

On the sensible heat energy, latent heat energy and potential energy of the troposphere over Dhaka before the occurrence of nor'westers in Bangladesh during the pre-monsoon season

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सार – इस शोध-पत्र में मानसून-पूर्व ऋतु के दौरान बांग्लादेश में काल बैसाखियों की घटना से पूर्व क्षोभमंडल के विभिन्न ऊर्जा घटकों का अध्ययन करने का प्रयास किया गया है। काल बैसाखियों की घटना की तारीखों में क्षोभमंडल के ऊर्जा घटकों की तुलना काल बैसाखियों की घटना न होने के दिन के ऊर्जा घटकों, साप्ताहिक और मासिक सामान्य मानों के साथ भी की गई है। मानसून-पूर्व ऋतु के दौरान क्षोभमंडल के संवेद्य ऊष्मा (एस.एच.) और गुप्त ऊष्मा (एल.एच.) में तत्त्वों में क्रमशः क्षोभमंडल की उष्णता और आर्द्रता की उपलब्धता के कारण मानसून-पूर्व ऋतु के आगे बढ़ने के साथ वृद्धि होती है। काल बैसाखियों की घटना की तारीख को क्षोभमंडल की संवेद्य ऊष्मा (एस.एच.) और गुप्त ऊष्मा (एल.एच.) की अधिकांश घटनाओं में क्रमशः धरातल के निकट से लगभग 300–200 hPa और लगभग 900 hPa स्तर से लगभग 400 hPa अथवा इससे अधिक की उल्लेखनीय रूप में वृद्धि होती है हालांकि इसमें अंतर-स्तर की भिन्नताएं होती हैं। 0000 यूटी.सी. पर क्षोभमंडल की गुप्त ऊष्मा में कमी बनी रहने पर निचले क्षोभमंडल में विशेष रूप से कुछ अपवाद होते हैं। ये अपवाद तड़के कभी कभी निचले वायुमंडल में कम नमी की उपलब्धता के कारण हो सकते हैं। इसमें यह भी पाया गया है कि काल बैसाखियों की घटना की तारीखों को क्षोभमंडल की एच.एस. और एल. एच. की अधिकांश घटनाओं में क्रमशः धरातल के निकट से लगभग 300–400 hPa में साप्ताहिक नार्मल से ऊपर और निचले क्षोभमंडल में ये महत्वपूर्ण हो जाती हैं। संवेद्य ऊष्मा 850 और 650 hPa स्तरों के मध्य परत में सामान्य से कम और 400–300 hPa परत में अधिक मात्रा में रहती हुई ऊपरी क्षोभमंडल में मासिक नार्मल से उल्लेखनीय रूप से ऊपर पाई गई है। गुप्त ऊष्मा निचले क्षोभमंडल में मासिक नार्मल से उल्लेखनीय रूप से ऊपर होती है और यह मध्य क्षोभमंडल में मासिक नार्मल से नीचे हो जाती है। मानसून-पूर्व ऋतु के दौरान क्षोभमंडल में वायु की मात्रा की माध्य मासिक स्थितिज ऊर्जा (पी. ई.) लगभग मध्य क्षोभमंडल तक निचले क्षोभमंडल में कम हो जाती है और इसके बाद मानसून-पूर्व ऋतु के आगे बढ़ने के साथ ऊपरी क्षोभमंडल में बढ़ जाती है। बहुत सी घटनाओं में काल बैसाखियों की घटना की तारीखों को धरातल के निकट पी. ई. में घटती हुई प्रवृत्ति पाई गई है और बाद में इससे उर्ध्वधर में अनियमित व्यवहार का पता चलता है। साप्ताहिक नार्मल से काल बैसाखियों की घटना की तारीखों को पी. ई. की भिन्नताएं निचले वायुमंडल में कम होती हैं और इससे किसी निश्चित प्रवृत्ति के आगे बढ़ने का पता नहीं चलता है।

ABSTRACT. Attempts have been made to study the different energy components of the troposphere prior to the occurrence of nor'westers in Bangladesh during the pre-monsoon season. The energy components of the troposphere on the dates of occurrence of nor'westers have also been compared with the energy components of non-occurrence day, weekly and monthly normal values. During the pre-monsoon season, the sensible heat (SH) and latent heat (LH) content of the troposphere increase as the season progresses due to the warming of the troposphere and availability of moisture respectively. The SH and LH of the troposphere on the dates of occurrence of nor'westers increases significantly from near the surface to about 300-200 hPa and about 900 hPa level to about 400 hPa or more respectively in most of the cases, although it has inter-layer variations. There are some exceptions especially in the lower troposphere where there exists decrease in LH of the troposphere at 0000 UTC. These exceptions may be due to the availability of less moisture in the lower atmosphere on some occasions early in the morning. It has also been found that the SH and LH of the troposphere on the dates of occurrence of nor'westers become significantly above weekly normal from near the surface to about 300-200 hPa and in the lower troposphere respectively in most of the cases. The SH is found to be below normal in the layer between 850 and 650 hPa levels and significantly above monthly normal in the upper troposphere, having maximum in the layer 400-300 hPa. The LH is significantly above the monthly normal in the lower troposphere, and it becomes below monthly normal in the mid-troposphere. During the pre-monsoon season, mean monthly potential energy (PE) of a parcel of air in the troposphere decreases in the lower troposphere upto about mid-troposphere and then

increases in the upper troposphere as the season progresses. The PE has a decreasing tendency near the surface on the dates of occurrence of nor'westers in many cases and then it shows erratic behaviour in the vertical. The variation of PE on the dates of occurrence of nor'westers from the weekly normal is minimum in the lower atmosphere and does not show any definite trend onwards.

