

Modified instability index of the troposphere associated with thunderstorms / nor'westers over Bangladesh during the pre-monsoon season

SAMARENDRA KARMAKAR and MD. MAHBUB ALAM*

Bangladesh Meteorological Department, Dhaka, Bangladesh

**Department of Physics, Khulna University of Engineering & Technology, Khulna, Bangladesh*

(Received 26 July 2007, Modified 28 October 2010)

e mails : malam@phy.kuet.ac.bd; mdalam@gmail.com

सार – इस शोध पत्र में बंगलादेश में गर्ज वाले तूफानों के बनने के लिए अनुकूल विभिन्न संशोधित सूचकांकों के महत्वपूर्ण मानों का पता लगाने के लिए भीषण गर्ज वाले तूफान/काल बैसाखी की घटना से संबंधित विभिन्न संशोधित स्थिर सूचकांक का अध्ययन किया गया है। मॉडिफाइड क्रॉस टोटल इनडैक्स (MCT), मॉडिफाइड वर्टिकल टोटल इनडैक्स (MVT), मॉडिफाइड टोटल टोटलस इनडैक्स (MTT), मॉडिफाइड स्वेट इंडैक्स (MSWI), मॉडिफाइड K-इनडैक्स (MKI) और मॉडिफाइड एनर्जी इनडैक्स (MEI) जैसे मॉडिफाइड इनस्टेबिलिटी इनडाइसिस सुबह के समय में क्षोभमंडल में CT, VT, TT, SWI, KI, और EI की तुलना में अधिक अस्थिरता दिखते हैं। ढाका में 0000 यू.टी.सी. पर विभिन्न मॉडिफाइड अस्थिर सूचकांक के $MCT \geq 20$ डिग्री से., $MVT \geq 26$ डिग्री से., $MTT \geq 46$ डिग्री से., $MSWI > 300$, $MKI \geq 40$ डिग्री से., और $MEI < -6$ जूलस/ग्रा. बंगलादेश में काल बैसाखी की घटना के महत्वपूर्ण मान हैं। संशोधित स्थिर सूचकांक का स्थानिक रूप से वितरण करने से पता चला है कि काल बैसाखी की घटना की तारीखों में 0000 यू.टी.सी. पर विशेष रूप बिहार, पश्चिम बंगाल और समीपवर्ती बंगलादेश में सतह पर बने निम्न दाब क्षेत्र में अधिकतम अस्थिरता पाई गई है।

प्रचंड तूफान की तीव्रता वाली भीषण काल बैसाखी के लिए ढाका में 0000 यू.टी.सी. पर विभिन्न संशोधित अस्थिर सूचकांक हैं : जो बंगलादेश में काल बैसाखी की घटना के लिए क्रमशः $MCT \geq 20$ डिग्री से., $MVT \geq 28$ डिग्री से., $MTT \geq 50$ डिग्री से., $MSWI \geq 500$, $MKI \geq 42$ डिग्री से. और $MEI < -8$ जूलस/ग्रा. हैं।

ABSTRACT. The present study is an attempt to study different Modified Stability Indices in relation to the occurrence of severe thunderstorms/nor'westers in order to find out the critical values of different modified indices favorable for the formation of thunderstorms in Bangladesh. Computations have also been made for the stations in and around Bangladesh for studying the spatial distribution of the modified stability indices. The Modified Instability Indices such as Modified Cross Total Index (MCT), Modified Vertical Total Index (MVT), Modified Total Totals Index (MTT), Modified SWEAT Index (MSWI), Modified K-Index (MKI) and Modified Energy Index (MEI) show greater instability of the troposphere in the morning as compared to CT, VT, TT, SWI, KI and EI. The critical values of different modified instability indices at 0000 UTC over Dhaka are: $MCT \geq 20^\circ C$, $MVT \geq 26^\circ C$, $MTT \geq 46^\circ C$, $MSWI > 300$, $MKI \geq 40^\circ C$ and $MEI < -6$ joules/gm respectively for the nor'westers to occur in Bangladesh. The spatial distributions of modified stability indices have revealed that maximum instability lies over the area of surface low pressure especially over Bihar, West Bengal and adjoining Bangladesh at 0000 UTC on the dates of occurrence of nor'westers. Nor'westers occur at the eastern end of the maximum instability.

For severe nor'westers of tornadic intensity, the critical values of different modified instability indices at 0000 UTC over Dhaka are: $MCT \geq 20^\circ C$, $MVT \geq 28^\circ C$, $MTT \geq 50^\circ C$, $MSWI \geq 500$, $MKI \geq 42^\circ C$ and $MEI < -8$ joules/gm respectively for the nor'westers to occur in Bangladesh.

Key words – Modified Vertical Total Index, Modified Cross Total Index, Modified Total Totals Index, Modified SWEAT Index, Modified Energy Index.

1. Introduction

Pre-monsoon season over Bangladesh extending from March to May is characterized by very good

convective activity all over the country. Convective activity progressively increases from March onwards as the season advances. Though the thunderstorm activity may continue over the country even during the southwest

monsoon season, the severity of thunderstorms is marked only in the pre-monsoon season, when they, on a number of occasions, are accompanied by squalls and hails (Srinivasan, *et al.*, 1973). Newton (1963) has identified (i) potential instability, (ii) low-level moisture, (iii) sheared and veered environmental winds and (iv) some triggering mechanism(s) as favourable synoptic conditions for severe storm development. It is very important for forecasters to be able to distinguish between severe and non-severe thunderstorms. Extreme instability, strong vertical wind shear and atmospheric instability are considered as deciding factors (McNulty, 1988; Johns and Doswell, 1992). Whereas Goliger *et al.* (1997) have considered the following meteorological features necessary for tornado formation (i) a deep layer of mid tropospheric dry air above a moist surface, (ii) steep moisture and temperature gradients, (iii) high surface temperature, (iv) low level convergence and upper air divergence, (v) vertical wind shear and (vi) atmospheric instability.

Bangladesh is a country with high incidence of thunderstorm activity. These thunderstorms generally develop over Bihar plateau and adjoining areas and subsequently move in a southeasterly direction. This convective activity in the region of Bangladesh and India is known as “Nor’wester” or “Kalbaishakhi”.

