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

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सार –इस शोध पत्र में भीषण गर्जन के साथ तूफान/कालबैसाखी बनने से संबंधित घटनाओं से संबद्ध विभिन्न स्थिरता सूचकांकों के अध्ययन का प्रयास किया गया है जिसके आधार पर बंगलादेश में गर्ज के साथ तूफान बनने के अनुकूल विभिन्न सूचकांकों का चरम मान ज्ञात किया जा सके। स्थिरता सूचकांकों के स्थानिक वितरण का अध्ययन करने के लिए बंगलादेश तथा उसके आसपास के स्टेशनों के आंकड़ों का भी अभिकलन किया गया है। बंगलादेश में कालबैसाखी के समय ढाका में 0000 यू. टी. सी. पर शोल्टर स्थिरता सूचकांक (एस. आई.), उन्नयन सूचकांक (एल. आई.),ओसांक सूचकांक (डी. पी. आई.), शुष्क अस्थिर सूचकांक (डी. आई. आई.),तिर्यक योग सूचकांक (सी. टी.),शीर्षयोग सूचकांक (वी. टी.),योगफलों का योग सूचकांक (टी. टी.), ऊर्जा सूचकांक (ई. आई.),स्वेटसूचकांक (एस. डब्ल्यू. आई.) और के.-सूचकांक (के. आई.) के चरम मान क्रमशः $\leq +3°$ से., $\leq 0°$ से., $\leq -3°$ से., $\leq 0°$ से., $\geq 16°$ से., $\geq 24°$ से., $\geq 40°$ से., -6 जूल / ग्राम, >200 और >34° से., होने का पता चला हैं।

विभिन्न स्थिरता वाले सूचकांकों के स्थानिक वितरण से यह पता चला है कि बंगलादेश अथवा पूर्वी मध्य प्रदेश, बिहार, पश्चिम बंगाल और उससे सटे हुए बंगलादेश में ज्ञात किए गए सूचकांकों जैसेः–एस. आई., एल. आई., डी. पी. आई., डी. आई. आई तथा इ. आई., के ऋणात्मक मान इन क्षेत्रों की अत्यधिक अस्थिर स्थिति का संकेत देते हैं। इन सूचकांकों के ऋणात्मक क्षेत्रों का बिहार, पश्चिम बंगाल एवं समीपवर्ती उड़ीसा तथा बंगलादेश के निम्न दाब क्षेत्रों के साथ संयोजन और 3–4 कि. मी. या इससे अधिक ऊँचाई पर उपरितन वायु में चक्रवातीय परिसंचरण बंगलादेश में कालबैसाखी होने के लिए अनुकूल स्थितियाँ हैं। कालबैसाखी के घटित होने की तिथियों को सी. टी., वी. टी.,एस. डब्ल्यू. आई., के. आई. और टी. टी., के अधिकतम मान बंगलादेश अथवा पूर्वी मध्य प्रदेश, बिहार,पश्चिम बंगाल तथा समीपवर्ती बंगलादेश में पाए गए हैं जिससे उनके अत्यधिक अस्थिर क्षेत्र होने का पता चलता है। सामान्यतः कालबैसाखी इन सूचकांकों के अधिकतम मान वाले क्षेत्रों में अथवा पूर्वोतर/पूर्वी भाग के अधिकतम मान वाले क्षेत्रों में घटित हुई हैं।

ABSTRACT. The present study is an attempt to study different stability indices in relation to the occurrence of nor'westers in order to find out the critical values of different indices favourable for the formation of thunderstorms and severe thunderstorms in Bangladesh. Computations have also been made for the stations in and around Bangladesh for studying the spatial distribution of the stability indices. The critical values of Showalter Stability Index (SI), Lifted Index (LI), Dew-point Index (DPI), Dry Instability Index (DII), Cross Total Index (CT), Vertical Total Index (VT), Total Totals Index (TT), Energy Index (EI), SWEAT Index (SWI) and K-Index (KI) at 0000 UTC over Dhaka may be taken as $\leq +3°$ C, $\leq 0°$ C, $\leq -3°$ C, $\leq 0°$ C, $\geq 16°$ C, $\geq 24°$ C, $\geq 40°$ C, -6 Joule/gm, >200 and >34° C respectively for the nor'westers to occur in Bangladesh.