Key words – Sensible heat, Latent heat, Potential energy, Nor'wester, Pre-monsoon season.

1. Introduction

Thunderstorms occur most frequently in the humid continental regions of the tropics. Bangladesh falls in the humid region of the tropics. As a result, the country faces severe thunderstorms especially during the pre-monsoon season. These thunderstorms are known as nor'westers in Bangladesh. The thunderstorm clouds *i.e.*, cumulonimbus clouds incur substantial vertical development where their tops usually reach well into the upper levels of the troposphere. However, most of the cumulonimbus cloud tops are restricted in height by the tropopause. As a norm, Cumulonimbus tops reach between 35,000 ft and 60,000 ft; and when they penetrate the stratosphere their tops can reach 70,000 ft (Krishnamurti, 2003). In order for a Cumulonimbus to develop into a severe storm there needs to be a mechanism to maintain the core of rising air and protect it from the effects of the cold failing precipitation. Rising air is lifted by an advancing squall line and results in a tilted updraft that is protected from the effects of falling precipitation. The development of severe storm clouds requires a strong feed of warm moist air into the base of the cloud and a contrasting feed of cooler air into the middle layers of the cloud. This mechanism is associated with the changes in the thermodynamic characteristics of the troposphere, especially the SH and LH of the troposphere. To study the changes in these thermodynamic properties before the occurrence of severe thunderstorms/nor'westers is an important task for a meteorologist in order to predict nor'westers.

In India-Bangladesh-Pakistan sub-continent, some works on nor'westers and local severe storms have been made by different authors such as Rai Sircar (1953), Koteswaram and Srinivasan (1958), Sen and Gupta (1961), De and Sen (1961), Nandi and Mukherjee (1966), Mukherjee and Bhattacharya (1972), Kumar (1972), Mukherjee *et al.*, (1977) and Chowdhury and Karmakar (1986). It may be mentioned that these works are not related to the tropospheric energy. Chowdhury *et al.*, (1991) studied some aspects of tropospheric energy in relation to nor'westers over Bangladesh by using data of one year only during March-May and studied a few cases only. They also studied some instability indices of the troposphere for these cases. Das *et al.*, (1994) made an investigation on the synoptic conditions and other meteorological conditions associated with the formation,

intensity and location of five local severe storms. But no extensive works have so far been made to study the changes in the thermodynamic properties prior to the occurrence of nor'westers in Bangladesh during the pre-monsoon season.

This paper is an attempt to study the SH, LH and PE of the troposphere over Dhaka before the occurrence of several nor'westers over Dhaka as well as Bangladesh with a view to find out some criteria for their occurrence. The results are likely to be useful in the forecasting of nor'westers.

