Blue corresponds to SLI12 for NTD and red for a TD respectively. It shows that thunderstorms start occurring by end of March and maximum during April and May. The SLI12 on TD ranges between -3 and -9 °C. In this case, low values of SLI12 are associated with higher thunderstorm probability and *vice versa*. On the other hand, higher values of K, TTI and DCI and SWEAT are associated with higher thunderstorm probability and *vice versa*.

4.2. *Computation of threshold value*

Tables 4(a&b) and 5(a&b) summarise the threshold values obtained for each of the indices for 0000 UTC and 1200 UTC when TSS and HSS are maximum. Tables 4(a) shows that the SHI_m (< 3 °C) and DCI (> 35 °C) are best in predicting thunderstorms at 0000 UTC. The TSS obtained for these indices are 36% and 29% respectively (highlighted). On the other hand, if HSS is considered as the defining score, then SHI_m (< 2 °C) and K (> 33 °C) indices have highest HSS of 11% and 8% respectively. The Tables 5(a&b) show the threshold values and skill scores obtained when TSS and HSS reach a maximum based on 1200 UTC. The DCI > 41 °C and SLI < -4 °C yield best scores with TSS as 43% and 45% while DCI >45 °C and SLI < -5 °C yield best score with HSS as 34 and 33% respectively. It is clear from Tables [4(a&b) and 5(a&b)], that the threshold/benchmark value of each index obtained by choosing two different skill scores TSS and HSS is slightly different. It is seen that if maximum HSS is chosen as the criterion for obtaining the threshold

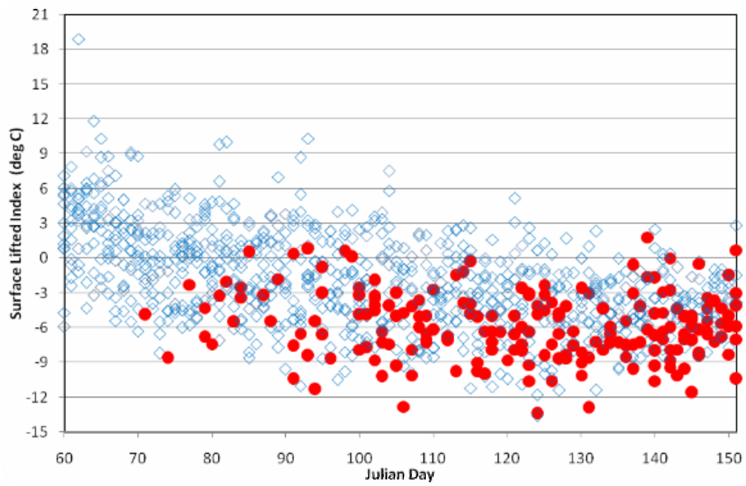

Fig. 1(a). Scatter plot of surface lifted index for 1200 UTC (SLI12) over Bangalore during 1991-2003, Blue is non-thunderstorm day and Red is thunderstorm day

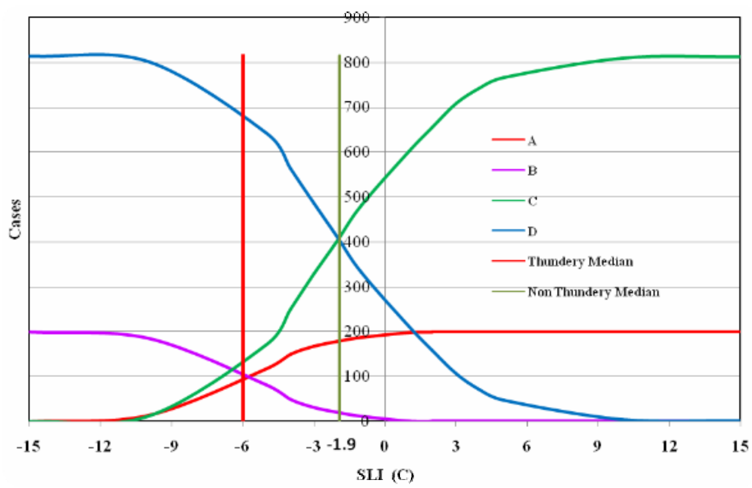

Fig. 1(b). Variation of different elements of contingency table w.r.t SLI for 1200 UTC over Bangalore during 1991-2003