The spatial distribution of different Stability Indices reveals that maximum negative values of SI, LI, DPI, DII and EI lie over the eastern Madhya Pradesh, Bihar, West Bengal and adjoining Bangladesh indicating the highly unstable area. The negative 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. Maximum values of CT, VT, SWI, KI and TT exist over eastern Madhya Pradesh, Bihar, West Bengal and adjoining Bangladesh indicating the highly unstable area. Normally, nor'westers have been found to occur at the northeastern or eastern part of the area of maximum instability.

Key words – Showalter Stability Index, Lifted Index, Dew-point Index, Dry Instability Index, Cross Total Index, Vertical Total Index, Total Totals Index, and K-Index.

1. Introduction

A stability index is a measure of the potential instability of the atmosphere over a specified region. 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 severe weather forecaster can then take a closer and more precise examination of these areas, incorporating all available parameters, tools, and experience into making a final forecast (Thomson and Lin, 1985).

Over the years, studies of convective out-breaks have helped to isolate those altered during convective development. These careful isolations have led to the development of the many stability indices that are in use by forecasters today. Since each storm outbreak may have its own varying environment, one index may prove to be more accurate over another within a particular storm setting.

Meso convective systems (MCS) are responsible for much of the beneficial precipitation and most of the severe weather (heavy rains, high winds, hail, tornadoes and lighting) that occur in Bangladesh during the pre-monsoon season (March-May). The accurate forecasting of severe thunderstorms and tornadoes during this season remain a challenging problems for operational meteorologists. 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. Stability indices, determined from environmental soundings, have been used by forecasting offices to locate the area in which the severe weather is likely to occur (Faubush *et al.*, 1951; Showalter, 1953; Galway, 1956; Miller, 1972). These stability indices provide necessary conditions (but not sufficient) conducive to storm occurrence.

In Bangladesh, the meteorologists use some of the stability indices to forecast severe thunderstorms, known as nor'westers or Kalbaishakhis. But except a few studies (Chowdhury and Karmakar, 1986; Das *et al*. 1994) extensive studies have not so far been done on the stability indices to determine the stability criteria.

In the present study, the stability indices have been investigated for a large number of severe thunderstorms in order to find out the critical values of different indices favourable for the formation of thunderstorms in Bangladesh and those are suggested. The stability indices those have been studied are Showalter Stability Index (SI), Lifted Index (LI), Dew-point Index (DPI), Dry Instability Index (DII), Cross Total Index (CT), Vertical Total Index (VT), Total Totals Index (TT), SWEAT Index (SWI), Energy Index (EI) and K-Index (KI). To calculate these stability indices, the low-level data at 850 hPa has been used. Computations have also been done at the stations in and around Bangladesh for studying the spatial distribution of the stability indices.

2. Data source

Real time rawinsonde data of 0000 UTC of the pre-monsoon season during 1990-95 at different isobaric heights from 1000 hPa 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 have been used for this study.

3. Methodology of stability analyses

The stability indices have been investigated for a large number of severe thunderstorms in order to find out the critical values of different indices favourable for the formation of thunderstorms in Bangladesh. For these stability indices, the low-level data at 850 hPa has been used. Computations have also been made for the stations in and around Bangladesh for studying the spatial distribution of the stability indices. The following, stability indices are calculated by using the data at 0000 UTC for this study purpose.

Showalter Stability Index : $SI = T_{500} - T_{p500}$ (1)

Lifted Index : $LI = T_{500} - T_{p500}$ (2)

The lifted Index can be used as a predictor of latent instability (Galway, 1956). LI values less than -6° C can be considered to be extreme with heavy to strong thunderstorm potential (McNulty, 1995) in the US.

Dew-point Index : $DPI = T_{500} - T'_{d500}$ (3)

Dry Instability Index : $DII = T_{600} - T'_{600}$ (4)

Cross Total Index : $CT = T_{d850} - T_{500}$ (5)

The critical value of CT is 18 or more for the thunderstorms to occur.

TABLE 1

Showalter Stability Index (SI) and its frequency at 0000 UTC at Dhaka

Range of SI (°C)	Frequency (f)	% of the total
12 to 9	1	1.56
9 to 6	3	4.64
6 to 3	7	10.94
3 to 0	19	29.69
0 to -3	23	35.94
-3 to -6	9	14.06
-6 to -9	2	3.13
Total	64	100

TABLE 2

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

Range of LI (°C)	Frequency (f)	% of the total
9 to 6	1	1.56
6 to 3	2	3.13
3 to 0	10	15.63
0 to -3	22	34.38
-3 to -6	25	36.06
-6 to -9	4	6.25
Total	64	100

Vertical Total Index : $VT = T_{850} - T_{500}$ (6)

Total Totals Index : $TT = T_{d\,850} + T_{d\,850} - 2T_{500}$ (7)

The SWEAT Index : $SWI = 12T_{d\,850} + 20\,(TT - 49) + 2f_8 + f_5 + 125\,(S + 0.2)$ (8)

None of the terms may be negative. Hence if $T_{d850} < 0$, the first term is set to zero; If $TT < 49$, 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_8 between 130° and 250°, α_5 between 210° and 310°, $\alpha_5 - \alpha_8 > 0$, and both f_8, $f_5 \geq 15$ knots.