The accurate forecasting of severe thunderstorms/nor’westers during the pre-monsoon season (March-May) in Bangladesh remains a challenging problem for operational meteorologists. Many factors are responsible for the occurrence of these thunderstorms. Among them are low-level advection of warm, moist air, mesoscale convective instability and an approaching upper level short wave trough. These features are measured directly at 12 hourly intervals or 24 hourly intervals in a country like Bangladesh. To facilitate the analysis of the stability of air masses, it is convenient first to prepare a chart, which shows the general distribution of a significant stability parameter. Meteorologists prepare charts of different stability indices to delineate the area of instability of the atmosphere conducive to the formation of thunderstorms. Some of the stability indices are Showalter Stability Index (SI), Lifted Index (LI), Dew-point Index (DPI), Dry Instability Index (DII), Severe Weather thrEAT (SWEAT) Index, Energy Index (EI), etc. [Showalter, 1953; Faubush *et al.*, 1951; Darkow, 1968; Miller, 1972; Galway, 1956; Chowdhury and Karmakar, 1986; Das *et al.*, 1994; Karmakar and Alam, 2006;] have been computed by using the 850 hPa levels as the low-level.

Since the 850 hPa level sometimes remains relatively dryer and the low-level moisture plays a vital role in the formative stages of thunderstorm, 925 hPa level can be

used as the low level. Not only that, the use of 850 hPa data gives some values in the morning showing the stability of the atmosphere and it becomes cumbersome to take any conclusive decision regarding the occurrence of nor’wester in Bangladesh specially in the afternoon or early night. From this point of view, the stability indices have been modified by considering the data at the boundary layer *i.e.*, 925 hPa level. This paper deals with the analysis of different modified stability indices with relation to the occurrence of nor’westers in Bangladesh.

2. Data used

Real time rawinsonde data of 0000 UTC of the pre-monsoon season during 1990-1995 at different isobaric heights from 1000 to 100 hPa at Dhaka, Chittagong and some Indian stations surrounding Bangladesh have been collected from the GTS link of Storm Warning Centre of Bangladesh Meteorological Department and the data have been used for this study.

3. Methodology of stability analysis

Some of the stability indices have been modified by taking into account of the low level moisture and temperature. The reason is that the low level moisture plays an important role in convective activity. Generally, forecast of nor’westers is made on the basis of 0000 UTC rawinsonde observations, which are used to compute the instability indices. Practically, it is seen that the atmosphere remains stable in the early morning of the day of occurrence of nor’westers in many occasions. It is because of the fact that there is less moisture or no moisture at 850 hPa level on many days of occurrence. As a result, the existing instability indices show stable atmosphere. Moreover, the isobaric surfaces were designated before as 1000, 850, 700 hPa and so on, but recently 925 hPa has been included as an isobaric surface and as such 925 hPa data have been considered in most cases instead of 850 hPa to modify the stability indices. The different modified stability indices are given below:

$$\begin{array}{ll} \text{Modified Cross} & : \text{MCT} = T_{d925} - T_{500} \\ \text{Total Index (MCT)} & \end{array}$$

$$\begin{array}{ll} \text{Modified Vertical} & : \text{MVT} = T_{925} - T_{500} \\ \text{Total Index (MVT)} & \end{array}$$

$$\begin{array}{ll} \text{Modified Total} & : \text{MTT} = \text{MVT} + \text{MCT} \\ \text{Totals Index (MTT)} & = (T_{925} + T_{d925}) - 2T_{500} \end{array}$$

$$\begin{array}{ll} \text{Modified Severe} & : \text{MSWI} = 12T_{d925} + 20 (\text{MTT} \\ \text{Weather ThrEAT} & - 49) + 2f_9 + f_5 \\ \text{(MSWEAT) Index} & + 125 (S + 0.2) \\ \text{(MSWI)} & \end{array}$$

None of the terms may be negative. Hence if $T_{d925} < 0$, the first term is set to zero; if $MTT < 49$, the second term is set to zero; and the last term is set to zero if any of the following conditions are not met: α_9 between 130° and 250° , α_5 between 210° and 310° , $\alpha_5 - \alpha_9 > 0$, and both $f_9, f_5 \geq 15$ knots.

Modified Energy Index (MEI) : $MEI = MSE_{500} - MSE_{925}$

Modified K-Index (MKI) : $MKI = (T_{925} + T_{d925}) - (T_{d700} + T_{500})$

Where

T_{d925}, T_{d700} = Dew-point temperature at 925 and 700 hPa in $^\circ\text{C}$.

T_{925}, T_{500} = Dry bulb temperature at 925 and 500 hPa in $^\circ\text{C}$.

f_5, f_9 = Wind speed at 500 and 925 hPa in knots.

S = $\text{Sin}(\alpha_5 - \alpha_9)$.

α_5, α_9 = Wind direction at 500 and 925 hPa level.

MSE_{925}, MSE_{500} = Moist Static Energy at 925 and 500 hPa level.

4. Results and discussion

Different modified stability indices of the atmosphere prior to the occurrence of nor'westers at 0000 UTC have been determined for Dhaka, Chittagong and some Indian stations to study the degree of instability of the atmosphere for the formation of thunderstorms / nor'westers in Bangladesh. The different modified stability indices viz., MCT, MVT, MTT, MSWI, MEI and MKI with their frequencies are tabulated in Tables 1 to 3. Attempts have been made to find out the critical values of the indices for the formation of thunderstorms and to study the spatial distribution of these indices for delineating the area of unstable atmosphere. Comparative studies have also been done between stability indices and modified stability indices. The results of modified stability indices and their spatial distributions have been discussed in the following sections.