value, it results in reduction of POD, FAR and shifting the threshold/benchmark towards more a thundery value. Fig. 1(b) shows the variation of different elements of the contingency table as a function of SLI12. The thundery and non-thundery medians at -6 and -1.9 °C are also shown by two vertical lines. The red line in Fig. 1(b) shows the number of red dots of Fig. 1(a) or TD for which SLI12 ≤ -6 °C. The number of red dots for which SLI12 > -6 °C is represented by the magenta line. The deep green line represents the number of blue dots for which SLI12 ≤ -6 °C and the blue line represents blue dots when SLI12 > - 6 °C. Fig. 1(c) shows the variation of all the skill scores as a function of SLI12. The CSI, TSS and HSS increase monotonically, exhibit a distinct maximum at a particular value and then decrease, however, POD and FAR increase continuously. The CSI indicated by green line reaches a maximum of 33% for SLI12 equal to -4 °C. The TSS in blue line also suggests the threshold value of -4 °C when it is 45%. As mentioned above, the maximum value of HSS (33%) is achieved for a slightly lower value of SLI12 at -5 °C as compared to TSS. It is clear from Fig. 1(c) that NSS is maximum (99%) when SLI12 is equal to -4 °C and TSS and HSS are 45 and 33% respectively. The POD and FAR are 75 and 63% for this SLI12 equal to -4 ºC and hence this threshold was taken as the threshold/benchmark value.

4.3. *Verification of prediction*

The usefulness of these indices in predicting the thunderstorms over Bangalore was tested with an independent dataset of 3 years from 2004 to 2006. The skill scores for the selected indices for 0000 UTC and

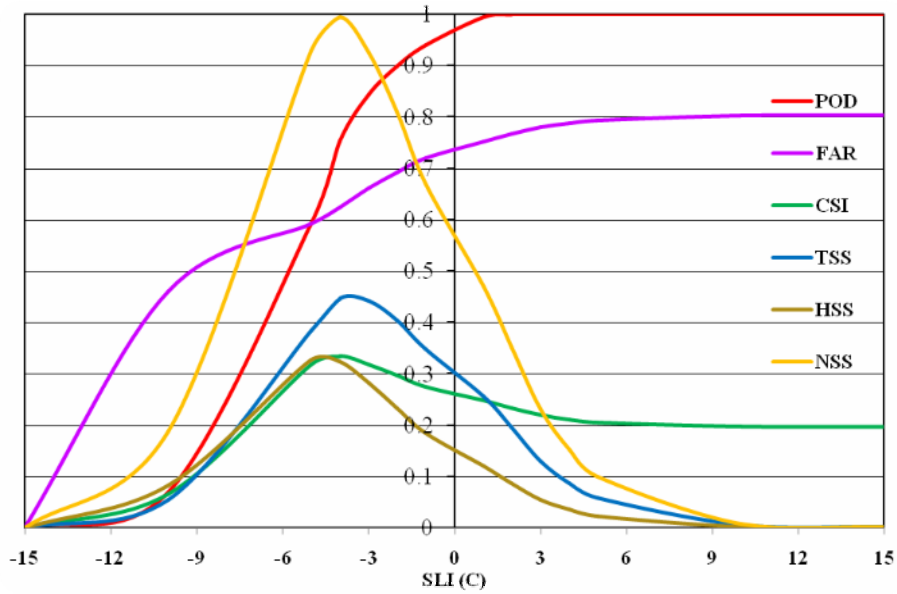

Fig. 1(c). Variation of different skill scores of SLI for 1200 UTC over Bangalore during 1991-2003

TABLE 4(a)

Skill scores of indices for maximum TSS for 0000 UTC

S. No.	Stability index	Threshold value	TSS (%)	HSS (%)	CSI (%)	POD (%)	FAR (%)	A	B	C	D
1.	K	>33 °C	27	8	11	72	88	59	23	442	538
2.	TTI	> 45 °C	22	6	10	72	90	60	23	516	510
3.	SLI	< -2 °C	23	5	10	88	90	73	10	673	359
4.	**DCI**	**>35 °C**	**29**	6	10	93	90	77	6	663	370
5.	HI	<15 °C	-3	-3	5	7	80	10	142	40	395
6.	SHI	<-2 °C	24	7	11	66	89	55	28	436	595
7.	**SHI_m**	**<3 °C**	**36**	11	13	80	86	66	17	420	549
8.	SWEAT	>50	20	4	9	84	91	62	12	605	338

TABLE 4(b)