Energy Index as defined by Darkow (1968) is :

$$EI = MSE_{500} - MSE_{850} \quad (9)$$

The K-Index (George, 1960) can be computed by

$$KI = (T_{850} - T_{500}) + T_{d\,850} - (T_{700} - T_{d\,700}) \quad (10)$$

TABLE 3

Dew-point Index (DPI) and its frequency at 0000 UTC at Dhaka

Range of DPI (°C)	Frequency (f)	% of the total
6 to 3	1	1.56
3 to 0	1	1.56
0 to -3	4	6.25
-3 to -6	16	25.00
-6 to -9	26	40.63
-9 to -12	11	17.19
-12 to -15	4	6.25
<-15	1	1.56
Total	64	100

TABLE 4

Dry Instability Index (DI I) and its frequency at 0000 UTC at Dhaka

Range of DII (°C)	Frequency (f)	% of the total
12 to 9	1	1.56
9 to 6	2	3.13
6 to 3	1	1.56
3 to 0	3	4.69
0 to -3	18	28.13
-3 to -6	21	32.81
-6 to -9	16	25.00
-9 to -12	2	3.13
Total	64	100

Where,

$T_{d\,850}$, $T_{d\,700}$ = 850 and 700 hPa dew–point temperature respectively in °C

T_{850}, T_{700}, T_{600}, T_{500} = 850, 700, 600 and 500 hPa temperature respectively in °C

$T'_{d\,500}$ = dew-point along a pseudo-adiabat to 500 hPa

$T_{p\,500}$ = temperature of a parcel lifted dry adiabatically from 850 hPa to its condensation level and moist adiabatically to 500 hPa

TABLE 5

Cross Total Index (CT) and its frequency at 0000 UTC at Dhaka

Range of CT (°C)	Frequency (f)	% of the total
-10 to 0	3	2.78
0 - 10	11	10.19
10 - 16	21	19.44
16 - 18	14	12.96
18 - 20	10	9.26
20 - 22	22	20.37
22 - 24	15	13.89
24 - 26	9	8.33
26 - 28	3	2.78
Total	108	100

TABLE 6

Vertical Total Index (VT) and its frequency at 0000 UTC at Dhaka

Range of VT (°C)	Frequency (f)	% of the total
< 22	1	0.93
22 - 24	4	3.70
24 - 26	17	15.74
26 - 28	23	21.30
28 - 30	28	25.93
30 - 32	18	16.67
32 - 34	14	12.96
34 - 36	3	2.78
Total	108	100

T'_{600} = surface temperature along a pseudo-adiabat to 600 hPa

f_8, f_5 = 850 and 500 hPa wind speed respectively in knots

S = Sin ($\alpha_5 - \alpha_8$)

α_5, α_8 = 500 and 850 hPa wind direction respectively.

MSE_{850}, MSE_{500} = Moist Static Energy at 850 and 500 hPa level.

4. Results and discussion

Different stability indices of the atmosphere prior to the occurrence of nor'westers (*i.e*., 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 stability indices *viz*., SI, LI, DPI, DII, CT, VT, TT, EI, SWI and KI with their frequencies are tabulated in Tables 1 to 10 respectively. 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. The results are described in the subsequent sub-sections.

TABLE 7

Total Totals Index (TT) and its frequency at 0000 UTC at Dhaka

Range of TT (°C)	Frequency (f)	% of the total
< 32	2	1.85
32 - 36	4	3.70
36 - 38	3	2.78
38 - 40	4	3.70
40 - 42	9	8.33
42 - 44	10	9.26
44 - 46	14	12.96
46 - 48	21	19.44
48 - 50	13	12.04
50 - 52	11	10.19
52 - 54	12	11.11
54 - 56	2	1.85
56 - 58	3	2.78
Total	108	100