TABLE 1

Modified Cross Total Index (MCT) and Modified Vertical Total Index and their frequencies at 0000 UTC over Dhaka

MCT			MVT		
Range of MCT ($^\circ\text{C}$)	Frequency (f)	% of the total	Range of MVT ($^\circ\text{C}$)	Frequency (f)	% of the total
10-16	2	1.85	24-26	2	1.85
16-18	3	2.78	26-28	11	10.19
18-20	3	2.78	28-30	28	25.93
20-22	11	10.19	30-32	41	37.96
22-24	18	16.67	32-34	13	12.04
24-26	26	24.06	34-36	8	7.41
26-28	22	20.37	36-38	3	2.78
28-30	19	17.59	>38	2	1.85
30-32	4	3.70			
Total	108	100		108	100

4.1. Modified Stability Indices and their frequencies at Dhaka in relation to the occurrence of nor'westers in Bangladesh

4.1.1. Modified Cross Total Index (MCT) and its frequency

Table 1 show that the maximum nor'westers occurs in the range of $24-26^\circ\text{C}$, which is about 24.07% of the total number of nor'westers. About 92.59% nor'westers occur when the MCT is greater than 20°C . The table also shows that 7.41% of nor'westers occur when the range of MCT is $10-20^\circ\text{C}$. Since 92.59% nor'westers occur when $MCT > 20^\circ\text{C}$ then we may consider the critical value of MCT is $\geq 20^\circ\text{C}$. For severe nor'westers of tornadic intensity, 87.50% occur when $MCT > 20^\circ\text{C}$, 68.75% of nor'westers occur when $MCT > 24^\circ\text{C}$ and 56.25% of nor'westers occur when $MCT > 25^\circ\text{C}$. Therefore, $MCT \geq 20^\circ\text{C}$ may be taken as the critical value for the severe nor'westers of tornadic intensity to occur in Bangladesh.

It is interesting to note that CT (Cross Total Index) in the morning has been found to be much lower than MCT in some cases and in those cases it is difficult to decide as to whether a nor'wester is going to occur in the afternoon or afterwards. For this reason MCT at 0000 UTC is better to be used in the forecasting of nor'westers in Bangladesh.

TABLE 2

Modified Total Totals Index (MTT) and Modified SWEAT Index (MSWI) and their frequencies at 0000 UTC over Dhaka

MTT			MSWI		
Range of MTT (°C)	Frequency (f)	% of the total	Range of MSWI	Frequency (f)	% of the total
42-44	1	0.93	100-200	1	0.93
44-46	1	0.93	200-300	8	7.41
46-48	3	2.78	300-400	20	18.52
48-50	7	6.48	400-500	32	29.63
50-52	9	8.33	500-600	30	27.78
52-54	7	6.48	600-700	12	11.11
54-56	25	23.15	700-800	4	3.70
56-58	19	17.59	>800	1	0.93
58-60	20	18.52			
60-62	11	10.19			
62-64	4	3.70			
64-66	1	0.93			
Total	108	100		108	100

TABLE 3

Modified Energy Index (MEI) and Modified K-Index and their frequencies at 0000 UTC over Dhaka

MEI			MKI		
Range of MEI J/gm (°C)	Frequency (f)	% of the total	Range of MKI (°C)	Frequency (f)	% of the total
12 to 6	1	0.93	34-40	4	3.81
6 to 0	5	4.63	40-42	4	3.81
0 to -6	21	19.44	42-44	6	5.71
-6 to -12	32	29.63	44-46	13	12.38
-12 to -18	34	31.48	46-48	14	13.33
-18 to -24	13	12.04	48-50	16	15.24
-24 to -30	2	1.85	50-52	14	13.33
			52-54	11	10.48
			54-56	7	6.67
			56-60	7	6.67
			60-64	7	6.67
			64-68	2	1.90
Total	108	100		105	100

4.1.2. Modified Vertical Total Index (MVT) and its frequency

Table 1 also shows that the maximum nor'westers occur in the range of MVT = 30-32° C, which is about 37.96% of the total number of nor'westers. About 98.15% nor'westers occur when the MVT is $\geq 26^\circ$ C. The critical value of MVT may be taken as MVT $\geq 26^\circ$ C. For severe nor'westers of tornadic intensity, 93.79% occur when MVT $> 28^\circ$ C and 75% of severe nor'westers occur when MVT $> 30^\circ$ C. Therefore, MVT $\geq 28^\circ$ C may be taken as the critical value for the severe nor'westers of tornadic intensity to occur in Bangladesh.

4.1.3. Modified Total Totals Index (MTT) and its frequency

Table 2 shows that maximum nor'westers occur in the range of MTT = 54-56° C, which is about 23.15% of the total number of nor'westers. 98.15% nor'westers occur when the MTT range is 46-66° C. The critical value of MTT may be taken as MTT $\geq 46^\circ$ C. For severe nor'westers of tornadic intensity, 93.75% occur when MTT $> 50^\circ$ C and 87.50% of severe nor'westers occur when MTT $\geq 52^\circ$ C. Therefore, MTT $\geq 50^\circ$ C may be taken as the critical value for the severe nor'westers of tornadic intensity to occur in Bangladesh.

4.1.4. Modified SWEAT Index (MSWI) and its frequency

It is seen also from the Table 2 that 9 out of 108 nor'westers (8.33%) occur when MSWI is 100-300. But maximum nor'westers (32 out of 108 *i.e.*, 29.63%) occur when MSWI is 400-500. Most of nor'westers *i.e.*, 99 out of 108 (91.67%) nor'westers occur when MSWI is ≥ 300 . So, MSWI ≥ 300 may be taken as the critical value for nor'westers to occur in Bangladesh.

For severe nor'westers with tornadic intensity, MSWI values are given below:

MSWI < 300: 12.50% (2 out of 16)

MSWI = 300-400: 12.50% (2 out of 16)

MSWI = 400-500: 18.75% (3 out of 16)

MSWI ≥ 500 : 56.25% (9 out of 16)

Above values of MSWI indicate that a few severe nor'westers may occur when MSWI is < 300. But it is also clear that severe nor'westers have greater probability to