Skill scores of indices for maximum HSS for 0000 UTC

S. No.	Stability index	Threshold value	TSS (%)	HSS (%)	CSI (%)	POD (%)	FAR (%)	A	B	C	D
1.	K	>33 °C	27	**8**	11	72	88	59	23	442	538
2.	TTI	> 47 °C	21	6	10	61	89	51	32	411	615
3.	SLI	<-4 °C	19	**7**	10	49	89	41	42	316	716
4.	DCI	>39 °C	24	**7**	10	70	89	58	25	476	557
5.	HI	<15 °C	-3	-3	5	7	80	10	142	40	395
6.	SHI	<-2 °C	24	7	11	66	89	55	28	436	595
7.	**SHI_m**	**<2 °C**	30	**11**	13	64	86	53	30	326	643
8.	SWEAT	>200	13	4	9	50	90	37	37	348	595

TABLE 5 (a)

Skill scores of indices for maximum TSS for 1200 UTC

S. No.	Stability index	Threshold value	TSS (%)	HSS (%)	CSI (%)	POD (%)	FAR (%)	A	B	C	D
1.	K	>36 °C	37	25	29	74	67	*145*	51	296	501
2.	TTI	> 47 °C	36	25	29	71	67	140	58	286	527
3.	**SLI**	<-4 °C	**45**	28	29	73	68	150	49	250	564
4.	**DCI**	>41 °C	**43**	28	32	81	66	160	38	308	506
5.	HI	<32 °C	31	24	38	80	58	144	37	199	207
6.	SHI	<-1 °C	38	26	28	71	68	130	52	276	555
7.	SHI_m	<1 °C	24	17	24	58	72	104	76	262	510
8.	BI	>100	-14	-7	16	67	83	140	68	691	155
9.	SWEAT	>100	29	16	23	76	76	113	36	351	404

TABLE 5 (b)

Skill scores of indices for maximum HSS for 1200 UTC

S. No.	Stability index	Threshold value	TSS (%)	HSS (%)	CSI (%)	POD (%)	FAR (%)	A	B	C	D
1.	K	>36 °C	37	25	29	74	67	*145*	51	296	501
2.	TTI	> 49 °C	33	28	29	57	63	113	85	193	620
3.	**SLI**	**<-5 °C**	38	**33**	32	59	59	118	81	171	643
4.	**DCI**	**>45 °C**	38	**34**	32	57	58	113	85	155	659
5.	HI	<22 °C	26	26	32	48	51	87	94	89	317
6.	SHI	<-2 °C	36	28	28	60	65	109	73	202	629
7.	SHI_m	<-1 °C	16	17	19	29	65	53	127	100	672
8.	BI	>100	-14	-7	16	67	83	140	68	691	155
9.	SWEAT	>300	22	24	21	32	61	47	102	74	681

1200 UTC were recalculated and the results are presented in the Tables 6(a&b). Table 6(a) shows the number of events and non-events correctly predicted using the selected indices which are computed using 0000 UTC RS/RW data. There are a total of 12% of TD and 88% of NTD observed during pre-monsoon season of 2004-2006. K (>33 °C) and SHI_m (<3 °C) have correctly predicted 61% and 67% of TD and NTD events together. These two indices have provided the best forecasts of 8% and 7% for TD and 53% and 62% for NTD respectively. Hence, K and SHI_m have the maximum ability to predict the TD and NTD for 0000 UTC over Bangalore. Table 6(b) shows the verification scores for the selected indices that are computed using 1200 UTC upper air data. It is seen from this table that SLI (<-4 °C) and DCI (>44 °C) have predicted 79% and 71% of TD and NTD events correctly. These indices have predicted 16% and 9% of thundery events correctly out of a total of 25% realized. Also, both of them have predicted nearly same number of (63% and 62%) non-thundery events correctly out of total of 75% realized. The POD for SLI (66%) is higher as compared to DCI (38%) and FAR is lower (44%) as compared to DCI (59%). Correspondingly, the TSS and HSS for SLI are also higher as compared to DCI. Hence it is concluded that SLI has the best ability in predicting the TD from a NTD for 1200 UTC over Bangalore city and airport.