TABLE 8

Energy Index (EI) and its frequency at 0000 UTC at Dhaka

Range of EI (J/gm)	Frequency (f)	% of the total
12 to 6	6	5.56
6 to 0	13	12.04
0 to -6	30	27.78
-6 to -12	36	33.33
-12 to -18	18	16.67
-18 to -24	4	3.70
-24 to -30	1	0.93
Total	108	100

TABLE 9

SWEAT Index (SWI) and its frequency at 0000 UTC at Dhaka

Nor'westers			Severe nor'westers with tornadic Intensity		
Range of SWI	Frequency (f)	% of the total	Range of SWI	Frequency (f)	% of the total
50-100	6	5.56	< 100	3	18.75
100-200	28	25.93	100-200	5	31.25
200-300	32	29.63	200-300	1	6.25
300-400	28	25.93	300-400	2	12.50
400-500	8	7.41	> 400	5	31.50
500-600	4	3.70			
600-700	2	1.85			
Total	108	100	Total	16	100

4.1. *Stability indices and their frequencies over Dhaka in relation to the occurrence of nor'westers in Bangladesh*

(*i*) *Showalter Stability Index (SI) and its frequency*

From Table 1 it is clear that for most of the events the SI was in between 3 to -3° C at 0000 UTC. There were 11 out of 64 (*i.e*., 17.19%) nor'westers has been occurred when SI above 3° C at 0000 UTC, which indicates that the atmosphere was highly stable. For these events the instabilities might have been occurred due to insolation as well as the moisture influx extended to a greater height. The table also shows that 53 out of 64 (*i.e*., 82.81%) of nor'westers occur when the SI < 3° C. It is interesting to note that that the atmosphere is treated as unstable when SI is below 0° C. But the percentage of occurrence is suggesting us to consider the critical value of SI is < 3° C at 0000 UTC over Dhaka. From the intensity analysis it has been found that 3 out of 5 severe nor'westers (60%) with marginal tornadic intensity occur when SI is < -3° C and 2 out of 5 severe nor'westers (40%) with marginal tornadic intensity when SI is 0 to –2° C. Also as per the criteria of SI, tornadoes are suspected when SI ranges between –3 and –6° C or below. This criterion does not always hold good for Bangladesh.

(*ii*) *Frequency of Lifted Index (LI)*

Table 2 shows that 3 out of 64 (*i.e*., 4.69%) thunderstorms / nor'westers occur when the LI is above 3° C at 0000 UTC, which indicates the stable atmosphere. 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 from the Bay of Bengal extending to a greater height in the afternoon. It is seen from the table that 10 out of 64 (15.63%) nor'westers occur when LI is 0 to +3° C. The table shows that 51 out of 64 (*i.e*., 79.68%) nor'westers occur when the LI < 0° C. The table also shows that maximum number of nor'westers occur in the range of LI is –3 to –6° C. As per the criteria of LI, no convective activity is possible when LI is above +2° C or above, showers are possible when LI ranges between 0 and –2°C, severe thunderstorms are likely when LI ranges between –2 to –4° C and tornadoes when LI is ≤ –4. It has been seen that 3 out of 5 severe nor'westers (60%) with marginal tornadic intensity occur when LI is < –3° C and 2 out of 5 severe nor'westers (40%) with marginal tornadic intensity when LI is 1 to –3° C.

From the above discussion, it may be concluded that thunderstorms are likely to occur over Bangladesh when LI is ≤ 0 and severe nor'westers with tornadic intensity are possible when LI < –3° C over Bangladesh.

(*iii*) *Dew- point Index (DPI) and its frequency*

Table 3 shows that 6 out of 64 (*i.e*., 9.38%) thunderstorms / nor'westers occur when the DPI is above 0° C at 0000 UTC, which indicates the stable atmosphere. It is seen from the table that 58 out of 64 (90.62%) nor'westers occur when DPI is ≤ 3° C. The table also shows that maximum number of nor'westers occur when DPI ranges between –6 to –9° C (26 out of 64 *i.e*., 40.63%). Therefore, DPI = –3° C may be taken as the critical value for the occurrence of nor'westers in

TABLE 10

K- Index (KI) and its frequency at 0000 UTC at Dhaka

Range of KI (°C)	Frequency (f)	% of the total
20 - 22	1	0.95
28 - 30	2	1.90
30 - 32	4	3.81
32 - 34	4	3.81
34 - 36	11	10.48
36 - 38	17	16.19
38 - 40	13	12.38
40 - 42	13	12.38
42 - 44	16	15.24
44 - 46	7	6.67
46 - 48	5	4.76
48 - 50	3	2.86
50 - 52	2	1.90
52 - 54	4	3.81
54 - 56	1	0.95
56 - 58	2	1.90
Total	105	100

Bangladesh. It has also been seen from the analysis of DPI that severe thunderstorms with tornadic intensity are likely to occur when DPI is < –4° C (4 out of 5 *i.e.*, 80%) and 20% severe nor'westers occur when DPI is > –2° C over Dhaka in the morning.