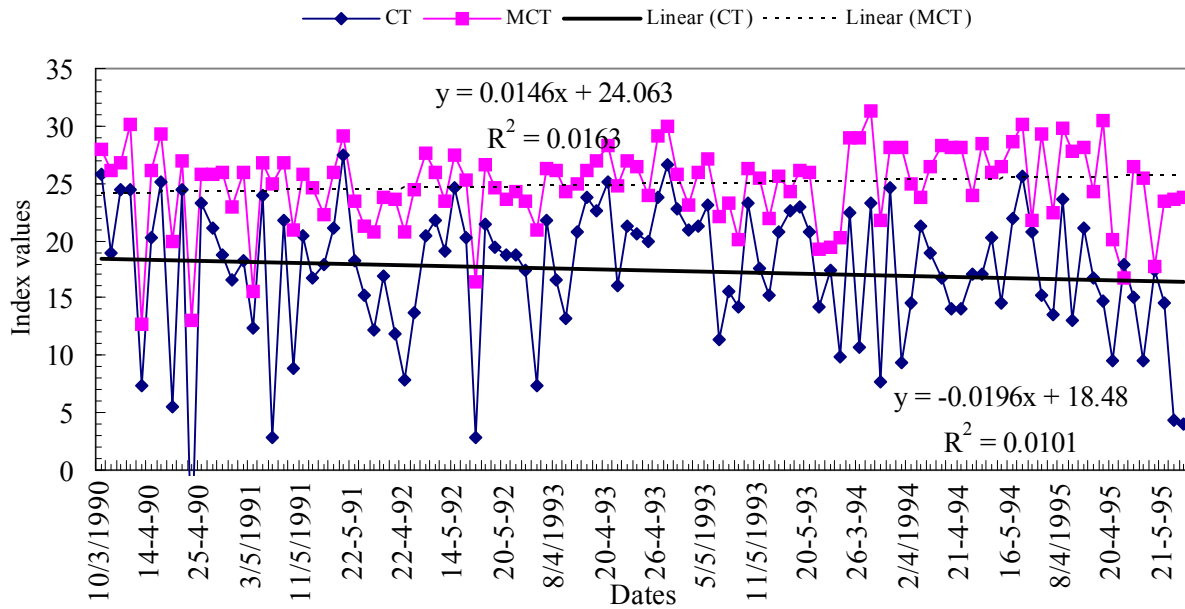


Fig. 1. Comparison of CT and MCT over Dhaka at 0000 UTC on the dates of occurrence of nor'westers in Bangladesh during 1990-1995

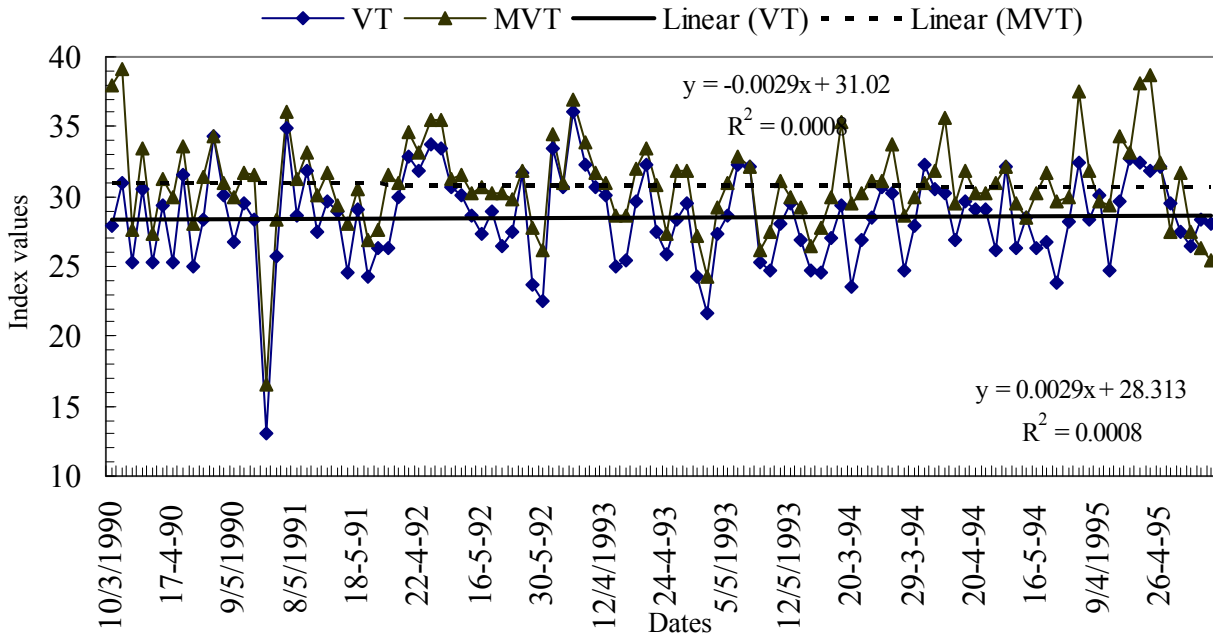


Fig. 2. Comparison of VT and MVT over Dhaka at 0000 UTC on the dates of occurrence of nor'westers in Bangladesh during 1990-1995

occur when MSWI is ≥ 400 (12 out of 16 *i.e.*, 75.00%) and 56.25% severe nor'westers with tornadic intensity occur in Bangladesh when MSWI is ≥ 500 . Therefore, MSWI ≥ 500 may be taken as the critical value for the occurrence of severe nor'westers with tornadic intensity.

4.1.5. Modified Energy Index (MEI) and its frequency

Table 3 shows that 6 out of 108 nor'westers (5.56%) occur when MEI is >0 Joule/gm and 102 out of 108