5. Conclusion

This study is an attempt to find out a suitable stability index and its threshold for predicting thunderstorms in pre-monsoon season over two Indian stations, namely Bangalore city and Airport. A set of nine stability indices for 0000 UTC and 1200 UTC are treated as potential predictors and have been computed using RS/RW data of Bangalore city for 1991-2003. The mean,

TABLE 6(a)

Verification of prediction at 0000 UTC. Total thundery days (TD) and non-thundery days (NTD) observed: 12% and 88%

S. No.	Index	Observation	Prediction TD (%)	Prediction NTD (%)
1.	K > 33 ºC	TD (%)	08	04
	(POD=65%, FAR=82%, CSI=16%, TSS=25%, HSS=12%)	NTD (%)	36	53
2.	SHI_m < 3 ºC	TD (%)	07	05
	(POD=58%, FAR=78%, CSI=19%, TSS=28%, HSS=17%	NTD (%)	26	62

TABLE 6(b)

Verification of prediction at 1200 UTC. Total thundery days (TD) non-thundery days (NTD) observed: 25% and 75%

S. No.	Index	Observation	Prediction TD (%)	Prediction NTD (%)
1.	SLI < -4 ºC	TD (%)	16	08
	(POD=66%, FAR=44%, CSI=44%, TSS=49%, HSS=47%)	NTD (%)	13	63
2.	DCI > 44 ºC	TD (%)	09	15
	(POD=38%, FAR=59%, CSI=25%, TSS=20%, HSS=21%)	NTD (%)	14	62

median and standard deviation are computed for each index for 0000 UTC and 1200 UTC and then *Z* test has been applied for finding out those indices which can differentiate a TD from a NTD. Further, the predictor (stability index) and predictand (occurrence of thunderstorm *vs* no thunderstorm) are treated as dichotomous variables and 2 × 2 contingency table is prepared for the predictors that are statistically significant. Six skill scores namely POD, FAR, CSI, TSS, HSS and NSS are generated from this contingency table starting from lowest to highest value of predictor. The predictors (indices) showing highest TSS or HSS are taken as the efficient predictors to be utilized for verification tests. The threshold/benchmark value of a predictor is obtained when NSS, which is a combination of both TSS and HSS, is maximum. After the fixation of the threshold value, the selected predictors are used to predict thunderstorm occurrence using the data for 2004-2006. Following findings are based on the above discussion:

(*i*) During pre-monsoon season afternoon or evening time is more prone to occurrence of thunderstorms over Bangalore city and Airport than midnight or morning.

(*ii*) The stability indices serving as predictors for thunderstorm occurrence have different statistical parameters for 0000 UTC and 1200 UTC. The statistical parameters for 1200 UTC are higher as compared to 0000 UTC. The *Z* test indicates that all the indices for 1200 UTC and 0000 UTC except BI are statistically significant at 99% confidence.

(*iii*) It is found that K and SHI_m are the most efficient predictors for 0000 UTC while SLI and DCI are most efficient predictors for 1200 UTC respectively. The threshold/benchmark value for the 0000 UTC predictors is found to be > 33 °C and < 3 ºC for which TSS scores are 29% and 27% and NSS score is 98%. For 1200 UTC, SLI and DCI are found to be the most efficient predictors with thresholds of < -4 °C and > 44 °C. The maximum NSS score of 98% and 99% is obtained for these threshold/benchmark values. It is seen that almost all the predictors are statistically significant but only few have good forecast skill. This is because the local topography plays an important role in thunderstorm initiation which cannot be represented statistically.

(*iv*) The two indices namely K and SHI_m have correctly predicted 61% and 67% of TD and NTD events together. They have scored nearly equally by correctly predicting 8% and 7% of TD and 53% and 62% of NTD for 0000 UTC.

(*v*) SLI and DCI have predicted 79% and 71% of TD and NTD events together correctly for 1200 UTC. Amongst SLI and DCI, SLI has scored better because it has predicted 16% of TD correctly out of a total of 25% observed for 1200 UTC. It has also been able to predict 63% of NTD correctly out of a total of 75% observed. The FAR is the lowest of 44% making the TSS and HSS to be the highest (49% and 47%) respectively. Hence it is concluded that SLI has the best ability in predicting the thundery/non-thundery days for 1200 UTC over Bangalore.

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References

Agnihotri, G., Venugopal, R. and Hatwar, H. R., 2013, "Climatology of thunderstorms and squalls over Bangalore", *Mausam*, **63**, 4, 735-740.

Barlow, W. R., 1993, "A new index for the prediction of deep convection", Preprints 17th Conference on severe local storms, St. Louis, MO American Meteorological Society, 129-132.

Boyden, C. J., 1963, "A simple instability index for use as a synoptic parameter", *Meteorological Magazine*, **92**, 198-210.

Chaudhuri, S. and Middey, A., 2012, "A composite stability index for dichotomous forecast of thunderstorms", *Theoretical and Applied Climatology*, DOI: 10.1007/s00704-012-0640-z.

George, J. J., 1960, "Weather forecasting for Aeronautics", Academic Press.