(*iv*) *Dry Instability Index (DII) and its frequency*

Table 4 shows that 7 out of 64 (*i.e.*, 10.94%) thunderstorms/nor'westers occur when the DII is above 0° C at 0000 UTC over Dhaka, which indicates the stable atmosphere. It is seen from the table that 57 out of 64 (89.06%) nor'westers occur when DII ≤ 0° C. The table also shows that maximum nor'westers occur when DII ranges between –3 and –6 (21 out of 64 nor'westers *i.e.*, 32.81%). Therefore, DII ≤ 0° C may be taken as the critical value for the occurrence of nor'westers in Bangladesh. It has also been seen from the analysis of DII that severe thunderstorms with tornadic intensity are likely to occur when DII is < –4° C (3 out of 5 *i.e.*, 60%) and 40% severe nor'westers occur when DII is > –2° C at Dhaka in the morning.

(*v*) *Cross Total Index (CT) and its frequency*

From Table 5 it is observed that the maximum nor'westers occur in the range of CT = 20-22° C, which is about 20.37% of the total number of nor'westers. About 67.59% nor'westers occur when the CT is ≥ 16° C. The table also shows that 84.25% nor'westers occur when CT range is 10-26° C. Therefore, the critical value of CT may be taken as CT ≥ 16° C. For severe nor'westers of tornadic intensity, 25% occur when CT < 10° C and 62.50% of severe nor'westers occur when CT > 20° C. Therefore, CT ≥ 20° C may be taken as the critical value for the severe nor'westers of tornadic intensity to occur in Bangladesh.

(*vi*) *Vertical Total Index (VT) and its frequency*

Table 6 shows that maximum nor'westers occur in the range of VT = 28-30° C, which is about 25.93% of the total number of nor'westers. About 92.59% nor'westers occur when the VT range is 24-34° C. The table also shows that 95.37% of nor'westers occur when VT > 24° C. The critical value of VT may be taken as VT ≥ 24° C. For severe nor'westers of tornadic intensity 31.25% occur when VT < 28° C, 68.75% occur when VT > 28° C and 31.25% of severe nor'westers occur when VT > 30° C. Therefore, VT ≥ 28° C may be taken as the critical value for the severe nor'westers of tornadic intensity to occur in Bangladesh.

(*vii*) *Total Totals Index (TT) and its frequency*

Table 7 shows that maximum nor'westers occur in the range of TT = 46 - 48° C, which is about 19.44% of the total number of nor'westers. About 87.96% nor'westers occur when the range of TT is 40 – 58° C. The critical value of TT may be taken as TT ≥ 40° C. For severe nor'westers of tornadic intensity, 68.75% occur when TT > 47° C and 56.25% of severe nor'westers occur when TT > 49.50° C. Therefore, TT ≥ 47° C may be taken as the critical value for the severe nor'westers of tornadic intensity to occur in Bangladesh. In one case (1 out of 16) of severe nor'wester with tornadic intensity, the TT has been found to be 31.30° C, which is much lower value. This low value may be attributed to the fact that the TT may be low in the morning and as the day time progress the atmosphere is more heated and more moisture is coming from the Bay of Bengal. As a result the atmosphere becomes more unstable and so nor'westers might have occurred.

(*viii*) *Energy Index (EI) and its frequency*

Table 8 shows that 19 out of 108 nor'westers (17.59%) occur when EI is above 0 Joule/gm and 89 out 108 nor'westers (82.41%) occur when EI is below 0 Joule/gm. 30 out of 108 nor'westers (27.78%) occur when EI ranges between 0 and –6 Joule/gm. Maximum