2. Data used

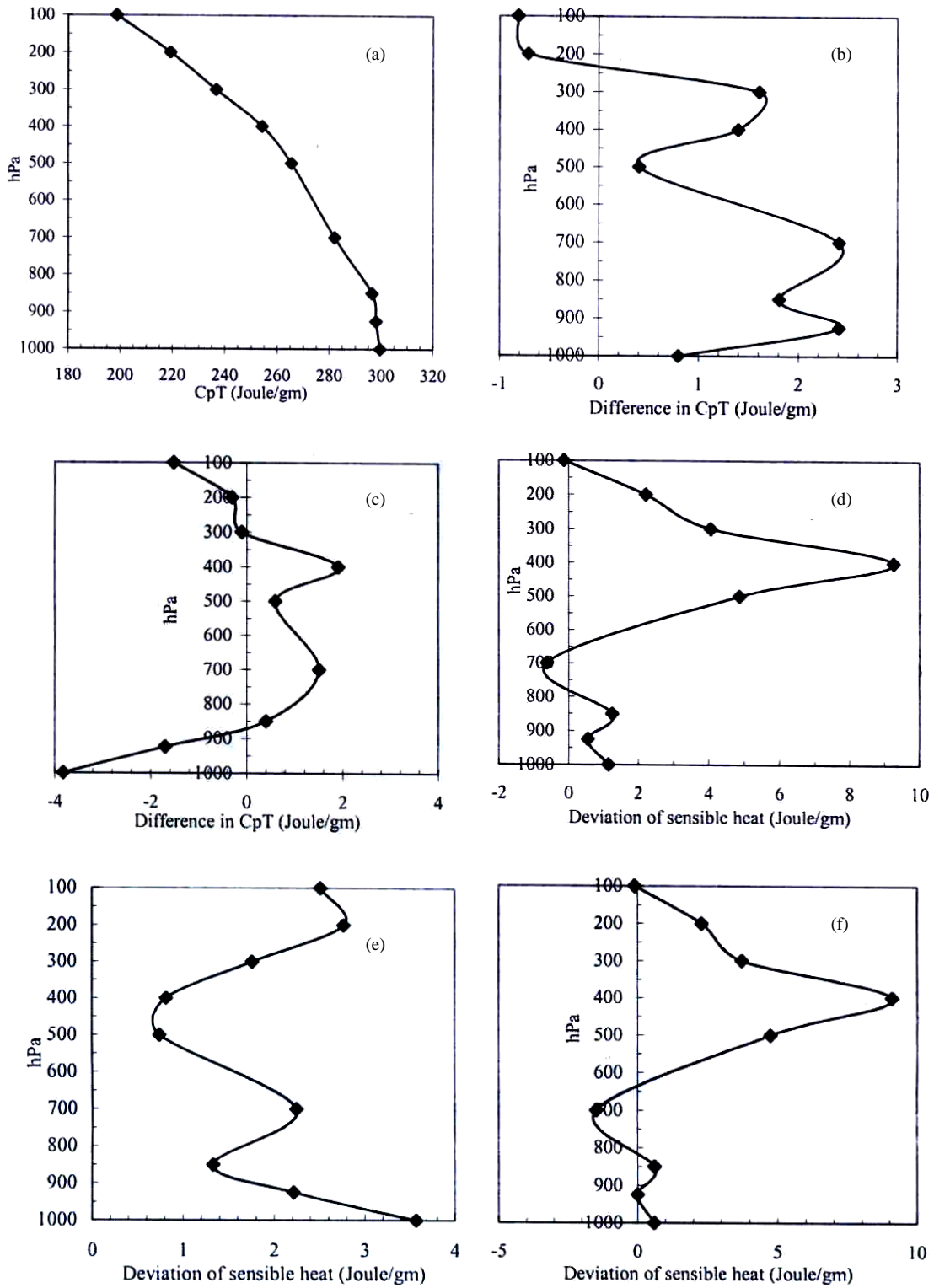
Real time rawinsonde data of 0000 UTC of March through May (*i.e.*, pre-monsoon season) during 1990-95 at different isobaric heights from 1000 to 100 hPa over Dhaka have been collected from the Bangladesh Meteorological Department (BMD) and the data have been used for this study. The date of 108 nor'wester which occurred in different locations of Bangladesh during the pre-monsoon season of 1990-95 has also been collected from BMD.

3. Method of analysis

Using the thermodynamic and hydrodynamic equations, the temperature, moisture, geopotential height in geopotential meter and velocity fields may be combined to obtain the equation for total energy of the troposphere. The total energy per unit mass of air may be expressed as

$$E = C_p T + gZ + Lq + \frac{1}{2}V^2 \quad (1)$$

Where C_p is the specific heat of air at constant pressure, T the temperature in °K, L the latent heat of phase change, q the specific humidity and V the scalar velocity. The kinetic energy term is normally two orders of magnitude smaller than the other terms and may be neglected. The first term $C_p T$ known as sensible heat per unit mass, the second term gZ is known as potential energy per unit mass and the third term Lq is known as the latent heat per unit mass.



Figs. 1(a-f). Vertical cross-section of SH on 23 March 1990 (date of occurrence), difference in SH on 7 April (date of occurrence), 6 April (date of non-occurrence), 1995 on 10 March (date of occurrence) and 9 March (date of non-occurrence), 1990 on 10 April 1990 and 16 May 1992 (date of occurrence), from the weekly normal on 10 April (date of occurrence) from the monthly normal respectively over Dhaka at 0000 UTC

TABLE 1

Monthly variation of SH, LH and PE of the troposphere over Dhaka at 0000 UTC during the pre-monsoon season

Pressure level (hPa)	Sensible heat (J/gm)			Latent heat (J/gm)			Potential energy (J/gm)		
	March	April	May	March	April	May	March	April	May
1000	296.52	298.98	300.05	30.22	38.52	41.90	0.88	0.63	0.41
925	294.18	297.46	297.73	21.56	26.02	34.03	7.54	7.36	7.15
850	290.62	294.75	295.28	15.60	17.10	25.23	14.69	14.57	14.37
700	279.78	282.16	284.40	8.24	10.15	14.37	30.56	30.66	30.56
500	264.18	265.19	268.44	1.89	2.25	3.55	56.78	56.75	57.15
400	252.86	254.02	258.48	0.86	1.03	1.62	72.90	73.58	74.00
300	237.24	239.89	244.42	0.17	0.29	0.53	93.02	93.43	94.70
200	221.06	221.64	223.68	0.006	0.01	0.024	120.19	120.62	121.88
100	199.62	199.31	196.80	0.00	0.00	0.00	161.64	162.13	163.22