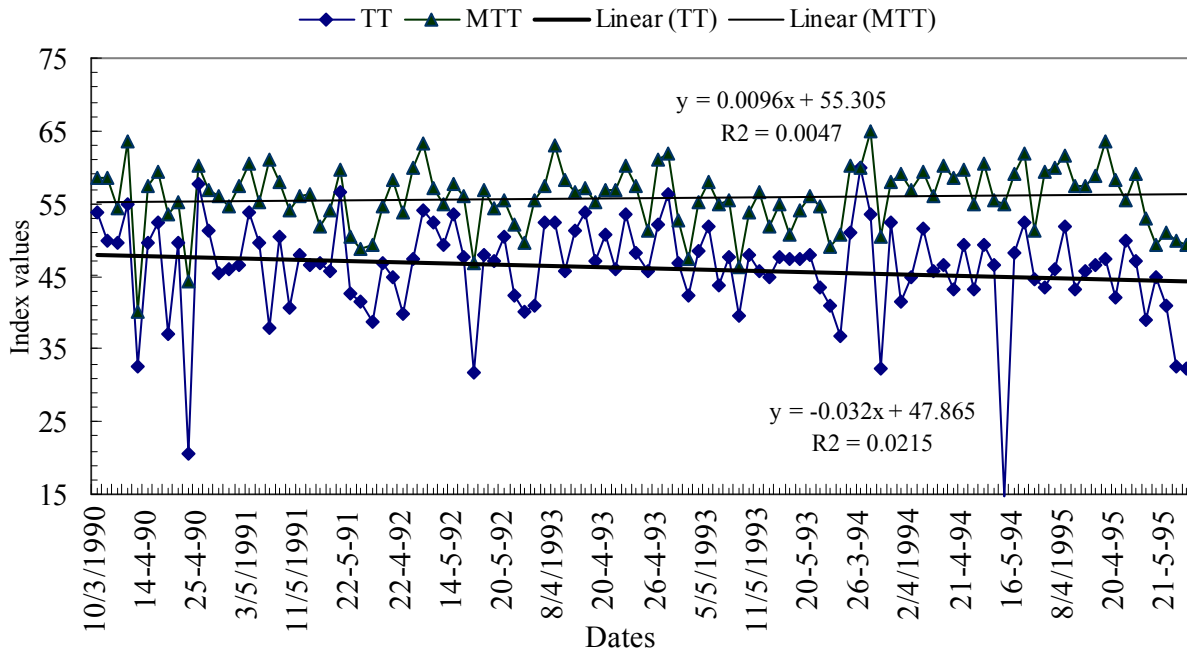


Fig. 3. Comparison of TT and MTT over Dhaka at 0000 UTC on the dates of occurrence of nor'westers in Bangladesh during 1990-1995

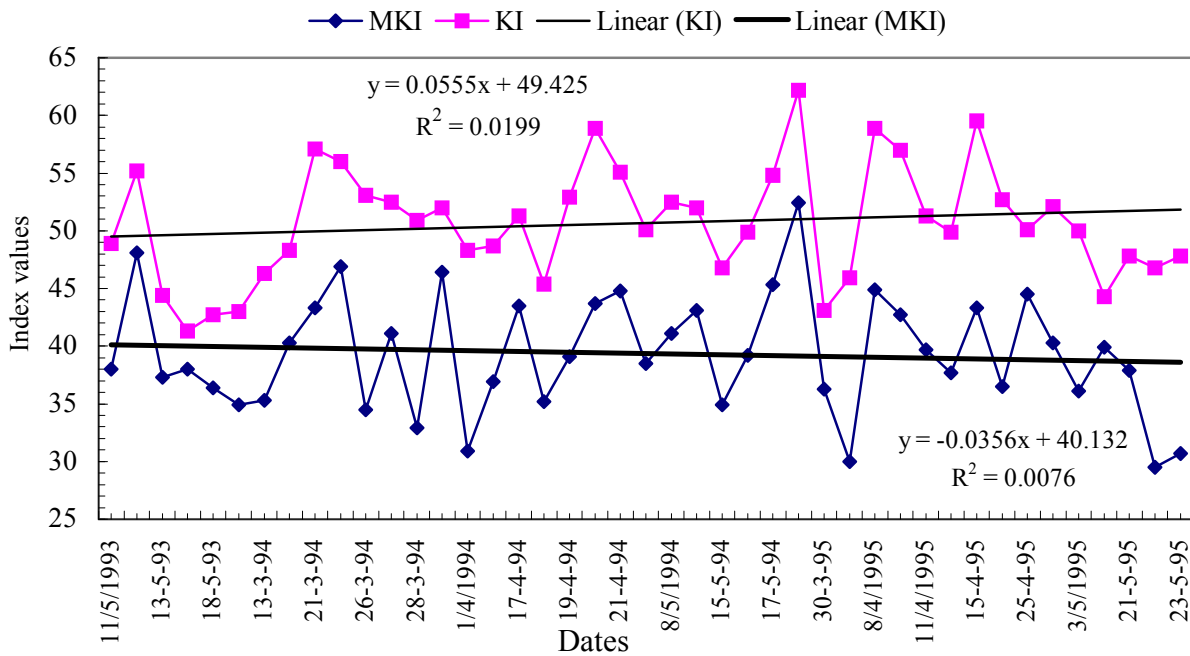


Fig. 4. Comparison of KI and MKI over Dhaka at 0000 UTC on the dates of occurrence of nor'westers in Bangladesh during 1990-1995

nor'westers (94.44%) occur when MEI is <0 Joule/gm. 21 out of 108 nor'westers (19.44%) occur when MEI ranges between 0 and -6 Joule/gm. Maximum number of nor'westers (34 out of 108 i.e., 31.48%) occur when MEI ranges between -12 and -18 Joule/gm and 66 out of 108

(i.e., 61.11%) nor'westers occur when MEI ranges between -6 and -18 Joule/gm. It has also been seen that 81 out of 108 (i.e., 75%) nor'westers occur when MEI is < -6 Joule/gm and in 25 cases EI shows stable conditions i.e., positive values. From the discussion, it may be

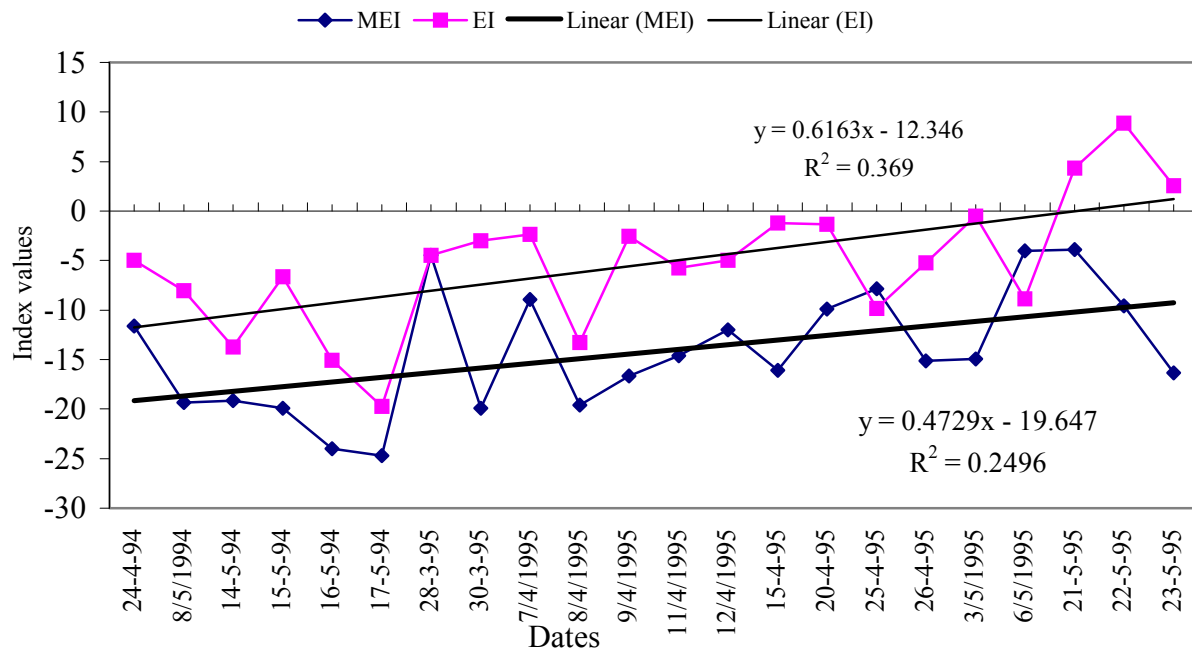


Fig. 5. Comparison of EI and MEI over Dhaka at 0000 UTC on the dates of occurrence of nor'westers in Bangladesh during 1990-1995

concluded that $MEI < -6$ Joule/gm can be taken as the critical value of MEI at 0000 UTC over Dhaka for the nor'westers to occur in Bangladesh.