Haklander, A. J. and Van Delden, A., 2003, "Thunderstorm predictors and their forecast skill for the Netherlands", *Atmospheric Research*, **67- 68**, 273- 299.

Huntrieser, H., Schiesser, H. H., Schmid, W. and Waldvogel, A., 1997, "Comparison of traditional and newly developed thunderstorm indices for Switzerland", *Weather and Forecasting*, **12**, 108-125.

Karmakar, S. and Mahbub Alam, M. D., 2011, "Modified instability index of the troposphere associated with thunderstorms/norwesters over Bangladesh during pre-monsoon season", *Mausam*, **62**, 2, 205-214.

Kunz, M., 2007, "The skill of convective parameters and indices to predict isolated and severe thunderstorms", *Natural Hazards Earth System Science*, **7**, 327-342.

Litta, A. J., Mohanty, U. C. and Mary, I. S., 2012, "The diagnosis of severe thunderstorms with high-resolution WRF model", *Journal of Earth System Science*, **121**, 2, 297-316.

Litynska, Z. J., Parfiniewicz, J. and Pinkowski, H., 1976, "The prediction of air mass thunderstorms and hails", *WMO Bulletin*, **450**, 128-130.

Marinaki, A., Spiliotopoulos, M. and Michalopoulou, H., 2006, "Evaluation of atmospheric instability indices in Greece", *Advances in Geosciences*, **7**, 131-135.

Means, L. L., 1952, "Stability index computation graph for surface data" p2 (Unpublished manuscript available from F. Sanders, 9 Flint St. Marblehead, MA 01945).

Meißner, C., Kalthoff, N., Kunz, M. and Adrian, G., 2007, "Initiation of shallow convection in the Black Forest Mountains", *Atmospheric Research*, **86**, 1, 42-60.

Miller, R., 1972, "Notes on analysis and severe storm forecasting procedures of the Air force", *Global Weather Central*, Technical Report 200 (rev), AWS, USAF (AWS Scott AFB, IL 62225) p102.

Mukhopadhyay, P., Sanjay, J. and Singh, S. S., 2003, "Objective forecast of thundery/non-thundery days using conventional indices over three northeast Indian stations", *Mausam*, **54**, 4, 867-880.

Rajeevan, M., Kesarkar, A., Thampi, S. B., Rao Radhakrishna, T. N. and Rajasekhar, M. B., 2010, "Sensitivity of WRF cloud microphysics to simulations of a severe thunderstorm event over Southeast India", *Annales Geophysicae*, **28**, 603-619.

Rao, Y. P. and Ramamurti, K. S., 1972, "Climatology of India and neighbourhood", *Forecasting Manual Report*, I-2 India Meteorological Department.

Schaefer, J, T., 1990, "The Critical Success Index as an indicator of warning skill", *Weather and Forecasting*, **5**, 570-575.

Schmeits, M. J., Kok, C. J. and Vogelezang, D. H. P., 2005, "Probabilistic forecasting of (severe) thunderstorms in the Netherlands using model output statistics", *Weather and Forecasting*, **20**, 134-148.

Showalter, A. K., 1953, "A stability index for thunderstorm forecasting", *Bulletin of American Meteorological Society*, **34**, 250-252.

Srinivasan, V., Ramamurthy, K. and Nene, Y. R., 1973, "Discussion of typical weather situations: Summer nor'westers and Andhis and large scale convective activity over peninsula and central parts of the country', *Forecasting Manual Report*, III-2.2, India Meteorological Department.

Steinackkeiten, R., 1977, "Moglichkeiten von Gewitterprognosen im Gebirge", *Wetter Leben*, **29**, 150-156.

Tajbakhsh, S., Ghafarian, P. and Sahraian, F., 2012, "Instability indices and forecasting thunderstorms: the case of 30 April 2009", *Natural Hazards and Earth System Sciences*, **12**, 403-413.

Tyagi, B., Krishna, N. V. and Satyanarayana, A. N. V., 2011, "Study of thermodynamic indices in forecasting pre-monsoon thunderstorms over Kolkata during STORM pilot phase 2006-2008", *Natural Hazards*, **56**, 681-698.

Tyagi, A., 2007, "Thunderstorm climatology over Indian region", *Mausam*, **58**, 2, 198-212.

Wilks, D. S., 1995, "Statistical Methods in the Atmospheric Sciences: An Introduction", Academic Press.

Yamane, Y., Taiichi, H., Dewan, A. M. and Akter, F., 2010, "Severe local convective storms in Bangladesh: Part II - Environmental conditions", *Atmospheric Research*, **95**, 407-418.