These energy components are expressed in Joule/gm. The LH of phase change (L) is a function of air temperature and is given by

$$L = 597.3 - 0.566 (T-273) \text{ in Cal/gm} \quad (2)$$

The specific humidity (q) can be computed by using the equation:

$$q = \frac{0.62197 \times e}{P - 0.37803 \times e} \quad (3)$$

where e is the actual vapour pressure (hPa) and can be obtained from the Clausius-Clapeyron equation:

$$\ln \frac{e}{6.11} = \frac{18 \times 4.186 \times L}{8.3144} \left(\frac{1}{273} - \frac{1}{T_d} \right) \quad (4)$$

where T_d is the dew-point temperature in °K

4. Results and discussion

The daily rawinsonde observations at 0000 UTC over Dhaka from March to May (*i.e.*, pre-monsoon season) during 1990 through 1995 have been compiled for the standard isobaric heights from the surface to 100 hPa level. The results have been used to compute the daily, weekly and monthly mean values of the energy components for 6 years (1990-95). These mean values for 6 years have been treated as the daily, weekly and monthly normal in this study. The energy components such as SH, LH and PE on the dates of occurrence of several nor'westers, which occurred over Dhaka as well as

in Bangladesh during the pre-monsoon period of 1990-95, have been compared with the daily, weekly and monthly normal values as well as the normal values of the previous week. Comparison of the above energy components between the dates of occurrence and non-occurrence of several nor'westers has also been made in the present study. The maximum and minimum values of the energy components at each level of the troposphere over Dhaka for several cases of nor'westers have been picked up and studied graphically for obtaining a criterion for the occurrence of nor'westers. The results have been discussed in the subsequent sub-sections.

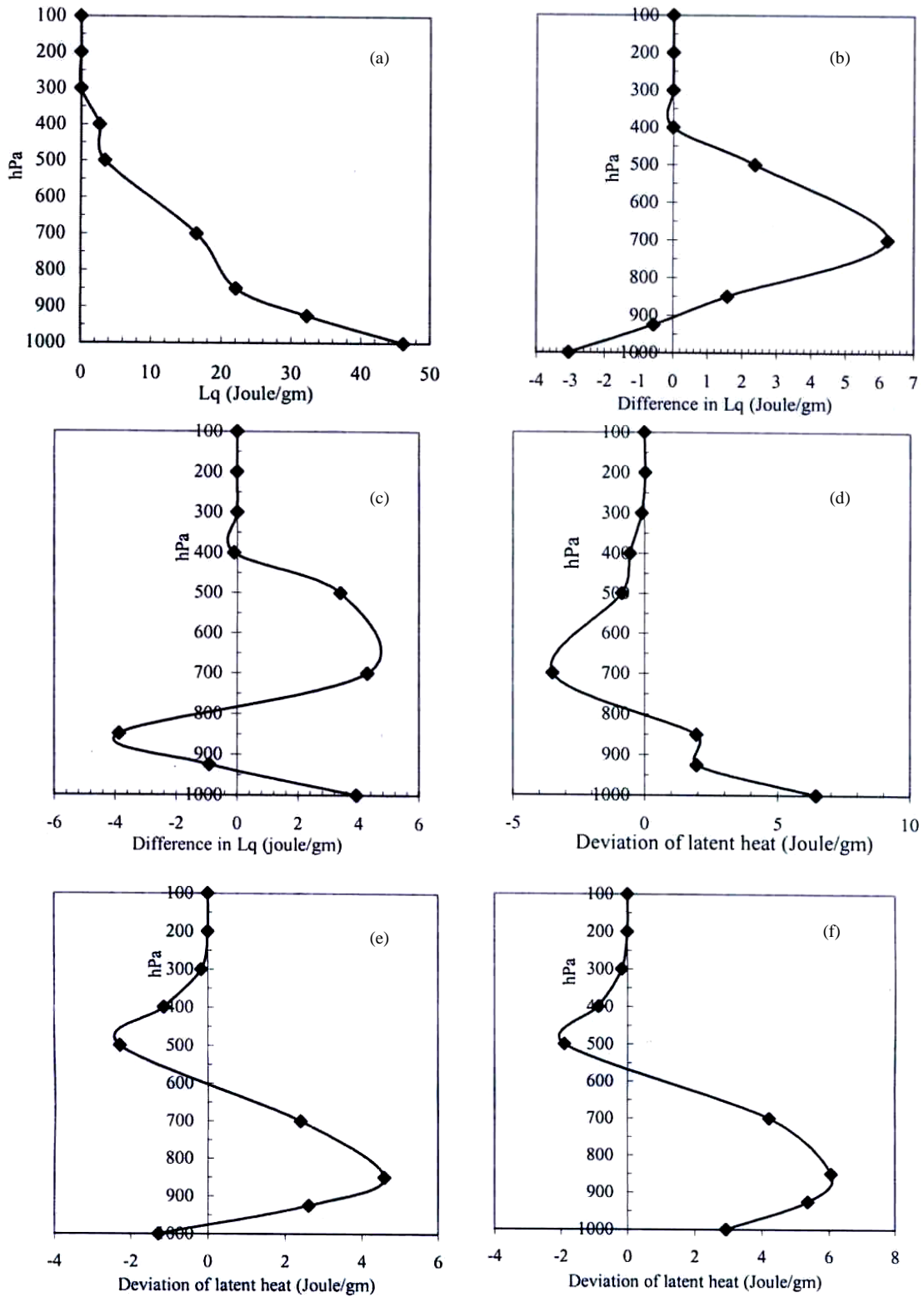
4.1. Sensible heat (SH) content of the troposphere