It has also been observed that severe nor'westers with tornadic intensity occur even though the atmosphere remains stable with MEI ranges of 0–6 (5 out of 16 *i.e.*, 31.25%) at 0000 UTC. 25% of severe nor'westers (4 out of 16) occur when MEI ranges from –6 to –12, 62.50% of severe nor'westers (10 out of 16) occur when $MEI < -8$ Joule/gm and 43.75% (7 out of 16) nor'westers occur when MEI is < -12 Joule/gm. Therefore, $MEI < -8$ Joule/gm may be taken as the critical value for the occurrence of severe nor'westers with tornadic intensity in Bangladesh.

4.1.6 Modified K- Index (MKI) and its frequency

Table 3 also reveals that most of the values of MKI ranges between 40 and 56, when 80.95% (85 out of 105) nor'westers occur in Bangladesh. It can also be seen from the table that maximum nor'westers occur in the range of $MKI = 48-50^\circ C$, which is about 15.24% of the total number of nor'westers. The table also shows that 96.19% of nor'westers occur when $MKI > 40^\circ C$. The critical value of MKI may be taken as $MKI \geq 40^\circ C$ for nor'westers to occur in Bangladesh. For severe nor'westers of tornadic intensity, 93.33% occur when $MKI > 42^\circ C$ and 66.67% of severe nor'westers occur when $MKI > 50^\circ C$.

Therefore, $MKI \geq 42^\circ C$ may be taken as the critical value for the severe nor'westers with tornadic intensity to occur in Bangladesh.

From the above discussion and the tables it is apparent that the modified instability indices are better to indicate the instability of the troposphere. Of these instability indices MEI and MKI sometimes give some erratic results, which show stable atmosphere but nor'westers are found to occur in Bangladesh in that conditions. Therefore, it is apparent that MCT, MVT, MTTI and MSWI are essential indices for a better forecast at an occasion along with favorable surface and upper air synoptic conditions.

4.2. Comparison of different stability indices with modified stability indices at Dhaka on the dates of occurrence of nor'westers in Bangladesh

Different stability indices on the dates of occurrence of nor'westers have been compared with the corresponding modified stability indices and are discussed. The CT, VT, TT, KI, EI, MCT, MVT, MTT, MKI and MEI have been computed using the relevant data on the dates of occurrence of nor'westers (108 cases) in Bangladesh during the period March-May of 1990-1995 and their comparison have been drawn and are presented in Figs. 1-5.

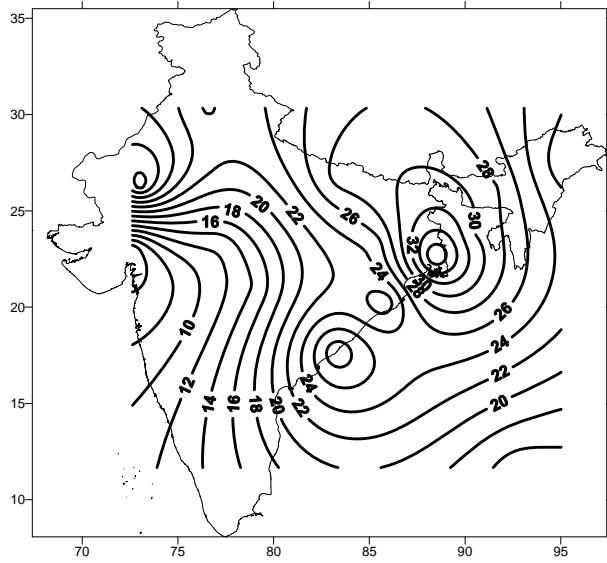


Fig. 6. Spatial distribution of MCT on 17 May 1994, the date of occurrence of nor'westers in Bangladesh

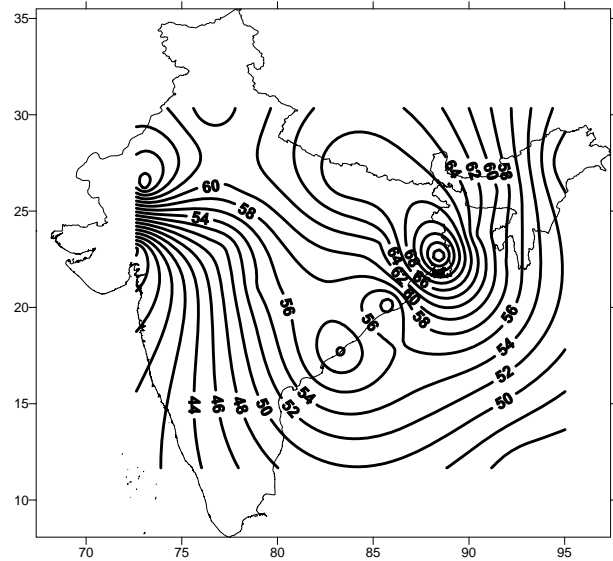


Fig. 8. Spatial distribution of MTT on 17 May 1994, the date of occurrence of nor'westers in Bangladesh