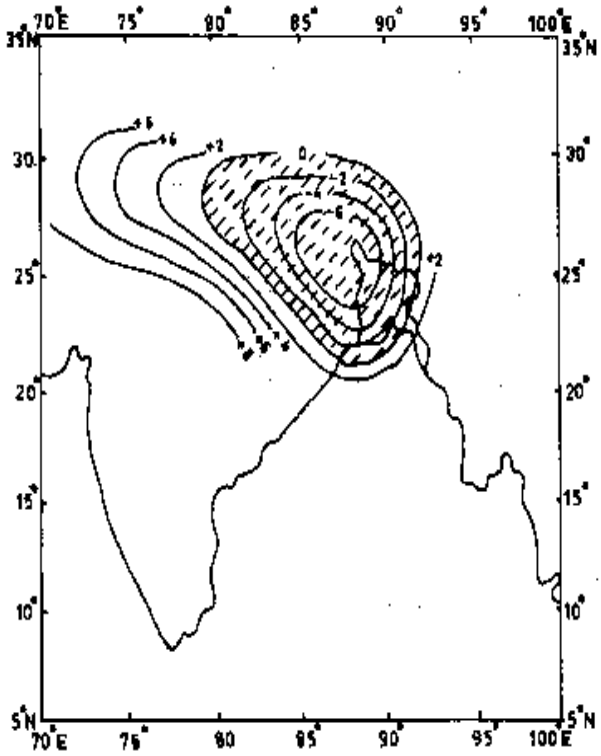

Fig. 1

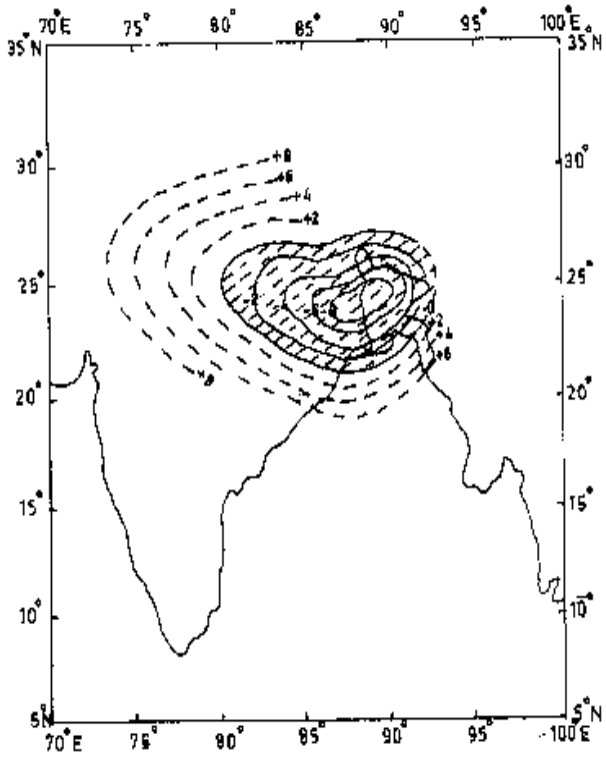

Fig. 2

Figs. 1&2. Spatial distribution of SI and LI on 14 April 1990, the date of occurrence of nor'wester in Bangladesh

number of nor'westers (36 out of 108 *i.e.*, 33.33%) occur when EI ranges between –6 and –12 Joule/gm. From the discussion, it may be concluded that EI = –6 can be taken as the critical value of EI at Dhaka for nor'westers to occur in Bangladesh. 18.75% of severe nor'westers (3 out of 16) occur when EI is 0 to –6 and 50% of severe nor'westers occur when EI ≤ –6. Therefore, EI ≤ –6 may be taken as the critical value of EI over Dhaka for the occurrence of severe nor'westers with tornadic intensity in Bangladesh.

It has also been observed that severe nor'westers with tornadic intensity occurred even though the atmosphere remains stable with EI of 0 - 7 (5 out of 16 *i.e.*, 31.25%) at 0000 UTC and it goes against the existing theory. This means that the stable atmosphere in the morning changes into unstable atmosphere in the afternoon due to incoming solar radiation, favourable surface and upper air synoptic conditions and moisture influx from the south.

(*ix*) *SWEAT Index (SWI) and its frequency*

It is seen from the Table 9 that 6 out of 108 nor'westers (5.56%) occur when SWI is ≤ 100 and 102 out of 108 (94.44%) nor'westers occur when SWI is ≥ 100. But maximum nor'westers (74 out of 108 *i.e.*, 68.52%) occur when SWI is > 200. So, SWI > 200 may be taken as the critical value for nor'westers to occur in Bangladesh. Table 9 also indicates that severe nor'westers may occur when SWI is < 200. But it clear that severe nor'westers have greater possibility to occur when SWI is > 200 and severe nor'westers with tornadic intensity occur in Bangladesh when SWI > 300. Therefore, SWI > 300 may be considered as the critical value for the formation of severe nor'westers with tornadic intensity over Bangladesh.