4.1.1. SH over Dhaka at 0000 UTC during the pre-monsoon season

The vertical cross-section of the SH of the troposphere over Dhaka at 0000 UTC has been studied for the pre-monsoon season. The vertical distribution pattern is shown in Fig. 1(a) as an example. The Figure shows that the SH of the troposphere decreases with height for obvious reason as the temperature decreases with height. During the pre-monsoon season, mean monthly SH of the troposphere has been computed by using the data for the period 1990-95 and the results are given in Table 1. The table shows that the SH of the troposphere increases as the season progresses.

4.1.2. Comparison of SH on the dates of occurrence and non-occurrence of nor'westers

The SH of the troposphere over Dhaka at 0000 UTC on the dates of occurrence and non-occurrence of



Figs. 2(a-f). Vertical cross-section of LH on 23 March 1990, difference in LH on 10 March (date of occurrence) and 9 March (date of non-occurrence), 1990 on 23 March (date of occurrence) and 22 March (date of non-occurrence), 1990 on 30 May 1992 and on 26 March 1993 (date of occurrence), from the weekly normal on 26 March 1993 (date of occurrence), from the monthly normal respectively over Dhaka at 0000 UTC

nor'westers has been compared with each other. The vertical cross-section of the difference in SH on the dates of occurrence and non-occurrence has been studied and some results are shown in Figs. 1(b-c) as an example. It has been found that the SH of the troposphere on the dates of occurrence of nor'westers increases significantly with that of non-occurrence day of nor'westers from near the surface to about 300-200 hPa in most of the cases, although it has inter-layer variations. Of course, there are some exceptions especially in the lower troposphere near the surface as can be seen from Fig. 1(c), where there exists decrease in SH of the troposphere at 0000 UTC. These exceptions may be due to the decrease in temperature on some occasions near the surface in the early morning because of cold air advection from the north/northwest.

4.1.3. *Comparison of SH on the dates of occurrence of nor'westers with the weekly normal*

The SH of the troposphere over Dhaka at 0000 UTC on the dates of occurrence of nor'westers has been compared with the weekly normal. The vertical cross-section of the deviation of SH on the dates of occurrence from the weekly normal has been studied and some results are given in Figs. 1(d-e) as an example. It has been found that the SH of the troposphere on the dates of occurrence of nor'westers increases significantly as compared to the weekly normal from near the surface to about 300-200 hPa or more in most of the cases, although it has inter-layer variations. The deviation of SH decreases and becomes normal or negative in the layer between 700 hPa and 500 hPa levels. This may be due to the decrease in temperature in the early morning because of cold air advection from the north/northwest. This cold air advection in this layer from the north/northwest is very essential to create the required instability for the formation of thunderstorms in conjunction with the warm and moist air advection in the lower troposphere.

4.1.4. *Comparison of SH on the dates of occurrence of nor'westers with the monthly normal*

The SH of the troposphere over Dhaka at 0000 UTC on the dates of occurrence of nor'westers has been compared with the monthly normal. The vertical cross-section of the deviation of SH on the dates of occurrence from the monthly normal has been studied and the vertical variation pattern is shown in Fig. 1(f) as an example. It has been seen that the deviation of SH from the monthly normal is positive in the lower troposphere and then it becomes negative in the layer between 850 and 650 hPa levels. Then the deviation increases tremendously in the upper troposphere, having maximum in the layer 400-300 hPa. The negative value in the layer between 850 and 650 hPa levels may be attributed to the cold air advection.