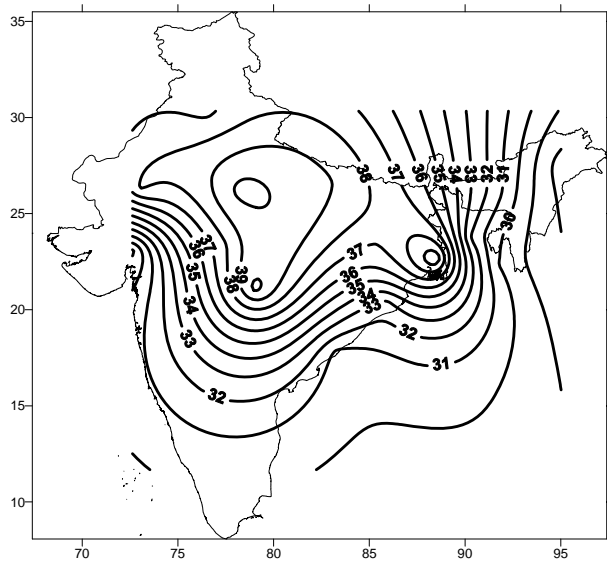


Fig. 7. Spatial distribution of MVT on 17 May 1994, the date of occurrence of nor'westers in Bangladesh

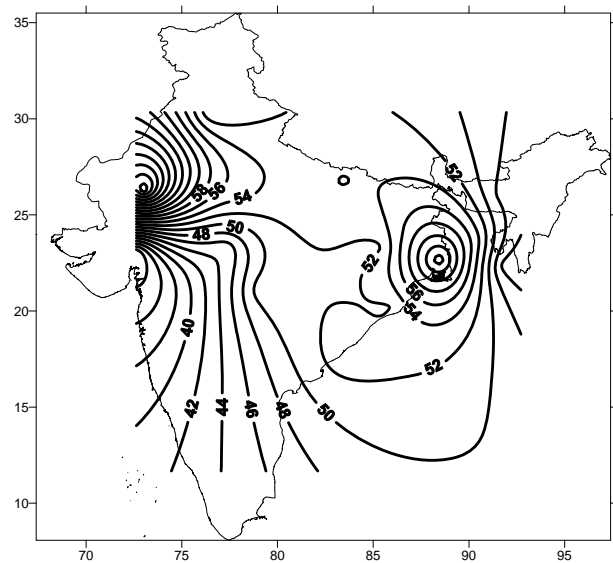


Fig. 9. Spatial distribution of MKI on 17 May 1994, the date of occurrence of nor'westers in Bangladesh

Fig. 1 shows that the MCT is always greater than the CT. It can be seen that CT values are less than 15°C in many cases and even less than 10°C . But MCT is almost greater than 15°C except one or two cases. This indicates that CT shows stable atmosphere in the morning, which leads the forecaster to be confused for forecasting of nor'westers in the afternoon/evening. In that respect, MCT gives much greater values indicating unstable atmosphere, which is favorable for the occurrence of nor'westers in Bangladesh.

MVT and MTT show the similar results as in the case of MCT and are shown in Figs. 2 and 3 respectively. The reason for the increased values of the MCT, MVT and MTT are due to the use of 925 hPa level data, where the temperature and dew-point temperature are greater than those of 850 hPa level. Therefore, it may be concluded that the modified indices are better guide to determine the instability of the lower troposphere for the occurrence of nor'westers in Bangladesh.

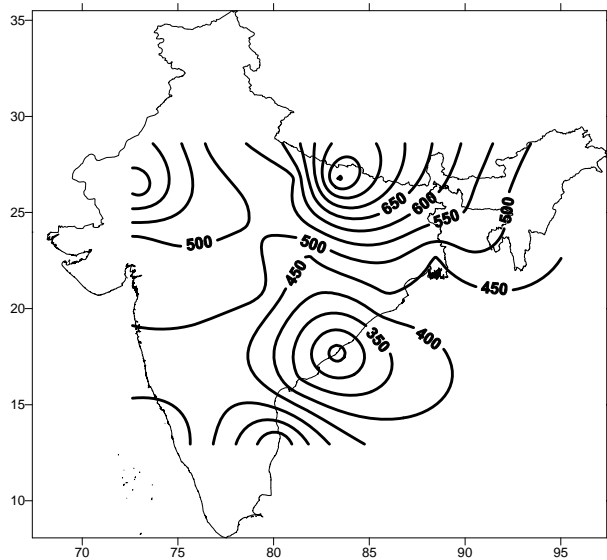


Fig. 10. Spatial distribution of MSWI on 14 May 1992, the date of occurrence of nor'westers in Bangladesh

The KI and EI have also been compared with the MKI and MEI and are shown in Figs. 4 and 5 respectively. Fig. 4 shows that the MKI is greater than the KI indicating relatively greater instability of the atmosphere. The pattern of variation is the same in both the cases. The variation of MEI and EI are also the same as shown in Fig. 5, which reveals that the MEI is much lower than the EI, showing relatively greater instability of the troposphere. The reason is that the moist static energy at 925 hPa is greater than that of 850 hPa. Therefore, MKI and MEI at 0000 UTC are better to be used for the forecasting of nor'westers in Bangladesh.

4.3. Spatial distribution of different modified stability indices in relation to the occurrence of nor'westers in Bangladesh

The different modified stability indices of the troposphere on the dates of occurrence of a number of nor'westers have been computed by using the rawinsonde data of Dhaka, Chittagong and a number of Indian stations surrounding Bangladesh at 0000 UTC and their spatial distributions have been studied critically.

The spatial distributions of MCT, MVT, MTT, MKI, MSWI and MEI on the dates of occurrence of nor'westers are given in Figs. 6-11 respectively. The spatial distributions of MCT, MVT and MTT (Figs. 6-8) show that an area of maximum positive values of these three Indices exists over eastern Madhya Pradesh, Bihar, West Bengal and adjoining Bangladesh indicating the highly unstable area. Nor'westers have been found to occur at the northeastern or eastern part of the unstable area. The

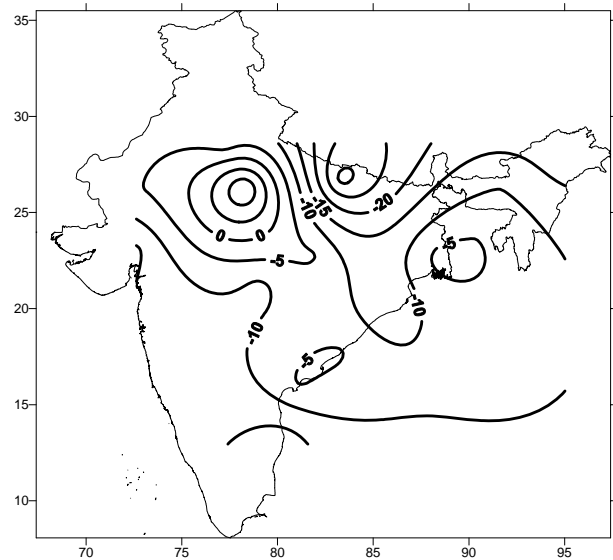


Fig. 11. Spatial distribution of MEI on 14 May 1992, the date of occurrence of nor'westers in Bangladesh

positive areas of the Indices in combination with the low pressure area over Bihar, West Bengal and adjoining Orissa and Bangladesh as well as the cyclonic circulation up to 3-4 km or above are favourable for the occurrence of nor'westers in Bangladesh.