(*x*) *K- Index (KI) and its frequency*

Table 10 reveals that most of the values of KI ranges between 34 and 48, when 78.10% nor'westers occur in Bangladesh. It can also be seen from the table that maximum nor'westers occur in the range of KI = 36 - 38° C, which is about 16.19% of the total number of nor'westers. About 66.67% nor'westers occur when the range of KI is 34 - 44° C. The table also shows that 89.52% of nor'westers occur when KI > 34° C. The critical value of KI may be taken as KI ≥ 34° C. For severe nor'westers of tornadic intensity 86.67% occur

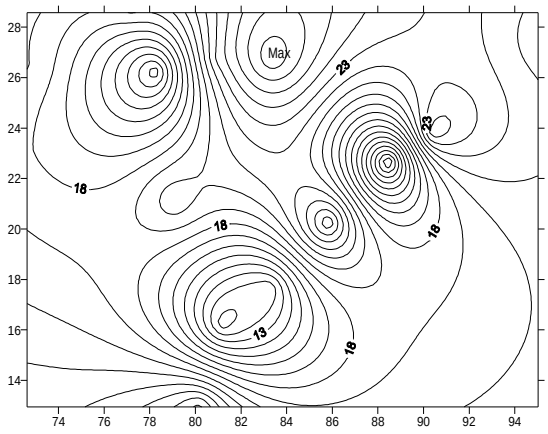

Fig. 3

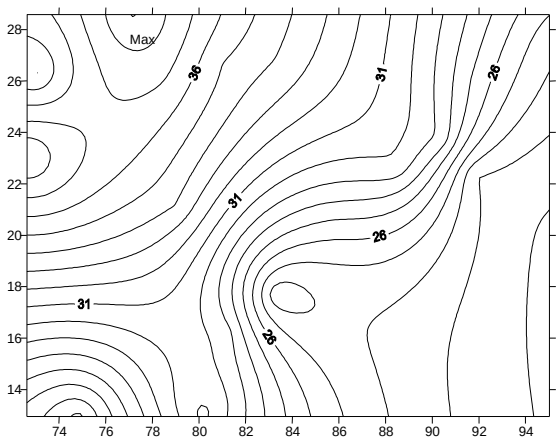

Fig. 4

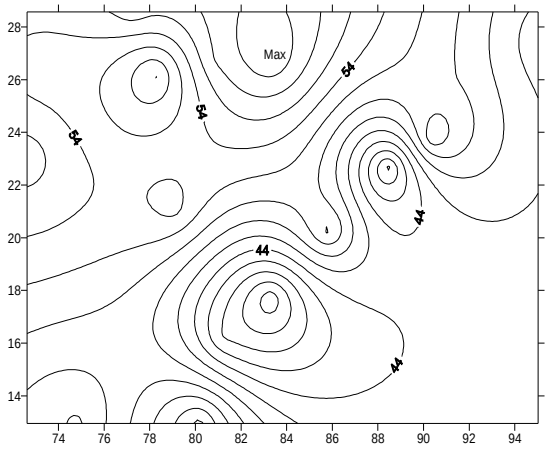

Fig. 5

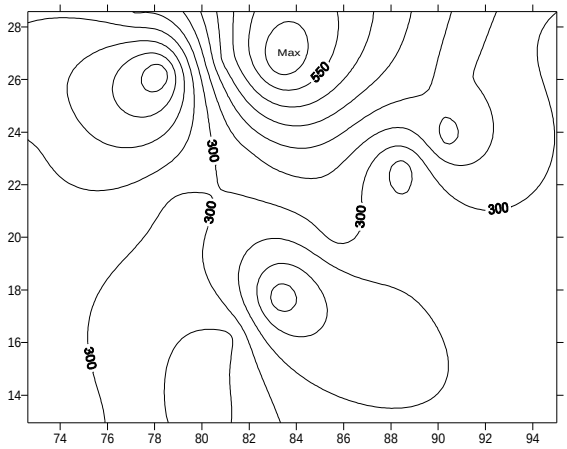

Fig. 6

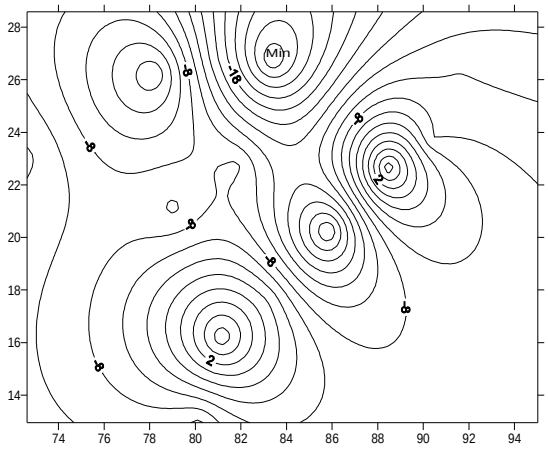

Fig. 7

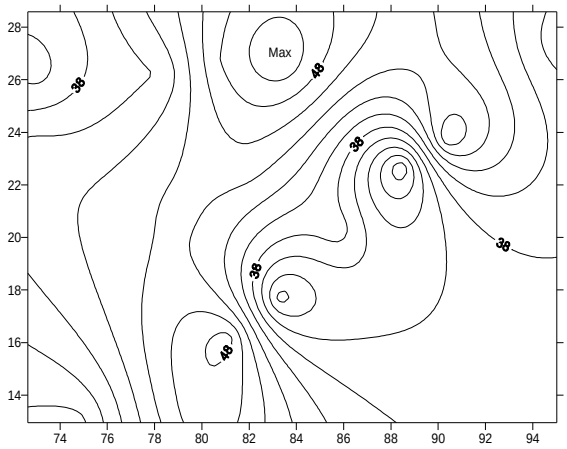

Fig. 8

Figs. 3-8. Spatial distribution of CT, VT, TT, SWI, EI and KI on 14 May 1992, the date of occurrence of nor'wester

when KI > 28° C, 73.33% occur when KI > 37°C and 53.33% of severe nor'westers occur when KI > 42° C. Therefore, KI ≥ 37° C may be taken as the critical value for the severe nor'westers of tornadic intensity to occur in Bangladesh.

4.2. *Spatial distribution of different instability indices*

The different 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 SI and LI on the dates of occurrence of nor'westers are given in Figs. 1&2. It has been seen from the analyses of these Stability Indices that maximum negative values lie over the eastern Madhya Pradesh, Bihar, West Bengal and adjoining Bangladesh indicating the highly unstable area. The negative 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. Normally, nor'westers have been found to occur at the northeastern or eastern part of the area of maximum instability.

The spatial distributions of CT, VT, TT, SWI and KI are given in Figs. 3-6 & Fig. 8 respectively. From the analyses of these indices, it has been found that an area of maximum values of these indices exists over eastern Madhya Pradesh, Bihar, West Bengal and adjoining Bangladesh indicating the highly unstable area. Nor'westers have also been found to occur at the northeastern or eastern part of the area of unstable area.