4.2. *Latent heat (LH) content of the troposphere*

4.2.1. *LH over Dhaka at 0000 UTC during the pre-monsoon season*

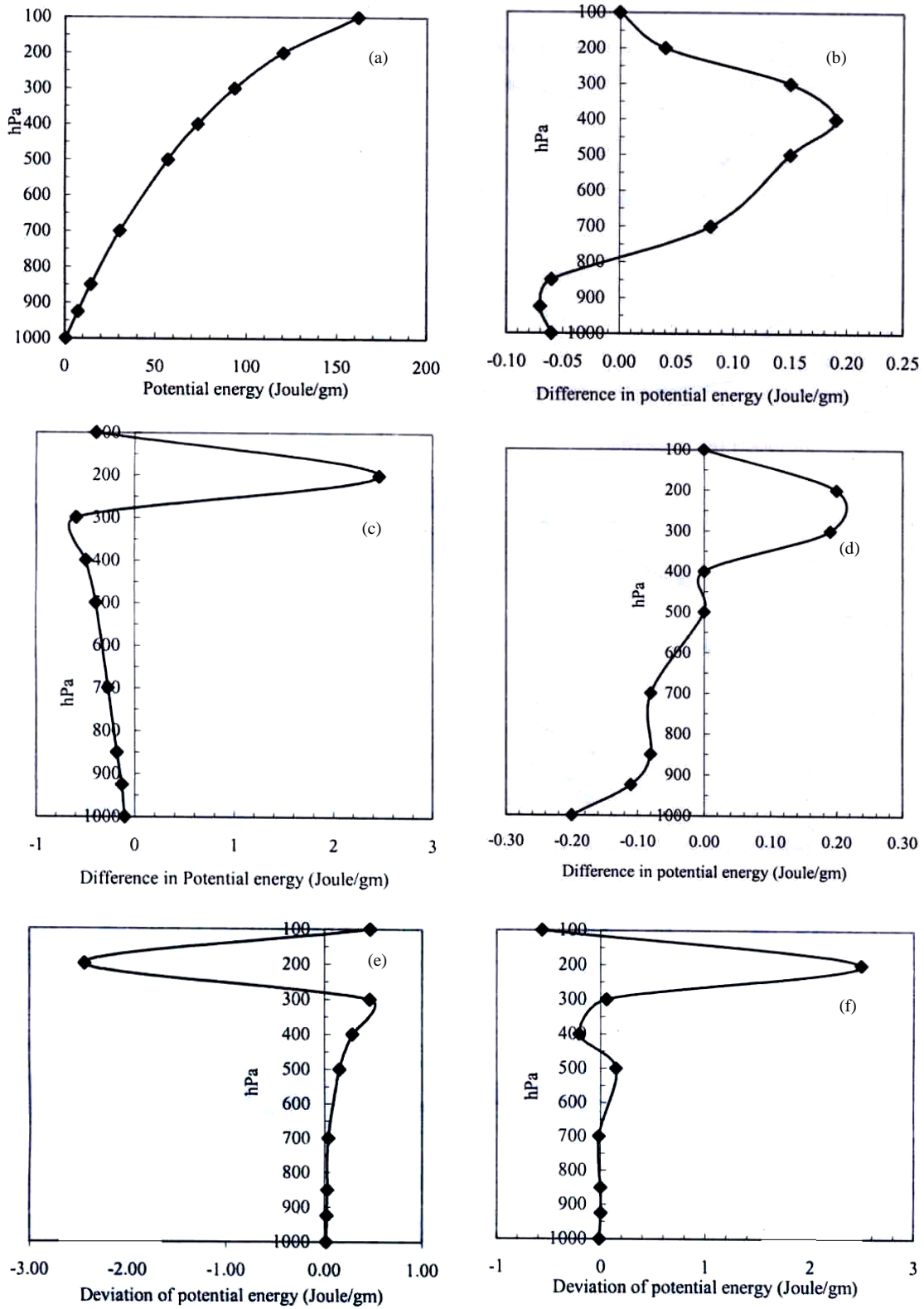
The vertical cross-section of the LH of the troposphere over Dhaka at 0000 UTC has been studied for the pre-monsoon season. The Fig. 2(a) shows that the LH of the troposphere decreases with height for obvious reason as the moisture decreases with height. The LH of the troposphere becomes zero at 100 hPa level. During the pre-monsoon season, mean monthly LH of the troposphere has been computed by using the data for the period 1990-95 and the results are given in Table 1. The Table shows that the LH of the troposphere increases as the season progresses. The Table also shows that more LH extends upto the top layer of the troposphere as the season progresses

4.2.2. *Comparison of LH on the dates of occurrence and non-occurrence of nor'westers*

The LH of the troposphere over Dhaka at 0000 UTC on the dates of occurrence and non-occurrence of nor'westers has been compared with each other. The vertical cross-section of the difference in LH on the dates of occurrence and non-occurrence has been studied, and some results are shown in Figs. 2(b-c) as an example. It has been found that the LH of the troposphere on the dates of occurrence of nor'westers increases significantly from about 900 hPa level to about 400 hPa or more in most of the cases, although it has inter-layer variations. Of course, there are some exceptions especially in the lower troposphere as can be seen from Figures, where there exists decrease in LH of the troposphere at 0000 UTC. These exceptions may be due to the availability of less moisture in the lower atmosphere on some occasions early in the morning. But there is a significant increase in LH above 900 or 850 hPa level, which extends upto about 400 hPa level. This may be attributed to the latent release due to condensation of moisture near the base of the thunderstorm clouds on the date of occurrence of nor'westers.