The spatial distributions of MKI and MSWI are shown in Fig. 9 and Fig. 10 respectively. The spatial distributions of these Indices show that the highly unstable area exists over the same area as in the cases of other indices. The maximum positive areas of MKI and MSWI, indicating the maximum instability, are almost over the surface low pressure area over Bihar, West Bengal and adjoining Bangladesh and nor'westers have been found to occur at the eastern end of the area of maximum instability.

The spatial distribution of MEI for different nor'westers has also been studied. An example of the distribution is shown in Fig. 11. This figure shows two areas of maximum negative areas indicating greater instability : one over Bangladesh and Gangetic West Bengal and the other over eastern Uttar Pradesh and Bihar. In general, the maximum negative area has been found over the surface low pressure area.

5. Conclusions

On the basis of the present study, following conclusions can be drawn:

- (i) The modified stability indices at 0000 UTC show relatively greater instability as compared to the existing

Stability Indices and therefore MCT, MVT, MTT, MSWI, MKI and MEI are comparatively better indices than CT, VT, TT, SWI, KI and EI for the prediction of thunderstorms/nor'westers to occur.

(ii) The study reveals that 92.59% nor'westers occur when the MCT > 20° C and 98.15% nor'westers occur when the MVT is >26° C. Most of nor'westers (91.67%) occur when MSWI is > 300 over Dhaka at 0000 UTC. It has also been seen that 75% nor'westers occur in Bangladesh when MEI is < -6 joules/gm at Dhaka in the morning and 96.19% of nor'westers occur when MKI > 40°C.

(iii) It has been found that 87.50%, 93.79% 56.25%, 62.50% and 93.33% severe nor'westers of tornadic intensity occur in Bangladesh when MCT >20° C, MVT > 28° C, MSWI is > 500, MEI < -8 joules/gm, MKI > 42° C respectively at Dhaka at 0000 UTC.

(iv) The critical values of different modified stability indices at 0000 UTC over Dhaka are: MCT ≥ 20° C, MVT ≥ 26° C, MTT ≥ 46° C, MSWI > 300, MKI ≥ 40° C and MEI < -6 joules/gm respectively for the nor'westers to occur in Bangladesh.

(v) The critical values of different modified stability indices at 0000 UTC over Dhaka are: MCT ≥ 20° C, MVT ≥ 28° C, MTT ≥ 50° C, MSWI ≥ 500, MKI ≥ 42° C and MEI < -8 joules/gm respectively for the severe nor'westers of tornadic intensity to occur in Bangladesh.

(vi) The spatial distributions of modified stability indices have revealed that maximum instability lies over the region of surface low pressure area especially over Bihar, West Bengal and adjoining Bangladesh at 0000 UTC on the dates of occurrence of nor'westers. Nor'westers occur at the eastern end of the maximum instability.

Acknowledgments

The authors are thankful to the Director of Bangladesh Meteorological Department (BMD) for providing the relevant data for the study. Thanks are also due to Mr. Abdul Mannan, Meteorologist, Mr. S. M. Quamrul Hassan, Meteorologist and Mrs. Masuda Mohi, Teliprinter Operator of BMD for their help in the preliminary compilation of data.

References

- Chowdhury, M. H. K. and Karmakar, S., 1986, "Pre-monsoon Nor'westers in Bangladesh with case studies", *Proceedings of the SAARC Seminar on Local Severe Storms*, Bangladesh Met. Dept., 147-166.
- Darkow, G. L., 1968, "The total energy environment of severe storms", *J. Appl. Met.*, **7**, 2, 199-205.
- Das, R. C., Munim, A. A., Begum, Q. N. and Karmakar, S., 1994, "A Diagnostic study on some local severe storms over Bangladesh", *Journal of Bangladesh Academy of Sciences*, **18**, 1, 81-92.
- Faubush, E. J., Miller, R. C. and Starrett, L. G., 1951, "An empirical method for forecasting tornado development", *Bull. Amer. Meteor. Soc.*, **32**, p19.
- Galway, J. G., 1956, "The lifted Index as a predictor of latent instability", *Bull. Amer. Meteor. Soc.*, **37**, 528-529.
- Goliger, A. M., Milford R. V., Adam B. F. and Edwards, M., 1997, "Inkanyamba-Tornadoes in South Africa", United Litho, ISBN 0-7988-5417-0.
- Johns, R. H. and Doswell III, C. A., 1992, "Severe local Storms Forecasting", *Weather and Forecasting*, **7**, 4, 588-612.
- Karmakar, S. and Alam, M., 2006, "Instability of the troposphere associated with thunderstorms/nor'westers over Bangladesh during the pre-monsoon season", *Mausam*, **57**, 4, 629-638.
- McNulty, R. P., 1988, "A meditation on Miller, Central region applied research paper 88-4 NOAA Tech. Memo NWS CR-88", NWS Central region, Kansa City, MO 33-38.
- Miller, R. C., 1972, "Notes on analysis and severe storm forecasting procedure of the Air Force Global Weather Central", *Technical Report 200*, Air Weather Service (MAC), U.S.A., p120.
- Newton, C. W., 1963, "Dynamics of severe convective storms", *Meteor. Mong.*, No. **27**, *Amer. Meteor. Soc.*, 33-58.
- Showalter, A. K., 1953, "Stability index for forecasting thunderstorms", *Bull. Amer. Meteor. Soc.*, **34**, 250-252.
- Srinivasan, V., Ramamurth, K. and Nene, Y. R., 1973, "Discussion of typical synoptic weather situations 2.2. Summer-Nor'westers and Andhis and large scale convective activity over Peninsula and central parts of the country, India Meteorological Department Forecasting Manual", Part III:2.2.