The spatial distribution of EI is shown in Fig. 7. It has been found from the analysis of EI that the area of minimum EI lies over eastern Madhya Pradesh, Bihar, West Bengal and adjoining Bangladesh, where the surface low and low-level circulation exist as has been observed from the analyses of surface and pilot charts (not shown here). The nor'westers have been found to occur at the northeastern or eastern part of the area of minimum EI, where the injection of moisture takes place from the Bay of Bengal. This area of minimum EI indicates the area of unstable atmosphere, which is favourable for the occurrence of nor'westers in Bangladesh.

5. Conclusions

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

(*i*) 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 nor'westers. But this stability may be thought of being destroyed because of the increasing day length, more incoming solar radiation and influx of moisture with its extension to a greater height in the troposphere.

(*ii*) The critical values of different stability indices *viz*., SI $\leq$ 3° C, LI $\leq$ 0° C, DPI $\leq$ -3° C, DII $\leq$ 0° C, CT $\geq$ 16° C, VT $\geq$ 24° C, TT $\geq$ 40° C, EI = -6, SWI > 200 and KI $\geq$ 34° C may be considered to occur nor'westers in Bangladesh.

(*iii*) The critical values of different stability indices *viz*., SI $\leq$ -3° C, LI $\leq$ -3° C, DPI $\leq$ -4° C, DII $\leq$ -4° C, CT $\geq$ 20° C, VT $\geq$ 28° C, TT $\geq$ 47° C, EI = -6, SWI > 300 and KI $\geq$ 37° C may be considered to occur severe nor'westers with tornadic intensity in Bangladesh.

(*iv*) Maximum negative values of SI**,** LI, DPI, DII and EI and maximum values of CT, VT, TT, SWI and KI lie over the eastern Madhya Pradesh, Bihar, West Bengal and adjoining Bangladesh indicating the highly unstable area. The negative 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. Normally, nor'westers have been found to occur at the northeastern or eastern part of the area of maximum instability.

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