4.2.3. *Comparison of LH on the dates of occurrence of nor'westers with the weekly normal LH*

The LH of the troposphere over Dhaka at 0000 UTC on the dates of occurrence of nor'westers has been compared with the weekly normal. The vertical cross-section of the deviation of LH on the dates of occurrence from the weekly normal has been studied and some results are shown in Figs. 2(d-e) as an example. It has been found that the LH of the troposphere on the dates of occurrence of nor'westers increases significantly as compared to the weekly normal in the lower troposphere in most of the



Figs. 3(a-f). Vertical cross-section of PE on 23 March 1990, difference in PE on 30 March (date of occurrence) and 29 March (date of non-occurrence), 1995 on 17 April (date of occurrence), and 16 April (date of non-occurrence), 1994 on 20 April (date of occurrence) and 19 April (date of non-occurrence) 1995 on 17 April (date of occurrence) 1994 from the monthly normal respectively over Dhaka at 0000 UTC

TABLE 2
Comparison of PE over Dhaka at 0000 UTC on the dates of occurrence of nor'westers in Bangladesh with that of the weekly normal and monthly normal

Pressure level (hPa)	Total cases	% Frequency			
		Above weekly normal	Below weekly normal	Above monthly normal	Below monthly normal
1000	107	45.79	54.21	47.66	52.34
925	108	50.00	50.00	51.85	48.15
850	108	50.93	49.07	51.85	48.15
700	108	57.41	42.59	57.41	42.59
500	108	55.56	44.44	57.41	42.59
400	108	47.22	52.78	47.22	52.78
300	108	50.00	50.00	42.59	57.41
200	108	45.37	54.63	36.11	63.89
100	107	51.40	48.60	50.47	49.53

cases, although it has inter-layer variations. The deviation of LH decreases and becomes normal or negative in the mid-troposphere. This may be due to the non-availability of moisture and delay of condensation process in the early morning.

4.2.4. Comparison of LH on the dates of occurrence of nor'westers with the monthly normal

The LH of the troposphere over Dhaka at 0000 UTC on the dates of occurrence of nor'westers has been compared with the monthly normal. The vertical cross-section of the deviation of LH on the dates of occurrence from the monthly normal has been studied and the vertical variation pattern is shown in Fig. 2(f) as an example. From figure it has been found that the deviation of LH from the monthly normal is positive and significantly above the monthly normal in the lower troposphere and then it becomes negative in the mid-troposphere. It becomes zero in the upper troposphere.

4.3. Potential energy (FE) of a parcel in the troposphere

4.3.1. FE over Dhaka at 0000 UTC during the pre-monsoon season

The vertical cross-section of PE of a parcel of air in the troposphere over Dhaka at 0000 UTC has been studied for the pre-monsoon season. The vertical distribution pattern of PE is shown in Fig. 3(a) as an example. From

figure it has been found that the PE of a parcel in the troposphere increases with height. During the pre-monsoon season, mean monthly PE of a parcel in the troposphere for the period 1990-95 is given in Table 1. The table shows that the PE of a parcel decreases in the lower troposphere up to about mid-troposphere and then increases in the upper troposphere. This indicates that contour height decreases in the lower troposphere and increases in the upper troposphere as the season progresses. The decrease in contour height in the lower troposphere is related with the decrease in surface pressure with the advance of the season.

4.3.2. Comparison of PE on the dates of occurrence and non-occurrence of nor'westers

The PE at different levels of the troposphere over Dhaka at 0000 UTC on the dates of occurrence of nor'westers has been compared with that on the dates of non occurrence of nor'westers and some results showing the difference in PE between the two dates are given in Figs. 3(b-d) as an example. It has been found that the PE has a decreasing tendency near the surface on the dates of occurrence of nor'westers in many cases and then it shows erratic behavior in the vertical.

4.3.3. Comparison of PE on the dates of occurrence of nor'westers with the weekly normal

The PE of a parcel of air in the troposphere over Dhaka at 0000 UTC on the dates of occurrence of

nor'westers has been compared with the weekly normal PE. The vertical cross-section of the deviation of PE on the dates of occurrence from the weekly normal has been studied and result is shown in Fig. 3(e) as an example. It has been found that the variation of PE is minimum in the lower atmosphere and does not show any definite trend (either above normal or below normal) onwards.

Table 2 gives the comparison of PE on the dates of occurrence of nor'westers with the weekly normal PE for about 108 nor'westers. It is seen that the PB is below normal at 1000 hPa level in 54.21% cases and it is normal or above normal from 925 hPa to 500 hPa level in many cases. There is no definite trend of variation in PB in the upper troposphere.

4.3.4. Comparison of PE on the dates of occurrence of nor'westers with the monthly normal

The PE of a parcel of air in the troposphere over Dhaka at 0000 UTC on the dates of occurrence of nor'westers has been compared with the monthly normal PE. The result of vertical cross-section of the deviation of PE on the dates of occurrence from the monthly normal is shown in Fig. 3(f) as an example. From figure it has been found that the variation of PE is minimum in the lower atmosphere and does not show any definite trend (either above normal or below normal).

Table 2 also gives the comparison of PE with the monthly normal PB for about 108 nor'westers. It is seen that the PE is below normal at 1000 hPa level in 52.34% cases and it is above normal from 925 hPa to 500 hPa level in many cases. The PE becomes below monthly normal in many cases up to 200 hPa level.

5. Conclusions

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

(i) During the pre-monsoon season, the SH of the troposphere increases as the season progresses due to the warming of the troposphere. The SH of the troposphere on the dates of occurrence of nor'westers increases significantly from near the surface to about 300-200 hPa in most of the cases. There are some exceptions may be due to the decrease in temperature on some occasions near the surface in the early morning because of cold air advection from the north/northwest.

(ii) The SH of the troposphere on the dates of occurrence of nor'westers increases significantly as compared to the weekly normal from near the surface to about 300-200 hPa or more in most of the cases. The SH on the dates of

occurrence of nor'westers is above monthly normal value in the lower troposphere and in the layer 400-300 hPa levels and it becomes below normal in the layer 850-650 hPa levels.

(iii) During the pre-monsoon season, mean monthly LH of the troposphere increases as the season progresses. The LH of the troposphere on the dates of occurrence of nor'westers increases significantly from about 900 hPa level to about 400 hPa or more in most of the cases, although it has inter-layer variations. There are some exceptions may be due to the availability of less moisture in the lower atmosphere on some occasions early in the morning.

(iv) The LH on the dates of occurrence of nor'westers increases significantly as compared to the weekly normal in the lower troposphere in most of the cases. In the lower troposphere the LH is significantly above the monthly normal and in the mid-troposphere it becomes below monthly normal.

(v) During the pre-monsoon season, mean monthly PE of a parcel in the troposphere decreases in the lower troposphere upto about mid-troposphere and then increases in the upper troposphere. The PE has a decreasing tendency near the surface on the dates of occurrence of nor'westers in many cases and then it shows erratic behaviour in the vertical.

(vi) The variation of PE from the weekly normal is minimum in the lower atmosphere and does not show any definite trend onwards. The PE remains below weekly normal at 1000 hPa level in 54.21% cases and it is normal or above normal from 925 hPa to 500 hPa level in many cases. The PE at 0000 UTC on the dates of occurrence of nor'westers has been nearly monthly normal in the lower atmosphere. The PE remains below monthly normal at 1000 hPa level in 52.34% cases and above normal from 925 hPa to 500 hPa level in many cases.

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References

- Chowdhury, M. H. K. and Karmakar, S., 1986, "Pre-monsoon nor'westers in Bangladesh with case studies", Proceedings of the Seminar on Local Severe Storms (SAARC), Dhaka, Bangladesh, 147-166.

- Chowdhury, M. H. K., Karmakar, S. and Khatun, A., 1991, "A diagnostic study on some aspects of tropospheric energy in relation to nor'westers over Bangladesh", Proceedings of the Seminar on Severe Local Storms (SAARC), Colombo, Sri Lanka, 19-28.
- 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.
- De, A. C. and Sen, S. N., 1961, "A radar study of pre-monsoon thunderstorms (nor'westers) over Gangetic West Bengal", *Indian J. Met. Geophys.*, **12**, 1, 51-60.
- Kumar, S., 1972, "An objective method of forecasting pre-monsoon thunderstorm/duststorm activity over Delhi and neighbourhood", *Indian J. Met. Geophys.*, **23**, 1, 45-50.
- Koteswaram, P. and Srinivasan, V., 1958, "Thunderstorms over Gangetic West Bengal in pre-monsoon season and the synoptic factors favourable for their formation", *Indian J. Met. Geophys.*, **9**, 4, 301-312.
- Krishnamurti, T. N., 2003, "Compendium on tropical meteorology for Aviation purposes, WMO-No. **930**, 28-30.
- Mukherjee, A. K. and Bhattacharya, P. B., 1972, "An early morning tornado at Diamond Harbour on 21 March, 1969", *Indian J. Met. Geophys.*, **23**, 2, 223-226.
- Mukherjee, A. K., Kumar, S. and Krishnamurty, G., 1977, "A radar study of growth and decay of thunderstorms around Bombay during pre-monsoon season", *Indian J. Met. Geophys.*, **28**, 4, 475-478.
- Nandi, J. and Mukherjee, A. K., 1966, "Tornado over north-west Assam and adjoining West Bengal on 19 April, 1963", *Indian J. Met. Geophys.*, **17**, 3, 421-426.
- Rai Sircar, N. C., 1953, "On the use of tephigrams for forecasting of nor'westers", *Indian J. Met. Geophys.*, **4**, 2, 269-278.
- Sen, S. N. and Sen Gupta, J. R., 1961, "A pre-monsoon thunderstorms with torn characteristics at Calcutta", *Indian J. Met. Geophys.*, **12**, 1, 41-48.
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